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# The Origin of Nonradiative Heating/Momentum in Hot Stars

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**NASA**



# The Origin of Nonradiative Heating/Momentum in Hot Stars

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Greenbelt, Maryland  
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## OPENING REMARKS

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This colloquium/workshop has been sponsored by the National Aeronautics and Space Administration and by the American Astronomical Society. We shall now begin three days of what I hope will prove to be invigorating talks and discussion.

Today we will refresh our memories about the evidence for the deposition of non-radiative energy and momentum in stellar atmospheres. A useful question to ask is how much nonradiative energy and momentum is deposited in the atmospheres of different stars.

Tomorrow we will review what has been established already by theory about the action of possible sources of nonradiative energy and momentum in the atmospheres of different stars. What are the possible sources of the additional energy and momentum deduced to be present in stellar atmosphere? What facilitates the transfer of energy and momentum from the source to the plasma?

On Thursday we shall concentrate on the early-type stars and try to clarify our conception of what is going on. It is important to do this, particularly for stars having spectral types earlier than about B2 because it turns out that the empirically selected classification criteria for such spectral types are to a great extent influenced by the amount of nonradiative energy deposited in the atmosphere. Traditionally, one considers a spectral type to be uniquely determined by the radiation field, that is by  $T_{\text{eff}}$ . We can no longer assume this, however.

We have had three forced cancellations which I am sure you will regret as much as I do: (1) Lawrence Aller has to go into hospital and therefore cannot be with us. Perhaps some of you would like to join in sending a "Get-Well" card to him; (2) Sidney Wolff, because of her obligations at Hawaii and at Kitt Peak cannot now join us, and (3) NASA has detailed Jim Ionson to work in downtown Washington for the next three months. We shall miss all of these people; each contributed much to organizing this conference.

Let us get to work.

# EVIDENCE FOR NON-RADIATIVE ACTIVITY IN HOT STARS

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## INTRODUCTION

Early-type stars are extremely luminous and the stars don't have outer-convection zones that carry a significant fraction of the luminosity. As a result, stellar wind theorists have focused on radiation processes that are surely occurring in the outer atmospheres, such as radiative acceleration and radiative heating. At this meeting we are being asked to consider departures from the radiative model. The departures can be discovered in several ways. First, from a theoretical perspective we can push the radiative theory to its limits, including all processes likely to couple gas flow with the outward flow of radiation (Castor et al. 1975; Abbott 1980, 1982). The most recent addition is inclusion of radiation driven shocks that may perhaps explain the soft X-ray flux from the stars (Lucy and White 1980, Lucy 1982). The computational approach is certainly necessary at some stage if we are to develop a real understanding of the mechanisms operating in the outer atmospheres. However, it inclines one to picture the atmosphere as spherically symmetric and in a state of steady radial outflow, as is assumed in setting up the mathematical problem. A second approach is to compare observations of large numbers of stars with general correlations that should arise from radiative models. For example, the terminal velocity and mass loss rates should depend on the stellar effective temperature, gravity, and luminosity to mass ratio. Broad spreads around the expected correlation would suggest that the radiative models are incorrect. However, stellar wind theorists can usually overcome these criticisms by adding another parameter to the radiative model. For example, Castor (1979) and Friend and MacGregor (1984) have shown that stellar rotation can modify wind velocity distributions. A third approach is to look for a few isolated observations that strongly violate the radiative model. This is the approach I will take here. In some cases this approach can appear to be unfair in that perhaps only a few out of dozens of observations violate the radiative expectations and yet I will focus on those "odd" cases. Nevertheless, the approach provides a guide to search for the many other anomalies that may exist.

It is useful to have an example of a non-radiative model to direct our discussions. I suggest we consider the well-known Skylab X-ray images of the sun (Vaiana, Krieger, and Timothy 1973). What we see is a broad array of magnetic structures, some extending above the photosphere by a tenth of a solar radius or more, and some tight loops containing very hot gas. Then we should note the flow from the sun comes primarily from the coronal hole regions. In a rather loose way, I will call flow from an isolated region of a stellar surface, a "plume." With the solar picture in mind, we should be looking for the following properties in at least some hot stars.

1) Evidence for high temperature regions, especially regions that are too hot to be explained by shocks that can be initiated and driven by radiative forces. As in the solar case, X-ray observations should be especially useful for discovering these hot regions.

2) Evidence for multi-plume flow. Non-spherically symmetric flow can be diagnosed by the effect it can have on the polarization of the light from a star. Surface dependent flow can also affect ultraviolet line profiles and may produce variability on rotational time scales.

3) Direct evidence for stellar magnetic fields. The fields can be detected through Zeeman-effect observations or through gyro-resonance radiation measured at radio wavelengths.

Unfortunately, there are only a few cases in which simultaneous observations are available for a star showing any one of these effects. Hopefully this situation will change in the near future.

Let us proceed by considering observational data from X-ray through to radio wavelengths. A wide variety of early type stars will be encountered as they show peculiarities that are dominant in one spectral region or another.

## II. X-RAY EVIDENCE

The X-ray emission from hot stars was discovered in the first observations of the Einstein Satellite (Harnden *et al.* 1979; Seward *et al.* 1979). For O stars the observed X-ray luminosity is proportional to the total stellar luminosity,  $L_X \approx 10^{-7} L_{\text{Bol}}$ . In several early reviews it was stated that this relation held for all early type stars extending as late as A7. That is no longer thought to be the case as none of the bright early A stars is now considered to be an X-ray source; the apparent detection of these stars can be attributed to ultraviolet "leaks" of the Einstein HRI detector (Golub 1984). Perhaps the break from the  $10^{-7} L_{\text{Bol}}$  law occurs as early as B2. Figure 1 shows  $L_X/L_{\text{Bol}}$  versus spectral type derived from observations with the imaging Proportional Counter (IPC). There is a rather large scatter around the  $10^{-7} L_{\text{Bol}}$  law that is probably real. As for the main sequence stars note the large difference in the  $L_X/L_{\text{Bol}}$  ratio for  $\tau$  Sco (B0 V) and  $\zeta$  Oph (O9.5 V). The latest main sequence star detected is HD 93695 (B5 V). There is a sharp decrease in the  $L_X/L_{\text{Bol}}$  ratio in the B supergiants beyond B2 as determined either from the IPC observations or from the effects of X-rays on ionization conditions in the wind.

More detailed information about the X-ray emitting regions in the hot stars can be derived from the X-ray spectra measured with the IPC and with the Solid State Spectrometer (SSS). Figure 2 shows the SSS spectra of the belt stars of Orion (Cassinelli and Swank 1983). The overall distribution is like that expected from a gas at a temperature of  $\sim 3 \times 10^6$  K. The stars spectra look rather similar and the X-ray flux is not strongly variable. There is no obvious absorption at 0.6 keV as might be expected from the K-shell edge of the oxygen atoms in the stellar winds. This presents a problem for spherically symmetric models in which X-rays are

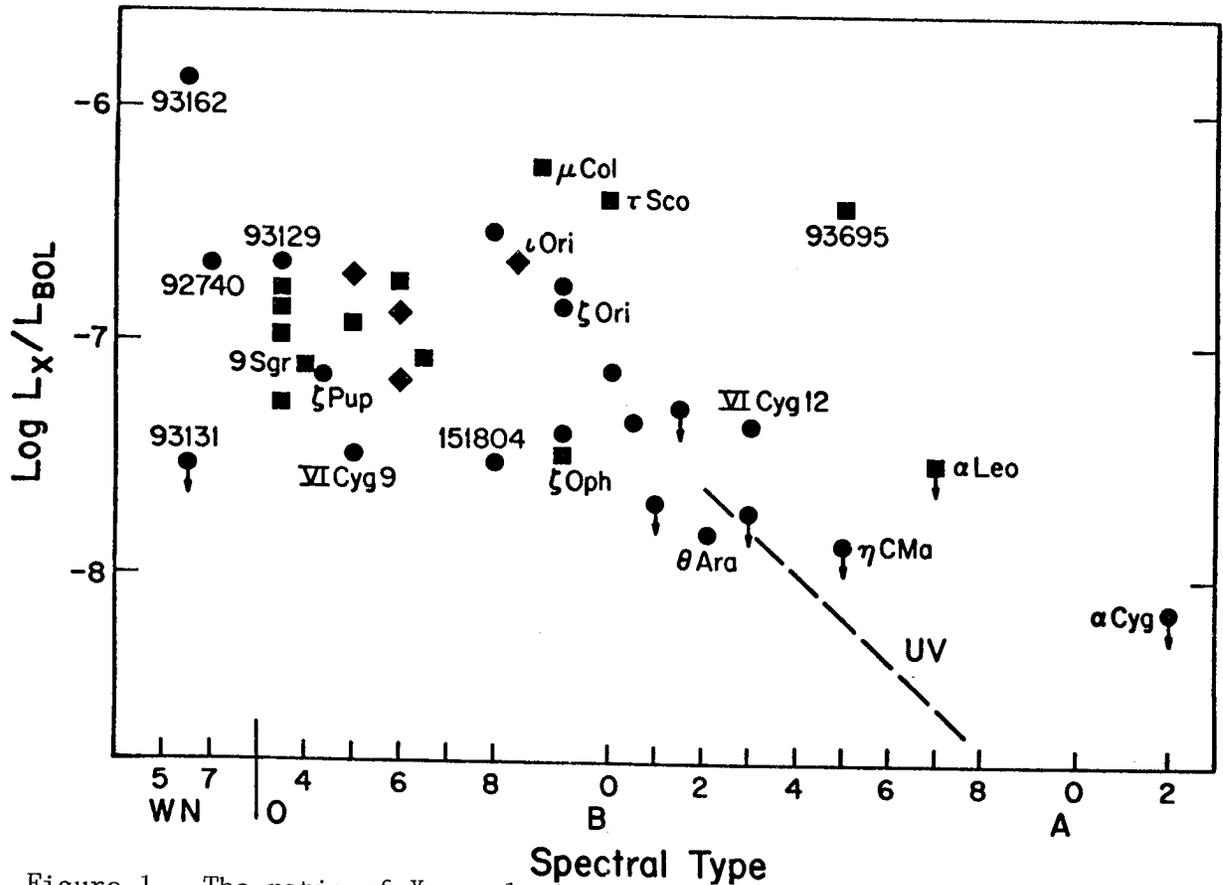


Figure 1. The ratio of X-ray luminosity to total luminosity as a function of spectral type for Wolf-Rayet and early-type stars. Main sequence stars are represented by squares, giants by diamonds, supergiants and other stars by circles. The dashed line labelled shows the X-ray luminosity of B supergiants based on estimates from Auger enhanced ultraviolet resonance lines (Odegard and Cassinelli 1982). The X-ray data are from Pallavicini *et al.* 1981, Cassinelli *et al.* 1981, and Bookbinder, 1984.

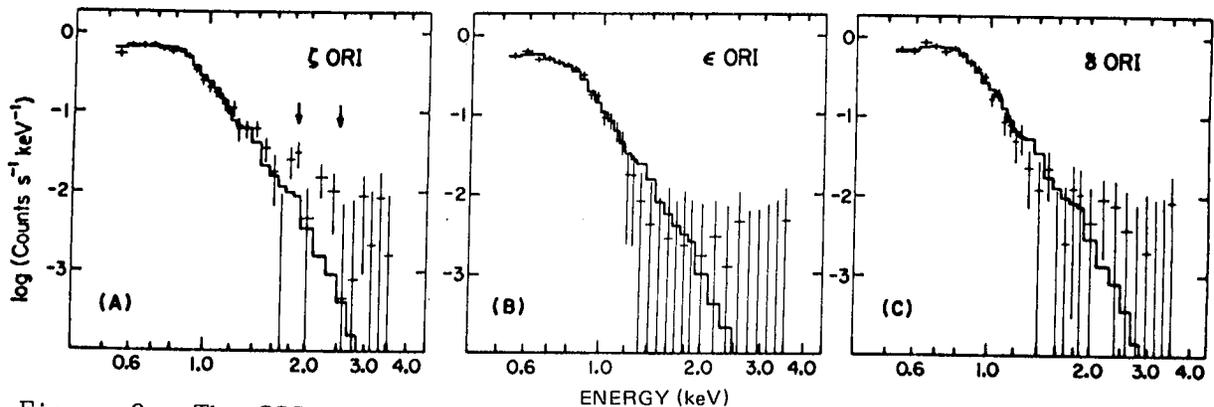


Figure 2. The SSS spectra of the three belt stars of Orion are shown with  $1\sigma$  error bars. The best fit single-component thermal source model is also shown for each spectrum. The arrows in the  $\zeta$  Ori frame indicate the location of lines Si XIII and S XV.

produced in thin regions near the base of the wind. Figure 3 shows a fit to the  $\epsilon$  Ori (B0 Ia) X-ray spectra derived from the thin base coronal model of Waldron (1984). A similar problem occurs for the shocked wind model of Lucy and White (1980) in which X-rays are generated by blob-wind interaction regions relatively close to the star. The lack of the 0.6 keV X-ray absorption has been taken as support for models in which X-rays are produced entirely by periodic shocks embedded in radiation driven winds (Lucy 1982). If that explanation is correct then the X-rays tell us nothing about possible non-radiative structures at the base of the wind. However, there are some problems with the purely radiatively driven shock model and there are reasons to propose that some of the X-ray flux arises from magnetic structures at the base of the wind.

Figure 4 shows a comparison of Lucy's shock model with the  $\zeta$  Ori spectrum. The quantity  $v$  is a measure of the shock strength in the periodic shock model. The expected value in the theory is 0.4; this however produces far too few X-rays. If the shock parameter is increased to  $v = 3.4$ , the correct spectral distribution is attained, but now there are too many X-rays, so perhaps only 1 percent of the shocks need be strong. Having so few of the shocks producing essentially all of the X-rays would lead to large variations of the X-ray luminosity on the flow time scale of hours, and that is not observed. A plausible compromise is that strong shocks exist in the wind in the form of many small wisps, but there are other problems with the radiation driven shock model. The mechanism should only work for stars with strong winds; the Of stars and OB supergiants. Yet main sequence stars like  $\tau$  Sco and  $\zeta$  Oph are strong sources. For such stars the densities in the wind are low and the cooling is not sufficiently rapid to support the continual generation of shocks. The line radiative driving requires temperatures of order  $3 \times 10^5$  or less. This difficulty in regards to  $\tau$  Sco is discussed by Lucy and White (1980). Even for the Of and OB supergiants there may be problems. Lucy (1984) finds that when line scattering is accounted for the winds are an order of magnitude more stable against radiative shock growth than had been assumed previously. (However see Owocki and Rybicki; these proceedings.)

Let us therefore take a closer look at base coronae as the possible locations of the X-ray emission. Figure 5 shows the SSS spectrum of  $\zeta$  Ori (O9.5 Ia). The arrows in Figure 5A mark the location of the Si XIII and S XV lines (at  $\sim 2.2$  keV) that are seen in very hot X-ray sources. The presence of this emission in  $\zeta$  Ori indicates a need for a two component source model. The model fitting the spectrum (Figure 5B) has a hot component deeply embedded in the wind (as in a base corona) with a temperature of  $\sim 15 \times 10^6$  K. This high temperature exceeds the maximum temperature of a corona, or "escape temperature," derived from Parkers coronal wind theory of  $\sim 7 \times 10^6$  K for  $\zeta$  Ori. The high temperature therefore suggests magnetic confinement is occurring. Using the standard loop theory of Rosner, Tucker, and Vaiana (1978), one can find that a magnetic field of  $< 100$  gauss could account for the presence and the emission measure of the hot gas (Cassinelli and Swank 1983).

A similar SSS spectrum is seen in main sequence stars such as  $\tau$  Sco and

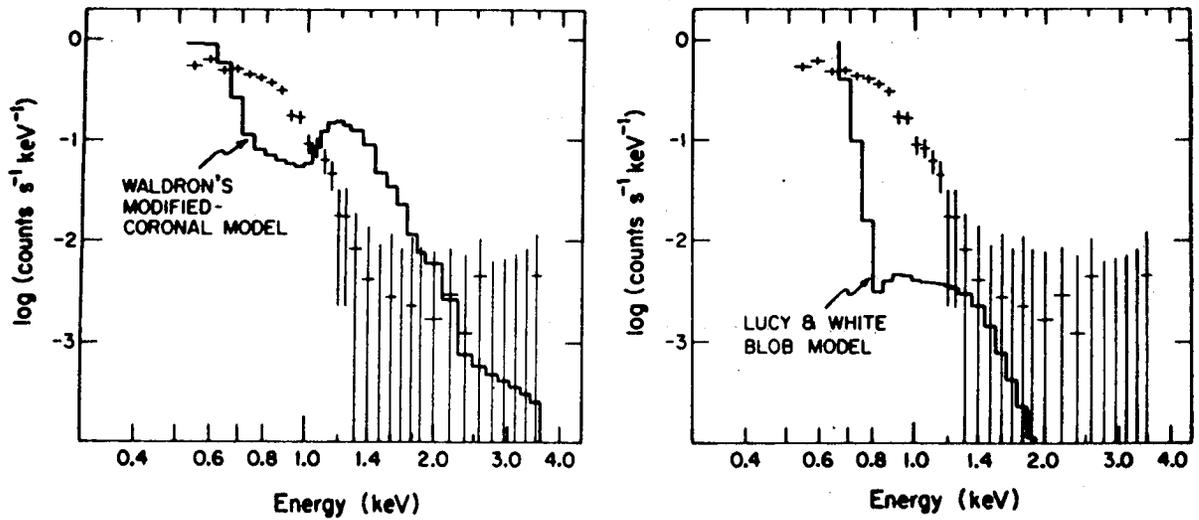


Figure 3. Shows the spectra predicted from two models to explain the X-ray spectra of O and OB stars. (left) Shows the Waldron (1984) modified base coronal model, which has less opacity in the wind than the slab coronal model because of higher wind ionization. (right) Shows the spectrum predicted from the radiatively driven blob model of Lucy and White (1980) for  $\zeta$  Pup in which X-rays are expected to be formed near the base of the wind.

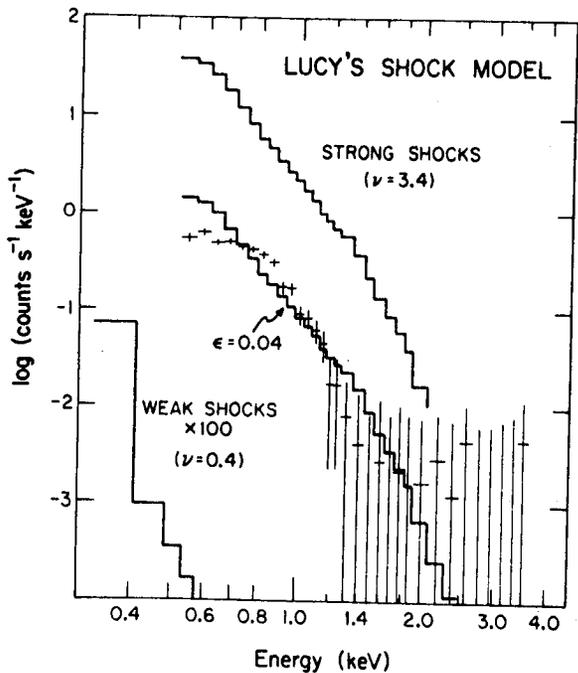


Figure 4. Compares the SSS spectrum of  $\epsilon$  Ori with the fit derived from Lucy's (1982) periodic shock model. The shocks are parameterized by the quantity  $\nu$ . Results for two values of  $\nu$  are shown. The preferred value in the theory is  $\nu = 0.4$ , but this value is seen to yield a spectrum that is far below (even after multiplying by 100) the observed distribution. The model with  $\nu = 3.4$  gives rise to a spectrum that is sufficiently hard but predicts more X-rays than are needed to fit the observation. If a fraction,  $\epsilon = 0.04$ , of the X-rays are assumed to come from these strong shocks a reasonably good fit is achieved as is shown.

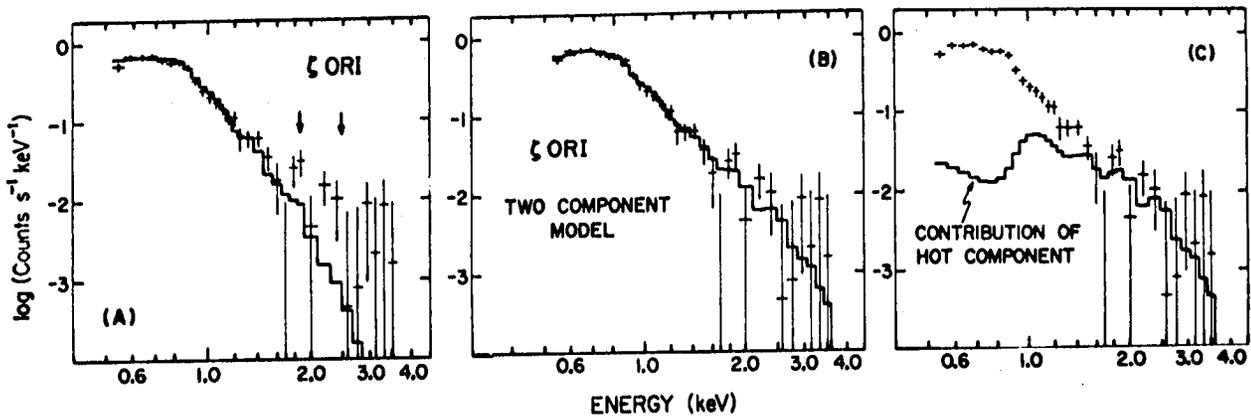


Figure 5. Model fits to the SSS spectrum of  $\zeta$  Ori. A) Shows the best fit single component model with a source temperature of  $T_s = 3.8 \times 10^6$  K. B) Shows a best fitting two component model in which there is a contribution from a deep lying hot component. c) Shows the contribution of the hot component that has a temperature  $T_s = 15 \times 10^6$  K.

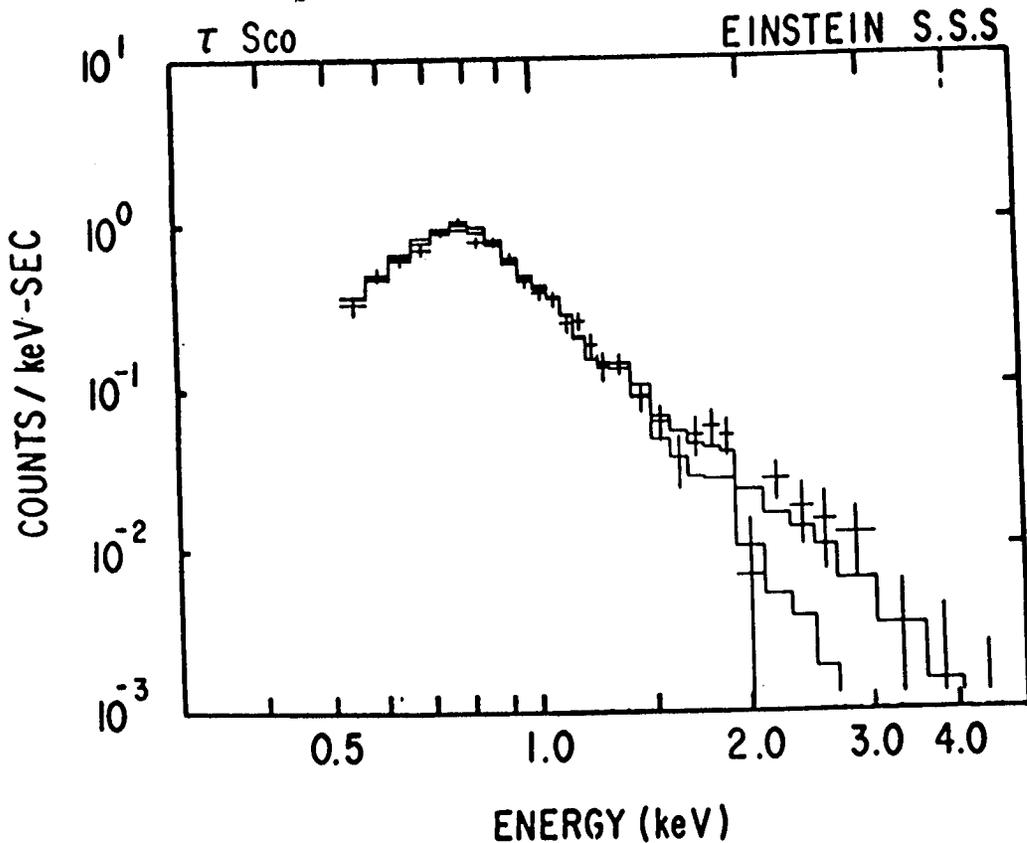


Figure 6. The SSS spectrum of  $\tau$  Sco Bo V. The spectrum below 1.5 keV can be fitted with a source with  $T_s = 5.3 \times 10^6$  K. At high energies there is clear evidence for the presence of a second hotter source, with  $T > 15 \times 10^6$  K, perhaps confined magnetically at the base of the wind.

$\zeta$  Oph (Swank, these proceedings). Figure 6 shows the SSS spectrum of  $\tau$  Sco that indicates the presence of gas with  $T > 15 \times 10^6$  K. The stars cannot easily be explained with the periodic shock model, so the hot gas is almost certainly at the base of the wind.

There is an alternative to the radiation driven shock model for producing hot gas in the outer parts of massive winds. Mullan (1984) suggests, from analogy with the sun, that there are collisions between fast streams and slow streams in the winds. Mullan calls these CIR's for Co-Rotating Interaction Regions.

### III. ULTRAVIOLET EVIDENCE

Strong lines of "superionization stages" of ionization are seen in the ultraviolet spectra of O and B stars. The O VI  $\lambda 1030$  line is seen with displaced absorption in supergiants as late as B0.5 Ia (Morton 1979). N V  $\lambda 1240$ , C IV  $\lambda 1550$ , and Si IV  $\lambda 1400$  are seen persisting to progressively later B supergiants. These ionization stages are well above those that could be produced by the photospheric radiation fields. The Copernicus satellite discovery of the ions gave the first convincing evidence that high temperature regions exist in the outer atmospheres. The general behavior versus spectral type gave evidence for the emission of X-rays from hot stars before the Einstein satellite was launched (Cassinelli and Olson 1979). Now that the O stars are in fact known to be X-ray sources, it is clear that the superionization throughout most of the wind can be explained by the Auger process, whereby two electrons are removed from, say, an oxygen ion upon K shell absorption of an X-ray photon. The ultraviolet lines do more than provide a redundant test of X-ray emission however. The profiles provide velocity information and allow us to put constraints on the spatial location of the various line producing regions.

Consider the profiles of  $\zeta$  Pup and  $\tau$  Sco shown in Figure 7. The  $\zeta$  Pup profiles have a broad absorption trough showing that O VI and N V are formed throughout the region in which the wind accelerates to terminal speed. The profile of N V is flat bottomed, unlike what is expected from a doublet. Lucy (1982b) has argued that this means that the velocity law of the wind is not monotonic but has a sawtooth form as needed in his periodic shock model. Hamaan (1980) argues that the flat bottom nature is evidence that there is  $100\text{--}200 \text{ km s}^{-1}$  macroturbulence in the winds.

In  $\tau$  Sco there is absorption redward of line center caused by material having a component of velocity falling toward the star. Lamers and Rogerson (1978) interpret this as turbulence at the base of the wind with a characteristic speed of  $\sim 150 \text{ km/sec}$ .

Upflows and downflows that can crudely be considered "turbulence" occur in spicules on the sun. The presence of downflows in hot stars is at least suggestive of a solar-like structure. Morton (1983) discusses evidence for downflow in  $\iota$  Ori with a velocity of  $\sim 50 \text{ km s}^{-1}$ , as is shown in Figure 7. Observations made 7 years later no longer show the downflow component.

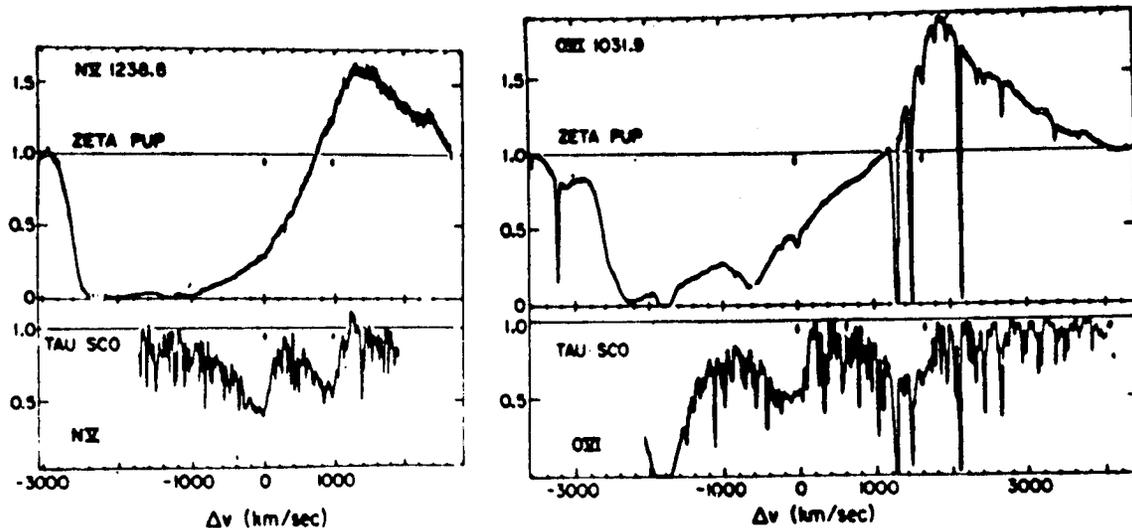


Figure 7. The spectra of  $\zeta$  Pup O4f and  $\tau$  Sco BOV in the region of the resonance doublets of O VI and N V. The horizontal axes give the velocity ( $\text{km s}^{-1}$ ) in the frame of the star. The arrows indicate the laboratory wavelength of the lines. In the O VI spectral region, the strong line at  $-1900 \text{ km s}^{-1}$  is Ly  $\beta$ . The sharp lines in the spectrum of  $\zeta$  Pup are interstellar lines. Adapted from Lamers (1975).

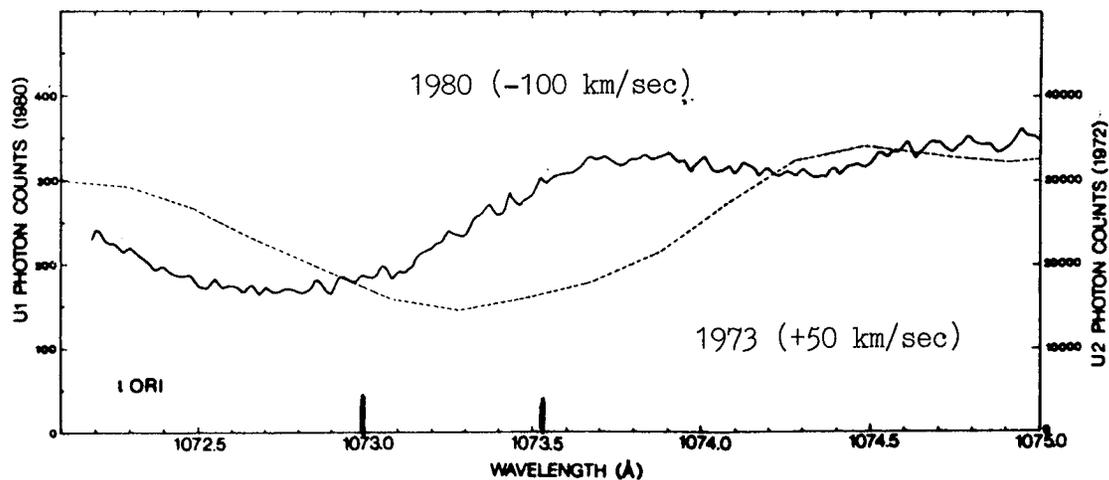


Figure 8. Copernicus spectrum of 1 Ori in the region of the S IV pair  $\lambda\lambda 1072.992, 1073.522$ . The heavy solid line represents the U1 high-resolution observations of 1980, and the dashed line, the lower resolution U2 data obtained some 8 yr earlier. During this interval the S IV profiles in 1 Ori indicate a shift from infalling material to outward mass flow.

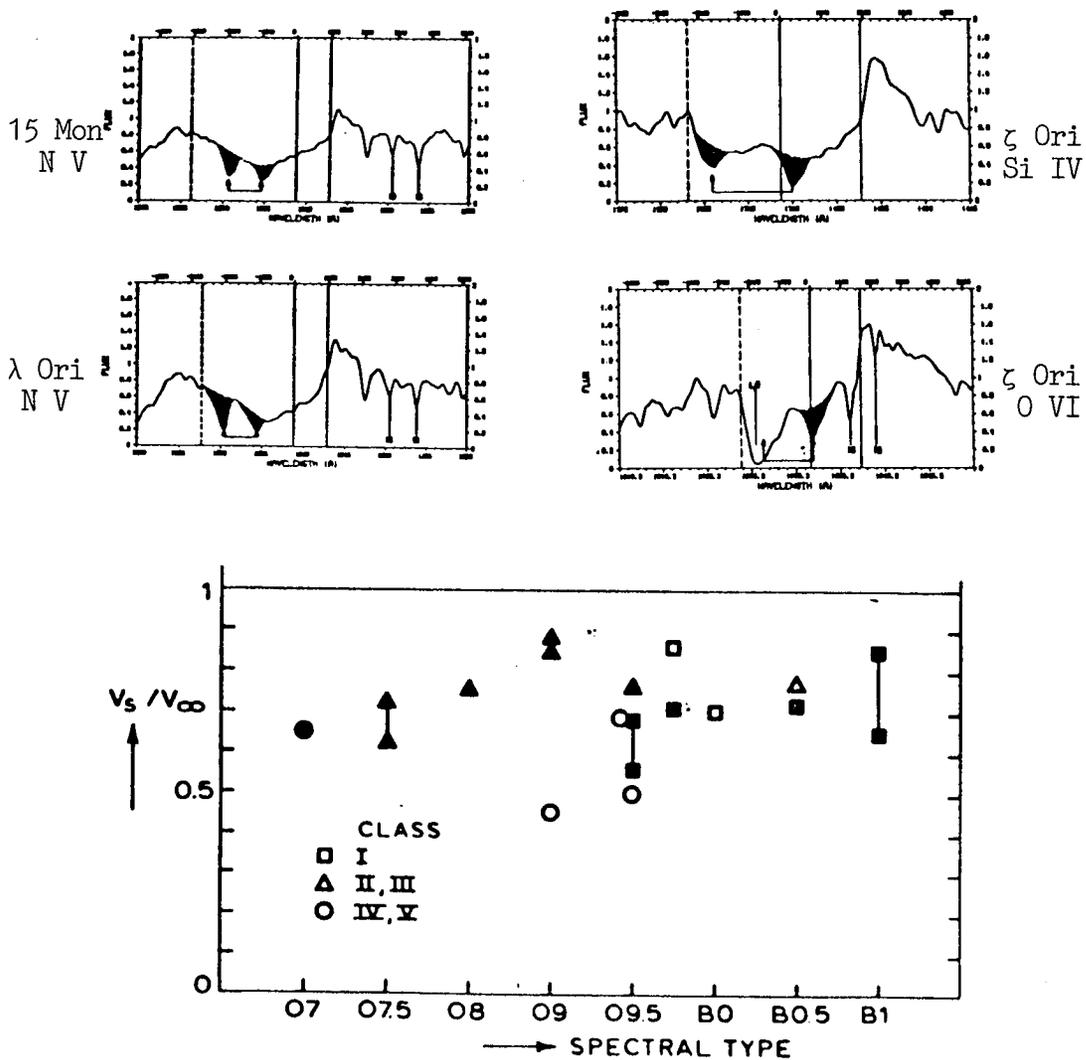


Figure 9. The top panel shows the narrow shortward displaced absorption features in several stars. The connected arrows indicate the doublet separations for the various UV lines. The bottom panel shows the ratio of the velocities of the absorption feature to the terminal velocity of the winds versus spectral type.

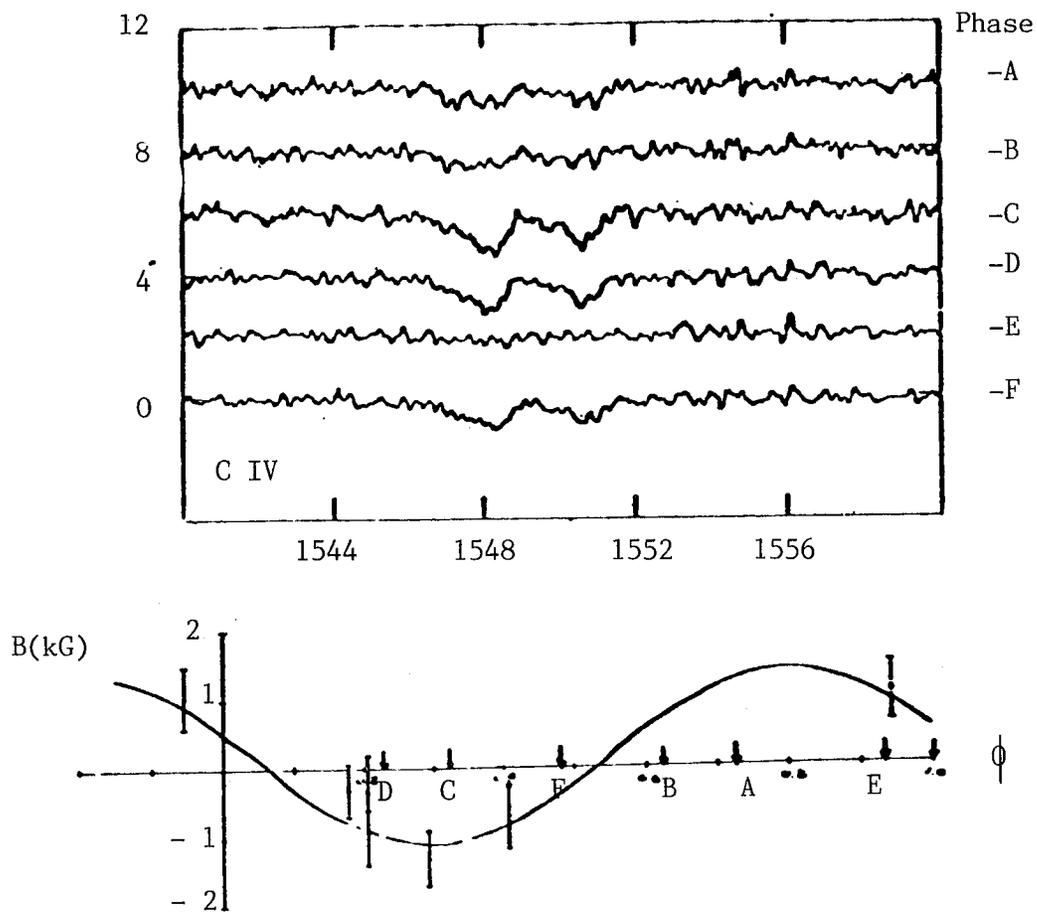


Figure 10. Observations of the Helium weak star 21699. The top panel shows the variation of the C IV  $\lambda 1550$  doublet versus phase. The bottom panel shows Zeeman polarimetry observations versus phase. The C IV line has maximum absorption at phases of maximum line of sight magnetic field.

An interesting property of UV line profiles that has received a great deal of attention lately is the presence of narrow displaced absorption components. In a study of 26 stars Lamers et al. (1982) found that ~two-thirds of the stars showed narrow features like those in Figure 9a. The features typically have widths of 100-500 km s<sup>-1</sup>, and their displacement is typically 0.75 times the terminal wind speed. The lines show up in all of the strong resonance lines at the same velocity. The column densities judged from the absorption depths are variable on timescales of hours to months while the velocity displacement can be constant for years (Snow, 1977).

Several interpretations have been given. Hamaan (1980) has suggested that the extra absorption is caused by a plateau in the velocity law. Lamers et al. (1982) favor instabilities that produce interactions between dense blobs and low density winds analogous to the Lucy and White (1980) model. Two plausible explanations invoke phenomena related to these occurring in the sun (Underhill and Fahey 1984; Mullan 1984). In Underhill and Fahey's model the absorption occurs in magnetic clouds associated with open field regions on the surface. Mullan proposed that the absorption occurs in the CIR regions. Should these types of model be correct, the long life of the velocity components may place useful constraints on the longevity of the magnetic regions on the stellar surface.

In recent years there has been intense study of IUE observations of chemically peculiar B stars (Barker et al. 1982, Brown et al. 1984). The helium-rich stars are typically of spectral type B2 V, and the helium-weak stars are in the spectral range B3-B9 V. These classes of stars are of particular interest because for them we have direct evidence for kilogauss fields from Zeeman polarimetric observations (Borra et al. 1983). Figure 10 shows the results of Brown et al. (1984) regarding the variations of C IV  $\lambda$ 1550 doublet in the helium weak star HD 21699. The phase of strongest outflow coincides with the phase of strongest line of sight magnetic field. This is as expected in the Shore and Bolton (1984) oblique rotator model. In the helium strong star HD 184927 Barker et al. (1982) also find periodically varying outflow. The gas is again clearly affected by the star's magnetic field.

The dipolar phenomena seen in the chemically peculiar stars may not be representative of that occurring in other early-type stars. Nonetheless it is encouraging to see such clear non-radiative effects in any class of early-type star. The observations may give us clues as to the behavior of gas flowing along locally open field regions.

#### IV. OPTICAL EVIDENCE

At optical wavelengths there exists several good techniques for studying the deepest regions of the winds where the flow originates.

Non-spherically symmetric outflow can be studied via polarization observations. Polarized light from electron scattering is produced primarily in the region from about 1.1 to 1.5 stellar radii; sufficiently

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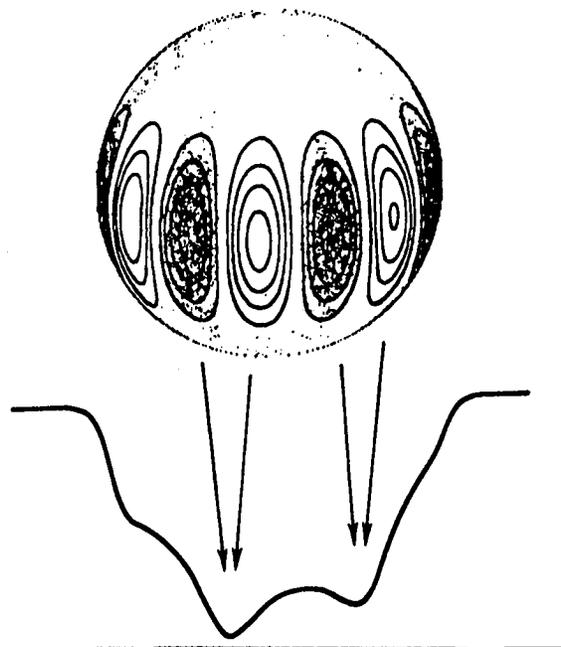
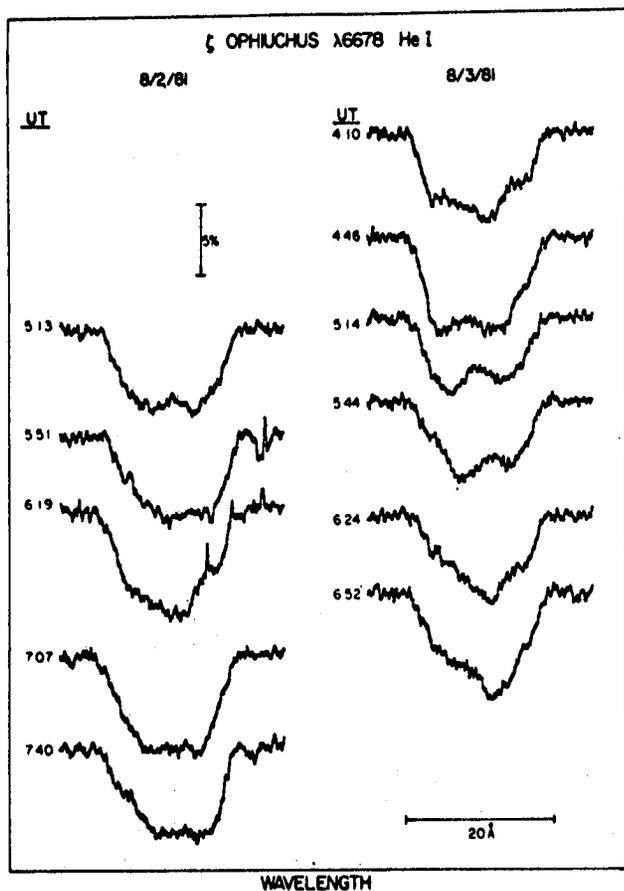


Figure 11. The left panel shows observations of the Helium I  $\lambda 6678$  line in  $\zeta$  Oph in August 1981. The right panel illustrates the non-radial pulsation model of Vogt and Penrod (1983) that provides an excellent fit to the observational material.

far from the star for the radiation field to be strongly peaked in the outward direction yet sufficiently deep for electron densities to be large. Lupie and Nordsieck (1984) have recently studied the behavior of the polarization in OB supergiants. Two-thirds of the stars showed random polarimetric variations at the 0.2 to 0.4 percent level on time scales of several days to months. Of particular interest is that the polarization varied not only in magnitude but also in position angle. This can be explained if the mass outflow occurs in plumes from the stars. The direction of polarization can change if there are more plumes in one quadrant of the stellar disk than in the neighboring quadrant. As the maximum polarization from a plume is around 2.5% and the observed polarization in P Cygni is 0.3%, it can be argued that the mass outflow from that star occurs from ~10 or fewer plumes near the base of the wind (Cassinelli, Nordsieck, and Murison 1984). This is particularly interesting because the radio observations of P Cygni by White and Becker (1982) indicate that the flow far out in the wind is spherically symmetric. Apparently some lateral spreading occurs in this star as the matter flows out.

Another exciting new development in optical astronomy concerns the study of non-radial pulsations in hot stars. This will be discussed later in the proceedings by Myron Smith. Figure 11 shows the profile variations of He I 6678 in  $\zeta$ Oph as analyzed by Vogt and Penrod (1983). They have explained the transient profile distortions by high-order non-radial oscillations. They also find a clear correlation between the amplitude of the oscillations and outbursts from the star. There is clear evidence for a mechanical process at work. The star is a strong hot X-ray source (Swank, these proceedings). Perhaps magnetic fields play a role in the transmission of energy from the photosphere to the coronal regions. On the other hand, the non-radial pulsations are not necessarily the ultimate "source" of outer atmospheric heating, but may be a symptom of an interior mechanism that is a source of both the pulsations and the outer atmospheric heating.

## V. INFRARED EVIDENCE

The standard explanation for excess infrared and radio emission from hot stars is this: The free-free opacity in a wind varies as  $\lambda^{-2}$ . Therefore as we look to longer wavelengths we see an effectively larger star. On the basis of this picture it had been thought that one could derive the run of density near the base of winds from IR observations. Radio observations should arise from regions at tens or hundreds of stellar radii where the density should be falling as  $r^{-2}$  and the radio flux would give a good measurement of the mass loss rate. Some interesting problems have arisen.

Castor and Simon (1983) have found the rise of velocity must differ substantially from star to star in order to fit the near IR excesses. (As explained in Abbott *et al.* (1984) the difference corresponds to  $\beta = 0.7$  to 2.0 in the law  $v/v_{\infty} = (1-R/r)^{\beta}$ . This would not be expected in the purely radiative picture. Perhaps the variety of inferred velocity laws is caused by a plume/loop structure in the atmospheres of the Of and OB supergiants.

Abbott, Telesco, and Wolff (1984) have pointed out an important discrepancy between the radio flux and the 10-20  $\mu$ m IR fluxes of two early O stars. This is illustrated in Figure 12. For 9 Sgr and Cyg OB2 No. 9 the infrared excess is negligible compared with the excess illustrated by the dotted line that was expected from the large mass loss rate derived from radio observations. This is really more a radio problem than an IR problem so we will return to it later.

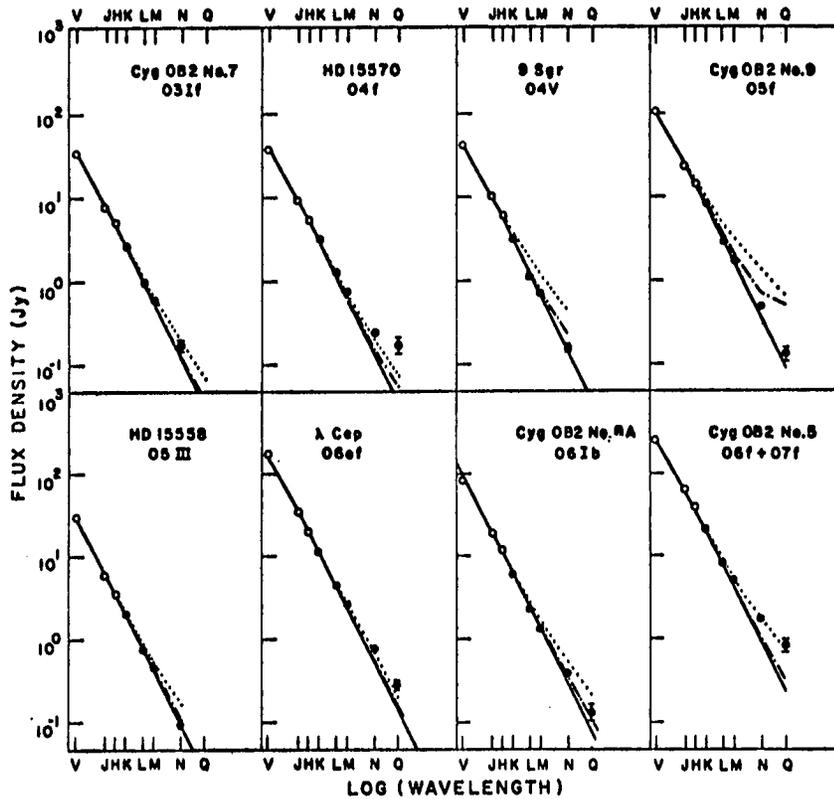


Figure 12. Near infrared observations of several early-type stars. Observations are illustrated by the circles. The solid line is the photospheric flux; the dotted line represents the infrared continuum expected for a model using a velocity law  $v/v_{\infty} = (1 - .99R_{*}/r)$  and using the mass loss rates derived from radio observations. Note the large discrepancy in the expected flux in 9 Sgr and Cyg OB2 No. 9.

IRAS data is now becoming available. Figure 13 shows data on  $\zeta$  Pup 04f presented by Lamers, Waters, and Wesselius (1984). The distributions with broad IR bumps are from Cassinelli and Hartmann (1977). These show the effects of coronal regions on IR distributions, and they clearly don't fit the data. Lamers *et al.* conclude that "the excellent agreement with the predicted flux for cold stellar winds shows that  $\zeta$  Pup does not have a thin corona nor a warm region near the star. It suggests the mass loss from a hot star is due to radiation pressure alone". Wolfire *et al.* (1984) have computed the IR flux from one of Waldrons (1984) thin coronal models for  $\zeta$  Pup. The size of the corona in Waldron's model is determined by fits to

Figure 13. The observed IR spectrum from the IRAS satellite is compared with predictions for various wind models of Cassinelli and Hartmann (1977). The models have different temperature structures which are shown in the top portion of the figure.

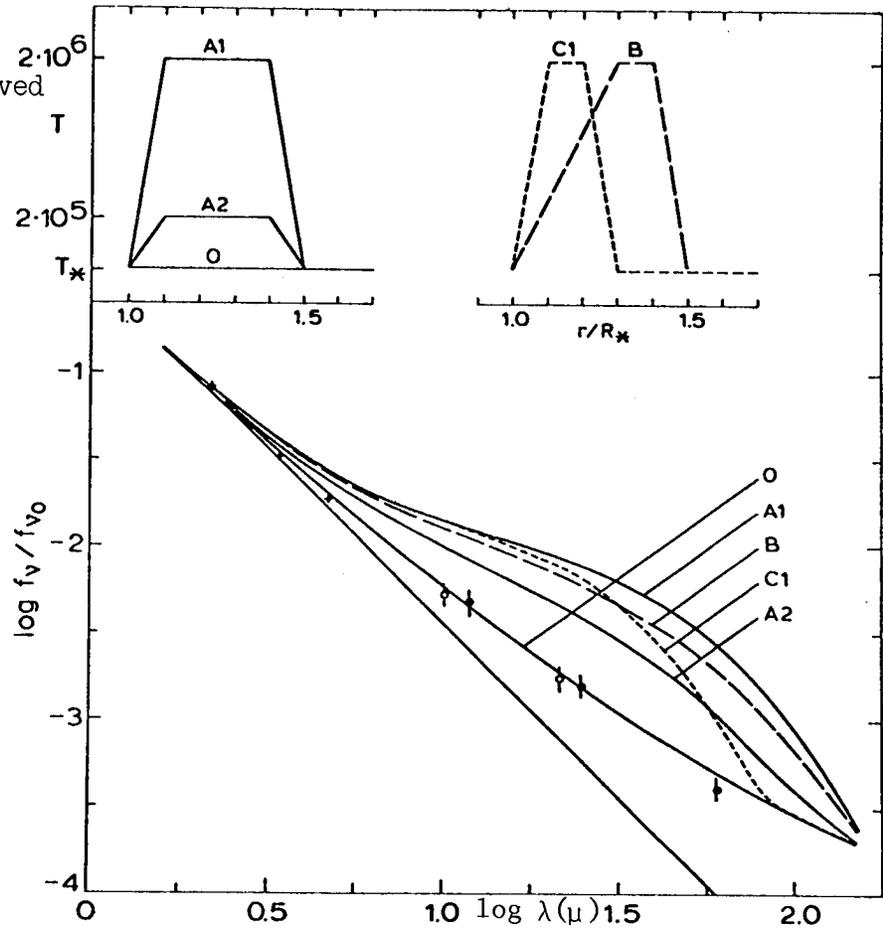
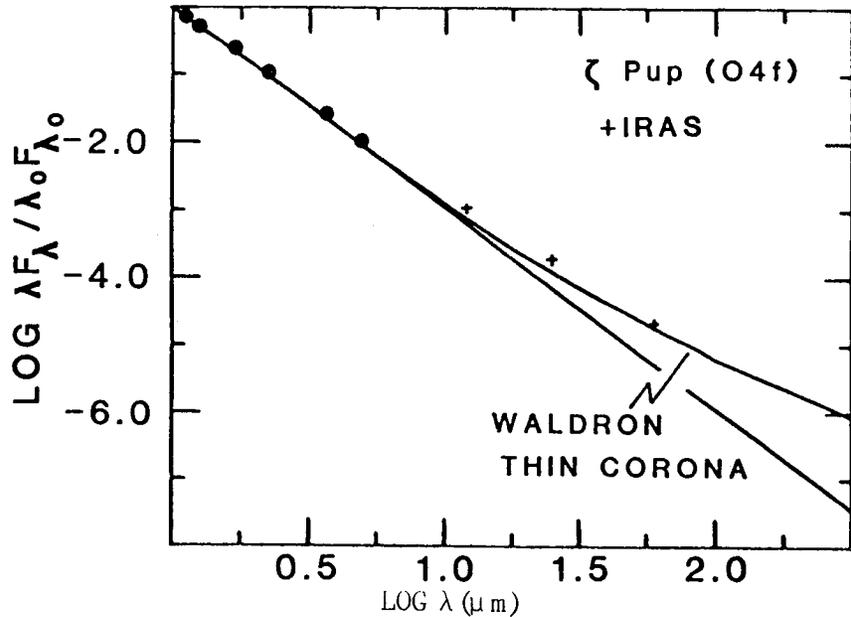


Figure 14. Shows a comparison of the predictions of the base coronal model of Waldron (1984) with the IRAS observations of  $\zeta$  Pup. The adjustable parameters for the model are the coronal emission measure and coronal temperature. These were chosen to provide good fits to Einstein X-ray observations



The predicted IR fluxes do not violate the IRAS observations, primarily because the coronal zone is very thin relative to those illustrated in Fig.13.

Einstein X-ray data. The result is shown in Figure 13. The fit is reasonably good and could be improved by adjustments to the velocity distribution at the base of the wind. It appears that the conclusions reached from IRAS regarding the absence of coronae cannot be supported.

## VI. RADIO EVIDENCE

Some of the most promising results giving evidence for non-radiatively produced emission are from VLA observations of hot stars. The mass loss rates derived for 9 Sgr and Cyg OB2 No. 9 assuming free-free emission are a factor of 10 or so larger than estimated from UV line profiles and IR continua (Abbott et al. 1983). The 6cm flux from Cyg OB 2 No. 9 was sufficiently large that in the standard radiative picture the star's wind should have been spatially resolvable with the VLA as had been the case with P Cygni (White and Becker 1983). It was not resolved and furthermore measurements at other radio wavelengths showed the spectrum does not fit the  $\nu^{-0.6}$  law expected for free-free wind emission. Figure 15 shows the distribution as explained by a warm wind model by White and Becker (1983). The bump is analogous to the IR coronal bump discussed earlier. The White and Becker (1983) temperature distribution is too peculiar to be considered plausible and the later discovery of variability of the radio flux led to the free-free explanation being rejected in favor of a non-thermal source (White 1984). Abbott et al. (1984) have interpreted the spectral results as non-thermal emission perhaps arising from a compact companion. There are evolutionary difficulties with this model as essentially all massive early stars have the same lifetime of  $\sim 2 \times 10^6$  years, so a massive star could not evolve into a compact state much sooner than the companion O4 V star.

Underhill (1983) has suggested the radio emission in early type stars is a combination of free-free and gyro-resonance radiation. White (these proceedings) is proposing that synchrotron emission could arise in hot star winds because of particles accelerated by the shocks in the wind. A similar suggestion is in Mullans (1984) paper regarding the CIR shock model.

An objection I have heard to the gyro-resonance models that is perhaps also relevant for the synchrotron models is that the winds are thick to free-free opacity and one couldn't see emission from non-thermal sources deeper in the wind. This problem is similar to one concerning the lack of a 0.6 keV absorption edge in the X-ray spectra. Rosner and Vaiana (1980) suggested the wind does not "cover" the low-lying hot plasma uniformly, and that there are spaces in the covering somewhat like the closed/open geometry of the sun. This idea has been suggested as an explanation for the radio observations by Underhill (1984). I can suggest we consider the possibility that the structure is like a cactus. If we were to give the diameter of the plant to the ends of the needles, a person with the wrong picture in mind could easily conclude that the green core could not be seen "because of its great depth" into the plant.

As a final point in the discussion of non-radiative evidence, there is exciting new evidence for non-thermal emission discovered serendipitously by Churchwell (1984) while observing  $\sigma$  Ori A with the VLA to

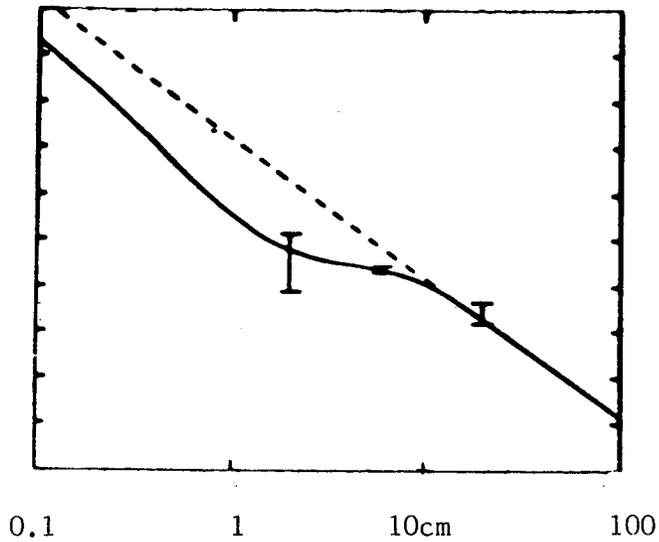


Figure 15. Radio spectrum of Cyg OB2 No. 9 measured with the VLA at 2, 6, and 20 cm. Dashed line is the spectrum of an isotropic stellar wind ( $v_{\infty}^2$ ), solid line is the spectrum of a wind which is cool near the star and hot far from the star.

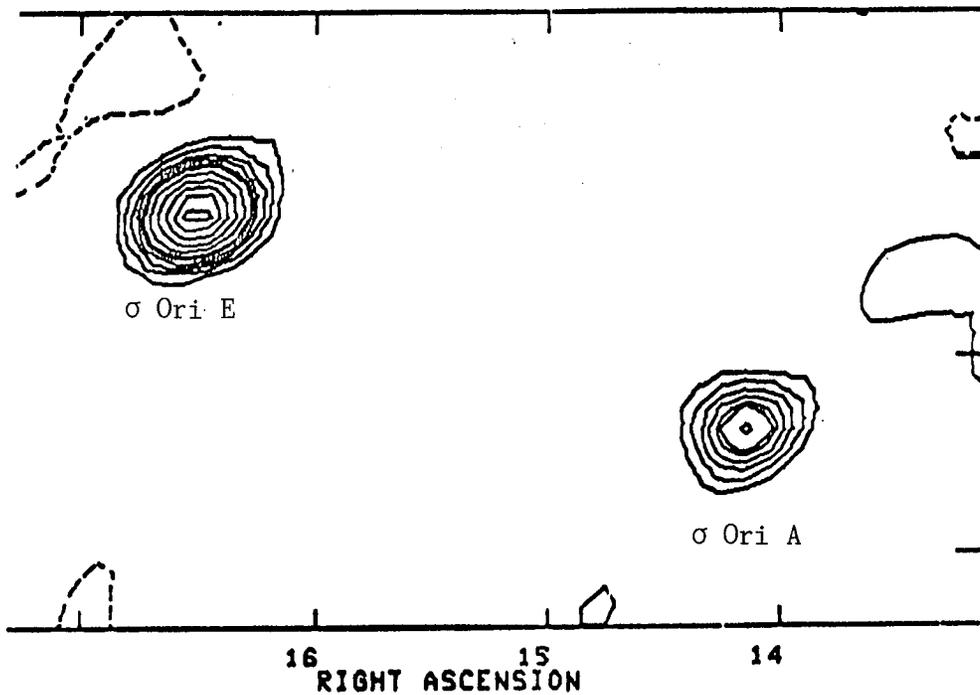


Figure 16. Shows a radio map of  $\sigma$  Ori in which the large flux from  $\sigma$  Ori E was discovered serendipitously (Churchwell 1984).

get its mass loss rate. Figure 16 shows that the chemically peculiar star  $\sigma$  Ori E is a much stronger radio source. The radiation from this star has a flat spectrum  $\nu^{0.07}$  and is circularly polarized at 42%. This is clear evidence for non-thermal emission. It will be interesting to see if similar evidence can be found for other early-type stars.

In conclusion, there is some evidence for non-radiative or even explicitly magnetic phenomena at essentially all wavelengths. Much of the data presented could perhaps be explained by some sort of spherical shell averaged model. Rather than confirming our interpretations to that type of model, however, I think we should keep in mind the picture of the loops and plumes that actually occur in the one star, the Sun, for which we can actually see the surface.

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#### DISCUSSION

R.L. White: There is a difficulty with the idea that the wind is very "porous" so that the surface of the star is visible. Many UV lines (e.g. the N V line in  $\zeta$  Pup) are very black in their absorption, so the wind gas must cover the star. It is very hard to have the gas optically thick in N V and other lines but optically thin in free-free.

Cassinelli: The line radiation transfer is sensitive to velocity gradients and the optical depth could be affected by non-monotonic velocity patterns which could occur either as in Lucy's shock model or as in the stream-stream CIR's of Mullan. It is not obvious to me that a multi-plume flow could not give rise to dark lines. Most O stars do not have completely saturated wind troughs; that is why we can see the discrete absorption features.

Abbott: I question whether you can "see" the surface of hot stars at radio wavelengths, even if the wind has plume-like structures. If, for example, the radio "photosphere" is at  $100 R_*$ , the density of the tube or hole in the wind must be very low compared to the surrounding wind, and you would need very strong fields, very far from the star, to maintain pressure equilibrium.

Cassinelli: The matter in the outflowing streams or blobs does not have to be in pressure equilibrium with the surrounding material. The lateral expansion will occur at the sound speed ( $\sim 30 \text{ km s}^{-1}$ ), and this is much, much less than the flow expansion speed which is greater than  $10^3 \text{ km s}^{-1}$ .

Underhill: In a paper accepted for the Ap.J. I have demonstrated that the light from B-type supergiants varies in an irregular manner with a small amplitude in the ultraviolet. The variations are comparable to those shown by intermediate-band photometry in the visible range. Rotation of a spotted disk appears to be an acceptable way of explaining the observations, especially those suggestive of small-amplitude changes in intervals from 6 to 20 days.

Sreenivasan: The analogy with the solar coronal regions having open field lines (enhanced wind and faster streaming velocities) and closed lines (regions with no wind or low-speed wind) is a useful one, but one has to be cautious in applying it to massive stars. The real question one wants to ask is how can one produce fast and slow streams so that they can collide somewhere away from the star to produce shocks. One does not have to invoke magnetic fields. There are other non-thermal sources of energy flux in massive stars in addition to the radiatively driven (cold) winds, e.g. a hot wind produced by shear turbulence in rotating stars. This circumstance can produce colliding streams resulting in shocks. You can get X rays from those streams also. In addition there are mechanisms such as nonradial oscillations.

Zirker: I hear a lot of discussion about highly structured hot-star atmospheres with plumes (streams) which may persist for long times. What mechanisms structure these atmospheres? Magnetic fields? Nonradial oscillations? If magnetic fields, how do we generate them? If oscillations, how do these propagate into the coronae and winds?

Cassinelli: In the case of the helium-rich and helium-weak stars we see clear evidence for matter streaming outwards above open field regions. Matter can be accelerated in many ways - by radiation pressure in lines, by Alfvén waves, or by centrifugal acceleration as in the fast magnetic rotator models. Magnetic fields can be primordial, since the stars are young. There may be mechanisms for generating fields in stars - as will be discussed by Praderie. Non-radial oscillations clearly occur in stars like  $\zeta$  Oph. The nonradial oscillations may be a symptom of the presence of a driving mechanism that could also drive energy to the outer parts of the atmosphere.

Walborn: The chemically peculiar B stars were isolated on the basis of optical spectroscopy and photometry. The magnetic fields were discovered subsequently which allows the interpretation that the Bp stars are oblique rotators. Landstreet and Borra observed non-peculiar B stars with similar sensitivity and found no fields. There is no observational evidence that the phenomena in peculiar B stars are relevant to the interpretation of the normal objects. However, a systematic survey of a large sample of O stars with the Landstreet-Borra technique has not been done. Such a survey would be very valuable.

Golub: Following your discussion of outer atmospheric structure in which optical polarization is seen within  $1.5 R_{\star}$  and winds with low polarization further out, it may be of interest to look at some of the solar data from Skylab. The first picture shows the X-ray corona and the white-light corona superimposed. It is clear that the streamers in the outer corona can be traced down to bright active regions. On the other hand, streams in the solar wind are traced to coronal holes which are the dark open field regions in between streamers. The second picture shows how high-speed solar wind streams are traced to dark coronal holes at the base of the corona. These pictures may help to visualize the "cactus model" you were talking about.

Owocki: If the Sun were seen as a star, **B** fields would not be directly detectable. Nonetheless, we know **B** fields organize the large-scale structure of the solar corona/wind. Therefore one does not need a detectable level of **B** field to achieve detectable structure. Structure may be more easily inferred by monitoring the rotational modulation of line core intensities, as is done for late-type stars, than by making direct measurements.

Chan: Whether the coronae are heated by magnetic fields or by shock waves, or whatever, the source of energy is important. Lack of a precisely described source should not be considered a difficulty against the magnetic heating picture. I shall discuss a model for wiggling the magnetic field lines from inside the star tomorrow afternoon.

Walborn: The star  $\tau$  Sco has highly peculiar enhanced ultraviolet wind features. Other low luminosity stars with high  $L_X/L_{B01}$  in your plot tended to be nearby, lightly reddened objects. Could extinction uncertainties be affecting  $L_X$  in this plot?

Bookbinder: The problem (pointed out by Walborn) of the apparently high  $L_X/L_{B01}$  values for late B stars is probably not due to our lack of understanding of X-ray extinction.

Abbott: One major difference between hot stars and solar-type stars is that the winds of the hot stars are opaque in many UV lines. Therefore, structures from the surface extending into the wind should be easy to detect in the P Cygni profiles which are not saturated. To my knowledge, rotational modulation of line profiles has not been observed in hot stars despite a great observational effort to look for it.

Cassinelli: If the flow was occurring through just one or two plumes, you would expect to see a rotational modulation. It is more likely that there are many plumes, say 10. In such a case, the rotational modulation might not be easily observable.

Underhill: The spectra of O stars and OB supergiants show wind profiles, and, for some stars, discrete components. The wind profiles can be interpreted using a low-density, spherically symmetric wind. The discrete components require the ejection of material from spots - see Underhill and Fahey (1984). Thus one has both types of mass loss. However, the density of the spherically symmetric wind may be 10 X less than what has been deduced in most cases because it is quite possible that the degree of ionization does not decrease outwards nearly so rapidly as assumed by the Castor and Lamers (1979) models.

Swank: Most neutron stars likely to be accreting from the winds of O and B stars, e.g.  $\gamma$  Cas and 4U1700-37 (HD 153919), which do not show regular pulsations, or X Per and 4U1223-62 (Wray 977) among pulsars, vary in luminosity (on time scales of 10 minutes to hours). In 4U1700-37 this is correlated with the amount of screening material indicated by the spectrum. Both effects would be consistent, at least naively, with wind inhomogeneities of lengths  $10^{10}$  to  $10^{11}$  cm, although other effects, e.g. a feedback between the wind accretion and photoionization by the X rays could complicate the picture. Inhomogeneities in the wind which could cause changes in sign of accreted angular momentum have also been appealed to as a possible explanation for the periodic fluctuations of Vela X-1 and 4U1223-62.

Sreenivasan: The fact that strong rotational modulation may not be seen should be understood on the basis of two consequences of stellar evolution: (i) As massive stars evolve, the surface rotation goes down as the stars keep losing mass owing to angular momentum loss. (ii) Not all stars of given mass start off with the same  $v \sin i$  on the main sequence. The value of  $v \sin i$  depends on the amount of angular momentum lost in the pre-main-sequence phase, and on the mass lost then. Although two proto stars start off with different masses, they may arrive on the main-sequence with the same mass.

Stars of the same ZAMS mass may have different mass-loss rates owing to their rotational velocities being different. These stars spin down at different rates as a result of this. In general, surface rotation goes to zero by the time a massive star has exhausted hydrogen in the core even when angular momentum transfer from the core to the surface is taken into account as the star evolves off the zero-age main-sequence line.

# EVIDENCE FOR NON-RADIATIVE ACTIVITY IN STARS WITH $T_{\text{eff}} < 10,000$ K

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## ABSTRACT

Major advances in the acquisition of evidence for and the understanding of nonradiative heating and other activity in stars cooler than  $T_{\text{eff}} = 10,000$  K has occurred in the last few years primarily as a result of the IUE and Einstein spacecraft and the VLA microwave facility. In this paper I critically review this evidence and comment on the trends that are now becoming apparent. The existence for nonradiatively heated outer atmospheric layers (chromospheres, transition regions, and coronae) in dwarf stars cooler than spectral type A7, in F and G giants, pre-main sequence stars, and close binary systems is unambiguous, and chromospheres exist in the K and M giants and supergiants. The existence of nonradiative heating in the outer layers of the A stars remains undetermined despite repeated searches at all wavelengths. Some important trends in these data are the decrease in plasma emission measure with age on the main sequence and decreasing rotational velocity. Variability and atmospheric inhomogeneity is commonly seen, and there is considerable evidence that magnetic fields define the geometry and control the energy balance in the outer atmospheric layers. In addition, the microwave observations imply that nonthermal electrons are confined in coronal magnetic flux tubes in at least the cool dwarfs and RS CVn systems. The chromospheres in the K and M giants and supergiants are geometrically extended as are the coronae in the RS CVn systems and probably in other stars.

## I. INTRODUCTION

This is an unusual and therefore special meeting. Ordinarily astronomers organize their meetings on topics defined by a type of object, such as stars of a certain spectral type or galaxies with common characteristics. In such meetings the goal is to develop a more comprehensive or at least a more coherent picture of the objects that all the participants in the meeting know and love. This meeting is different in that its goal is to understand better a phenomenon (nonradiative activity) that we know occurs in cool stars and the Sun, and that we suspect, but cannot yet prove, occurs in the hot stars as well. Thus, the topic is interdisciplinary, and two groups of people (hot star and cool star pundits) must attempt to learn from each other.

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\*Staff member, Quantum Physics Division, National Bureau of Standards.

Given the unusual nature of the meeting and the tentative nature of the "evidence" for nonradiative activity in the hot stars, I would like to make a modest request. My request is that we approach this topic with open minds and that we endeavor to listen and learn from each other. We should also be properly skeptical of both data and interpretation. A quick inspection of the literature of only ten years ago in this field (the outer atmospheres of cool stars) would demonstrate that, with hindsight, most of what was published then would now fall into four categories: (1) flagrantly wrong, (2) woefully inadequate, (3) hopelessly naive, or (4) outrageously simpleminded. It would not surprise me if a fearless reviewer of this topic in 1994 would say much the same thing about what is being published today. So, we should not fight overly tenaciously for our favorite models which, in a short period of time, will likely join the ever increasing garbage heap of astrophysical history.

Beginning in 1978, three events have totally changed our recognition and understanding of nonradiative activity in cool stars. The International Ultraviolet Explorer (IUE) satellite launched in 1978 has provided us with ultraviolet spectra of many stars of almost all types, providing evidence for  $10^4$ - $10^5$  K plasma in the chromospheres and transition regions (TRs) of many of these stars. The Einstein (HEAO-2) satellite, also launched in 1978, has detected soft X-ray fluxes from many stars of almost all types, providing evidence for  $10^6$ - $10^7$  K plasma in the coronae of many of these stars. Finally, the Very Large Array (VLA), dedicated in 1980, is observing microwave emission from an increasing number of cool stars and binary systems. These three events have totally changed the data base concerning nonradiative activity from famine to feast. So much has been learned in the last few years that a comprehensive review of the topic is no longer feasible. Instead, for this meeting I will concentrate on major achievements and problems, with particular emphasis on phenomena and stars that may be closely related to the main topic of this meeting -- hot stars.

Before proceeding, I should mention a number of reviews that provide more detailed treatments of different aspects of this topic. Broad surveys of X-ray emissions from stellar coronae include those of Vaiana (1981, 1983), Golub (1983), Stern (1983), and Linsky (1981a,b). Gibson (1981;1984), Gary (1984), and Mullan (1984a) have summarized the microwave observations of cool star coronae; and Linsky (1981c,1982), Brown (1983), and Baliunas (1983) have summarized the ultraviolet observations of stellar chromospheres and transition regions. The extensive evidence for mass loss in cool stars has been reviewed by Cassinelli (1979), Dupree (1982), and Hartmann (1981, 1983); and direct and indirect evidence for magnetic fields in these stars has been summarized by Vogt (1983), Marcy (1983), Zwaan (1983), and Linsky (1983a). Linsky (1982) has evaluated the energy balance in the outer atmospheres of cool stars. The X-ray, ultraviolet, and microwave emissions from the M dwarf flare stars has been reviewed by Gibson (1983), Johnson (1983), Worden (1983), Giampapa (1983a), and Linsky (1983b); and Giampapa (1983b) and Feigelson (1983) have reviewed similar data for the pre-main sequence stars. Finally, reviews of the emission from RS CVn binaries include those of Bopp (1983), Charles (1983), Linsky (1983a) and Mutel and Lestrade (1984); and Dupree (1983) has reviewed this topic for the contact binary systems.

## II. TYPES OF EVIDENCE FOR NONRADIATIVE ACTIVITY IN COOL STARS

I will define the term "nonradiative activity" to include those phenomena and physical properties that occur when the energy balance in a stellar atmosphere departs greatly from pure radiative equilibrium. Nonradiative heating produces hot atmospheric layers that by solar analogy we call chromospheres, transition regions, and coronae (see Linsky 1980). These layers are inhomogeneous and variable in time. In addition, momentum can be imparted to the outer layers of a star by a number of possible mechanisms to produce mass loss by a stellar wind. Except perhaps for the dusty M supergiants, the deposition of momentum in the winds of cool stars does not come directly from the stellar radiation field, and, therefore, could be considered an aspect of nonradiative activity. Thus in general terms the evidence for nonradiative activity consists of the following:

(1) Thermal radiation from plasmas substantially hotter than can be explained by an atmosphere in radiative equilibrium. The prime spectral diagnostics are X-ray and ultraviolet emission lines and continua, as well as thermal microwave emission. In addition, a few spectral features in the visible and near infrared, including the Ca II H and K and infrared triplet lines, H $\alpha$ , and He I 10830 Å and 5876 Å, are useful.

(2) Nonthermal radiation from relativistic particles in magnetic fields. Such radiation is detected during flares in the microwave and perhaps also in hard X-rays. Indeed, some portion of the "quiescent" microwave emission from M dwarfs could be nonthermal in character.

(3) Stochastic emission variations indicating flaring or rapid heating of atmospheric structures like magnetic flux tubes or active regions. An atmosphere in radiative equilibrium should be a steady emitter, since the stellar luminosity changes only on very long, evolutionary timescales, except during rare explosive events. Radial and nonradial pulsations, on the other hand, can occur even for an atmosphere in radiative equilibrium and could even be maintained by purely radiative processes.

(4) Large scale atmospheric inhomogeneities indicated by periodic variations of the stellar spectrum on a rotational time scale; for example, rotational modulation of the emission from bright active regions in the ultraviolet, X-ray, and microwave; or modulation of the optical continuum due to an inhomogeneous surface distribution of cool, dark starspots.

(5) Mass loss produced by such nonradiative acceleration processes as waves and an outwardly decreasing thermal pressure gradient.

In this review I will discuss the evidence for the first four points primarily by considering in turn the different spectral regions. As we proceed through this topic, it is important to keep in mind that the diagnostics of the heated or accelerated plasma may not be reliable for several reasons:

(1) Very small contrast between the sought after emission line and the background stellar photosphere — a problem especially important in the ultraviolet for early F and A-type stars.

(2) NonLTE effects. In some cases, nonLTE effects can produce a spurious emission spectral feature that appears to indicate heated plasma.

(3) Most stars are members of binary systems, and quite often the duplicity or multiplicity is not readily apparent either from optical imaging, composite colors, or variable radial velocities. Since the vast majority of stars are cool dwarfs that are faint in the optical but intrinsically bright in X-rays, ultraviolet emission lines, and microwave emission, one easily can be fooled into ascribing the evidence for hot plasma to the usually dominant primary star when, in fact, an unsuspected secondary star may be the source of much of the emission.

(4) Close companions often alter the adjacent star by tidally-induced rapid rotation, mass exchange, or X-ray illumination and heating. Furthermore, as in the case of the RS CVn-type binaries, magnetic fields of the two stars may interact and heat plasma between the two stars.

(5) Interstellar and circumstellar absorption can decrease or totally eliminate measurable X-ray and UV radiation from a star. Absorption effects are especially important for distant stars in the galactic plane such as pre-main sequence stars.

(6) Instrumental problems can be very important. For example, sensitivity limitations can lead to sample bias or the inability to observe whole classes of objects. The failure to detect high-excitation emission features does not imply that a given star lacks hot plasma, but merely that the emission measure of the plasma must be less than an empirical upper limit. Furthermore, subtle imperfections in the instruments themselves can lead to false conclusions. An example is the UV light leakage in the Einstein High Resolution Imager (HRI) that falsely implied that Sirius A and Vega are X-ray sources.

### III. EVIDENCE FOR HOT ( $10^6$ - $10^8$ K) CORONAL GAS: X-RAY EMISSION

X-ray emission in the continuum and discrete lines can be produced by thermal processes (free-free, free-bound, and bound-bound) and, in principle, by nonthermal processes involving high energy particles in magnetic fields. Both processes indicate a plasma heated by nonradiative processes. Early soft X-ray experiments on rockets and the ANS and SAS-3 satellites were able to detect only the very brightest X-ray sources among the nearby stars such as Capella and the dMe flare stars while flaring, but also curiously, Vega (A0 V) and Sirius (A1 V + WD). Many of these early detections were serendipitous. The HEAO-1 A2 all sky survey discovered that the RS CVn binary systems as a class are luminous X-ray sources ( $\log L_x = 30$ -31) (Walter et al. 1980), and detected several late-type dwarfs as quiescent and flaring sources.

Major progress required more sensitive imaging instruments, in particular the IPC and HRI focal plane instruments on Einstein (HEAO-2). These instruments detected X-ray emission from nearly every type of star except the luminous cool giants and supergiants (Vaiana 1981; Vaiana et al. 1981; Ayres et al. 1981; Helfand and Caillault 1982; Linsky 1981b), and in the process totally contradicted the previously held theory of acoustic wave heating of stellar coronae. The SSS instrument on Einstein obtained low resolution soft X-ray spectra of RS CVn systems, Algol, and one dMe star (Swank et al. 1981; Swank and Johnson 1982), while the higher resolution crystal spectrometer only had the sensitivity to observe Capella (Vedder and Canizares 1983). The EXOSAT spacecraft is now observing many targets, and future missions include ROSAT, which will undertake an all sky survey, and the AXAF, which will have very high resolution imaging capability.

Linsky (1981b) has summarized the physical quantities which can be inferred from these data. The imaging instruments (primarily the IPC and HRI) are useful for identifying X-ray sources, studying their time variability, and measuring the broad band (0.25-4 keV) flux. The IPC also provides only a rough estimate of the plasma temperature and emission measure for coronae hotter than about  $1 \times 10^6$  K. Low resolution spectroscopy (e.g., the Einstein SSS) allows one to distinguish multi-temperature plasmas and the corresponding emission measures.

Even though the Einstein satellite has provided essentially all of the information to date on stellar coronae, we clearly need greatly enhanced capability. For example, more sensitive imaging instruments are needed to study the luminous cool stars, A stars, and distant young stars. Significantly more sensitive spectroscopic instruments are needed to determine the temperature distribution, electron densities (from density sensitive line ratios), flow velocities, and energy balance in stellar coronae. Even with such improvements, interstellar absorption will severely compromise our ability to detect distant soft sources near the galactic plane.

Einstein detected many dwarf stars of spectral type F, G, K, and M. The M stars are particularly interesting because they are very luminous in X-rays ( $\log L_x = 27-30$ ), but there is evidence that the coolest M dwarfs are much less luminous (Golub 1983). A number of early F dwarfs have been detected, and the hottest late-type dwarf star detected to date is probably  $\alpha$  Aql (A7 IV-V,  $T_{\text{eff}} = 7650$  K) observed by Golub et al. (1983). Also, Canopus (F0 II) has been detected as an X-ray source by Ayres et al. (1981).

The question of X-ray emission from the A dwarfs is not yet resolved. Pallavicini et al. (1981) noted that Vega (A0 V) and Sirius A (A1 V) were detected by the HRI (but not the IPC) at values of  $L_x/L_{\text{bol}}$  an order of magnitude below the  $10^{-7}$  relation that characterizes the O and B stars. Golub et al. (1983) argued that these detections were real, but they later found that the HRI signal apparently was due to a spurious UV light leak. The authors also concluded that the X-ray emission detected from the other normal A-type stars at a level of  $\log L_x = 29$  is likely due to emission from known or suspected K and M dwarf companions, although two detected Ap stars in their sample exhibit no evidence of duplicity. We therefore have no unambiguous evidence as yet

that A-type stars have  $10^6$  K coronae; we can only say that if such coronae exist, they must be of low luminosity,  $\log L_x < 27$ .

To date the only evolved single stars detected as X-ray sources are F and G giants. Ayres et al. (1981) and Haisch and Simon (1982) have argued that a "dividing line" exists in the HR diagram separating the coronal stars (single giants earlier than about K1 III and main sequence stars) from the noncoronal stars (giants later than K2 III and supergiants later than about G2 Ib). Spectroscopic binaries, especially the tidally synchronous rapid rotators with periods less than 20 days, tend to be strong emitters ( $\log L_x = 30-31$ ). The RS CVn, Algols, and W UMa systems are examples.

Some important results concerning the hot plasma in the coronae of late-type stars include:

(1) There is a monotonic increase in  $L_x$  with decreasing age (see Stern 1983). This is based on systematic studies of the Hyades (age  $4 \times 10^8$  yr, Stern et al. 1981), Ursa Major (age  $1.6 \times 10^8$  yr, Walter et al. 1984), Pleiades (age  $6 \times 10^7$  yr, Caillault and Helfand 1984), and Orion stars (age  $10^6$  yr).

(2)  $L_x$  increases monotonically with increasing rotational velocity. This result may explain the age effect, and suggests that the heating processes are magnetic in character with the fields regenerated by a dynamo-type mechanism. There remains a disagreement, however, whether the functional dependence of X-ray emission on rotation is of the form  $L_x \sim (v \sin i)^2$  as proposed by Pallavicini et al. (1981) or  $L_x/L_{bol} = f(\Omega)$  as proposed by Walter (1981,1982). Also, there is evidence for saturation at high rotational velocities and young ages (Rucinski 1984; Caillault and Helfand 1984).

(3) Swank et al. (1981) have found that the coronae of RS CVn and Algol systems are characterized by two temperatures (one component at roughly  $5 \times 10^6$  and the other hotter than  $2 \times 10^7$  K). Swank and Johnson (1982) found a similar result for the dMe star system Wolf 630 AB.

(4) In their study of the eclipsing system AR Lac, Walter, Gibson, and Basri (1983) found evidence for discrete active regions in the coronae of both stars and that the K0 IV star possesses an extended component to its corona.

(5) Coronal X-ray emission can be quite variable, especially for the M dwarfs (e.g., Johnson 1981,1983; Golub 1983) and RS CVn systems.

(6) Coronal magnetic fields are needed both to confine the hot plasma and probably also to heat it.

#### IV. EVIDENCE FOR HOT ( $10^6-10^8$ K) CORONAL GAS: MICROWAVE EMISSION

The known or suspected mechanisms for microwave emission from stars include thermal bremsstrahlung, gyroresonance emission by thermal electrons spiraling in coronal magnetic fields, gyrosynchrotron emission from nonthermal

electrons, and coherent processes. Prior to the commencement of VLA observations in 1978, the types of late-type star detectable by interferometers such as the NRAO 3-element interferometer or single disk radio telescopes were severely limited by sensitivity and source confusion. The only detected sources consisted of dMe and RS CVn systems while flaring, interacting binary systems, and two M supergiants with massive winds ( $\alpha$  Ori and  $\alpha$  Sco). The factor of 100 better sensitivity (a  $3\sigma$  noise level of 0.1 mJy is achievable at 6 cm) and the factor of 400 better angular resolution of the VLA compared to a 100 m single disk telescope revolutionized the field of stellar radio astronomy just as Einstein revolutionized the field of stellar X-ray astronomy.

The VLA has now observed about a dozen dMe stars as quiescent and flaring radio sources (Gary and Linsky 1981; Linsky and Gary 1983; Topka and Marsh 1982; Fisher and Gibson 1983; Gibson 1983, 1984). These sources all appear to be variable. Since the dMe stars are detected at levels far above those predicted on the basis of bremsstrahlung from the coronal electrons inferred from the X-ray fluxes, and because the emission often is circularly polarized, these authors have argued that the quiescent flux likely is due to gyroresonant or synchrotron emission. The 6 cm luminosities for the quiescent emission lie in the range  $1 \times 10^{13} - 5 \times 10^{14}$  ergs/s/Hz.

No single dwarf stars of spectral types F, G, and K have definitely been detected despite several searches (Linsky and Gary 1983). Luminosity upper limits for nearby stars as low as  $3 \times 10^{12}$  ergs/s/Hz have been achieved for such stars as  $\epsilon$  Eri (K2 V) and 61 Cyg AB (K5 V + K7 V), but these limits are still above those predicted on the basis of bremsstrahlung from their X-ray coronae. Gary and Linsky (1981) originally detected the young star  $\chi^1$  Ori (G0.V), but repeated observations have revealed that the source is highly variable and the original detection could be explained by a flare on its M dwarf companion. No single A-type dwarfs have yet been detected, but observations of Am and Ap stars are now under way.

Among the late-type giants and supergiants, the only single (or widely separated binaries) detected are  $\alpha$  Ori (M2 Iab),  $\alpha^1$  Sco (M1 Ib),  $\alpha^1$  Her (M5 II), and  $\alpha$  Boo (K2 III) (cf. Newell and Hjellming 1982; Drake and Linsky 1983a). The emission mechanism is likely bremsstrahlung from a cool (6000-8000 K) chromosphere and wind. Also flares have been detected from  $\alpha$  Ori,  $\pi$  Aur (M3 II), and R Aql (gM5e-8e). None of the X-ray emitting F and G giants has yet been detected as a microwave source. On the other hand, RS CVn and Algol systems are readily detected as flaring and quiescent sources with single dish antennae and the Green Bank interferometer (Gibson 1981; Feldman 1983) and now also as quiescent sources with the VLA. With increasing separation (longer period), the RS CVn systems are often less luminous. An example is the nearest long period system, Capella (G6 III + F9 III), with a period of 104 days that has not been detected despite several attempts (Drake and Linsky 1983b). The 0.25 mJy upper limit at 6 cm is barely consistent with the flux expected on the basis of bremsstrahlung from the X-ray corona alone.

The following are some critical points learned from the data so far:

(1) Except for the K and M giants and supergiants, the emission seems to be coming from relativistic or very hot electrons confined by coronal magnetic fields. This conclusion is based on the large inferred brightness temperatures and detected circular polarization in some cases, indicative of gyrosynchrotron, gyroresonance, or maser emission. Furthermore, the maximum microwave emission of the eclipsing binary system YY Gem (dM1e + dM1e) occurs in phase with the meridian passage of the large starspot group and active region on the secondary star in the system (Linsky and Gary 1983).

(2) The microwave emission is highly variable on both short time scales ( $\geq 0.1$  sec flaring) (e.g., Lang *et al.* 1983) and long time scales of hours to days. The probable emission mechanisms (masering for the flares and gyrosynchrotron emission for the longer term variability) imply a highly structured corona similar to that of the Sun in which the local magnetic field confines and accelerates the emitting electrons.

(3) VLBI observations by Mutel *et al.* (1984) have shown that 20 cm emission from the RS CVn spectroscopic binary systems UX Ari and HR 1099 comes in part from large regions comparable in size to the binary separation. They argue on the basis of the deduced brightness temperatures and circular polarization that the emission is gyrosynchrotron radiation from a power law distribution of relativistic electrons.

(4) While the results to date are quite significant, stellar radio astronomy would greatly benefit from higher sensitivity, especially for VLBI measurements, and the ability to observe stars at large southern declinations.

## V. EVIDENCE FOR $10^5$ K (TRANSITION REGION) GAS AND $10^4$ K (CHROMOSPHERIC) GAS: ULTRAVIOLET AND OPTICAL DATA

The available evidence for the existence of chromospheric ( $10^4$  K) and transition region (TR,  $10^5$  K) plasma in the outer atmospheres of late-type stars consists primarily of emission lines observed in the ultraviolet. These lines are formed either by collisional excitation, recombination and subsequent cascade, or fluorescence. The first mechanism is generally thermal in character, although excitation by nonthermal electrons streaming down loops from the corona may contribute; the second and third are also thermal but non-local in the sense that the ionizing or stimulating radiation originates elsewhere, often in a higher temperature plasma. For example, the He I 10830 Å and He II 1640 Å lines are likely formed at relatively cool temperatures following ionization by coronal X-rays and subsequent recombination. The Ca II H and K lines and hydrogen H $\alpha$  lines are among the few lines in the visible which indicate chromospheric plasma. In addition to spectral lines, chromospheric plasma can be observable by microwave emission and ultraviolet continuum emission — the former has been detected so far only from K and M supergiants, and the latter so far only from dMe stars during flares.

The accumulation of evidence for the existence of nonradiatively heated chromospheres and TRs has been limited by our observational capability. Prior to observations from space, we could observe only relatively cool chromospheric

plasmas using the Ca II H and K lines and could obtain indirect evidence for hot coronae from the He I 10830 Å line (Zirin 1982). Linsky and Avrett (1970) and Linsky (1977) have summarized these data and the usefulness of various spectroscopic diagnostics. The first few space observations by rockets, balloons, and Copernicus, were superseded by IUE, which has observed hundreds of late-type stars in the 1200-3200 Å spectral region at both low and high resolution. These data in turn will be superseded by the more sensitive and versatile instruments on Space Telescope and the proposed Columbus mission. The capabilities of these instruments are summarized in Table 1.

It is important to recognize that instrumental spectral range and sensitivity limit the plasma temperatures that can be observed. For example, Copernicus was capable of observing only the Lyman alpha and Mg II lines in late-type stars (except for the very brightest stars like Capella), and thus could only observe plasma as hot as  $10^4$  K. IUE, on the other hand, can observe emission features of C IV at 1550 Å and N V at 1240 Å formed in plasma as hot as 150,000 K. The 912-1216 Å spectral range of Columbus contains the strong resonance lines of O VI formed at 300,000 K, and the 100-912 Å spectral range, also observable by Columbus, contains lines formed in coronal plasma as hot as  $3 \times 10^7$  K (Fe XXIV). Some of the brighter spectral lines available in the 100-2000 Å range are indicated in Figure 1.

Even with the powerful spectrometers forthcoming on ST and Columbus, our ability to study nonradiative heating in stellar chromospheres and TRs will be limited. For one thing, use of ST will be severely constrained by intense competition for telescope time, so that it will be difficult to monitor specific stars for long periods of time or to observe a large sample of stars of

Table 1  
Capabilities for Observations of Ultraviolet Spectra

Mission	Years Operational	Focal Plane Instrument	Spectral Range (Å)	Spectral Resolution ( $\lambda/\Delta\lambda$ )
Copernicus (OAO-C)	1972-78	Mg II, L $\alpha$ lines only	20,000 5,000	
International Ultraviolet Explorer (IUE)	1978 +	Short Wavelength (SWP Camera)	1175-2000	10,000 250
		Long Wavelength (LWR, LWP Cameras)	2000-3000	10,000 400
Space Telescope (ST)	1987(?) +	High Resolution Spectrometer (HRS) 1175-1700	1175-2300 2,000	100,000 20,000
		Faint Object Spectrometer (FOS)	1150-8000	1,000 100
Columbus	1991 +	900-1200	30,000	
		1200-2000	10,000	
		100-2000	1,000	

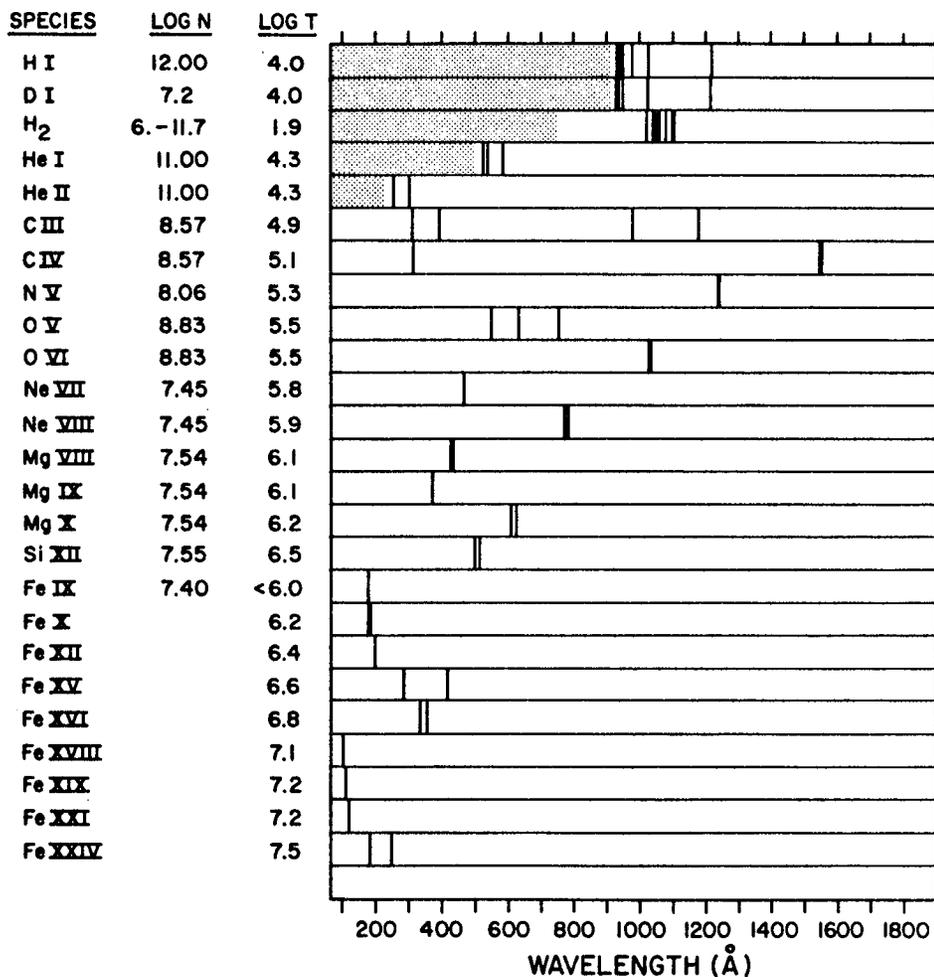


Fig. 1. Wavelengths of important spectral lines of abundant elements and molecular hydrogen (H<sub>2</sub>) that can be observed by the proposed Far Ultraviolet Spectroscopic Explorer (FUSE)/Columbus mission. Also indicated are the typical element abundances on a logarithmic scale where hydrogen is 12.00, and the temperatures of maximum fractional amount of each ion assuming collisional ionization equilibrium. Regions of continuous absorption by photoionization are indicated for hydrogen and helium. (From the Final Report of the FUSE Science Working Group.)

a given type. Furthermore, it will be difficult to observe a large spectral interval at high resolution because the HRS can measure only a few Angstroms of spectrum at one time in the 100,000 resolution mode. Even for the nearest stars, Columbus observations in the Lyman continuum will be affected by interstellar absorption, but it should be able to observe a great many late-type stars at wavelengths below 300 Å. Finally, the poor contrast between ultraviolet emission lines and the very bright photospheric continuum in stars earlier than about spectral type F0 severely hampers our ability to detect UV spectral signatures of nonradiative heating in these stars.

Emission lines formed in the chromospheres and TRs of main sequence stars later than spectral type F0 are readily detected by IUE and the Ca II H and K lines are easily observed by telescopes on the ground. The important lines from plasmas at 5000-10,000 K are Ca II (3933, 3968 Å), Mg II (2796, 2803 Å), H I (1216 Å), C I (1657 Å), Si II (1808, 1817 Å), and O I (1305 Å multiplet). At higher temperatures ( $3 \times 10^4 - 2 \times 10^5$  K) the strongest available emission lines are of C II (1335 Å), Si III (1892 Å), C III (1909 Å), Si IV (1393, 1403 Å), C IV (1548, 1550 Å), and N V (1238, 1242 Å).

The search for hot plasma in the early F and A-type stars with optical spectrographs and the IUE is severely hampered by the previously discussed contrast problem, and the existence of chromospheres and TRs on these stars is, therefore, an unanswered question at this time. This topic has been reviewed by Linsky (1981c) and most recently by Wolff (1983). The hottest stars exhibiting emission in the Ca II H and K lines are the F0 dwarf  $\gamma$  Vir N (B-V = 0.36, Warner 1968) and the F0 supergiant,  $\alpha$  Car (B-V = 0.15, Warner 1966). Occasionally, Ca II emission has been reported in the A7 III possible  $\delta$  Scuti star  $\gamma$  Boo (B-V = 0.19, LeContel et al. 1970; Auvergne, Le Contel and Baglin 1979). Dravins, Lind, and Särg (1977) demonstrated that transient emission occurs in the  $\delta$  Scuti stars from shock waves formed when the photosphere has maximum outward acceleration. Careful studies of the Ca II lines at high dispersion in the early A-type stars (e.g., Freire et al. 1978) and in A dwarfs in young clusters (Dravins 1981) show no evidence for emission.

Extending the search for emission features in the A-type stars to shorter wavelengths offers some prospect for improvement, because the photospheric continuum becomes fainter towards shorter wavelengths. In their extensive Mg II survey, Böhm-Vitense and Dettmann (1980) detected stars as early as  $\alpha$  Cae (B-V = 0.34), but the hottest dwarf star with detected Mg II emission features is  $\alpha$  Aql (B-V = 0.22), observed by Blanco et al. (1982) (see Fig. 2). Since this rapidly rotating A7 IV-V star also has been detected at Lyman alpha (Blanco, Catalano and Marilli 1980) and in X-rays (Golub et al. 1983), it must contain nonradiatively heated plasma with temperatures of  $10^4$  K to in excess of  $10^6$  K. Accordingly,  $\alpha$  Aql appears to be the earliest dwarf star that exhibits the nonradiatively heated atmospheric layers typical of the late-type stars.

Many investigators have searched the 1175-2000 Å region for evidence of emission in the C II, Si IV, and C IV lines. Among the earliest type stars detected are HD 127739 (B-V = 0.35, Saxner 1981), and the Ursa Major Stream star  $\alpha$  Crv (B-V = 0.32, Walter et al. 1984). Attempts to detect emission from A-type stars (e.g., Crivellani and Praderie 1982) have been unsuccessful so far. In particular, the detection of C IV emission in one spectrum of HD 21389 (A0 Ia) by Underhill (1980) is probably spurious in view of the narrow line widths and unusual flux ratio. The disappearance of the strongest emission features into the photospheric continuum "noise" is nicely illustrated by comparison of the spectra of representative Ursa Major Cluster stars shown in Figure 3. A quantitative assessment of the problem is depicted in Figure 4, where the surface fluxes in the C IV and C II lines of the Ursa Major and Hyades dwarfs are compared against the surface flux in the adjacent continuum, which rises exponentially with decreasing B-V. These data, together with the absence of verifiable continuum emission in excess of that expected on the

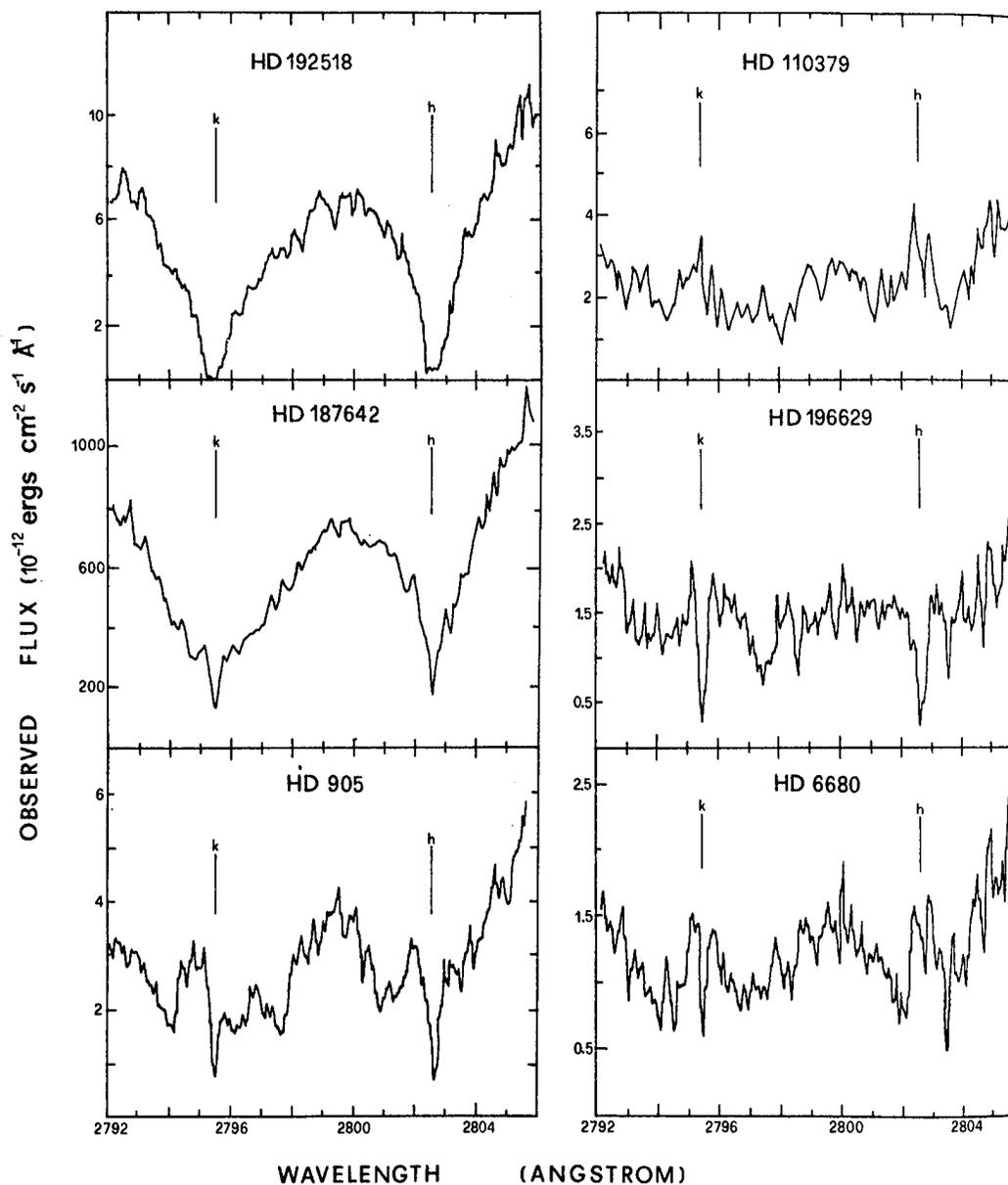


Fig. 2. IUE spectra of A- and F-type stars in the region of the Mg II lines observed by Blanco et al. (1982). The B-V colors for these stars are: 0.18 (HD 192518), 0.22 (HD 187642 =  $\alpha$  Aql), 0.31 (HD 905), 0.34 (HD 196629), 0.36 (HD 110379), and 0.40 (HD 6680). Weak Mg II emission features, on either side of the narrow interstellar absorption feature, first become visible in  $\alpha$  Aql (B-V = 0.22) and become more prominent in the cooler stars. The loss of contrast between possible Mg II emission features and the brightness of the photospheric Mg II line wings, which increases in brightness very rapidly toward smaller B-V, makes it difficult to find emission features in stars hotter than  $\alpha$  Aql.

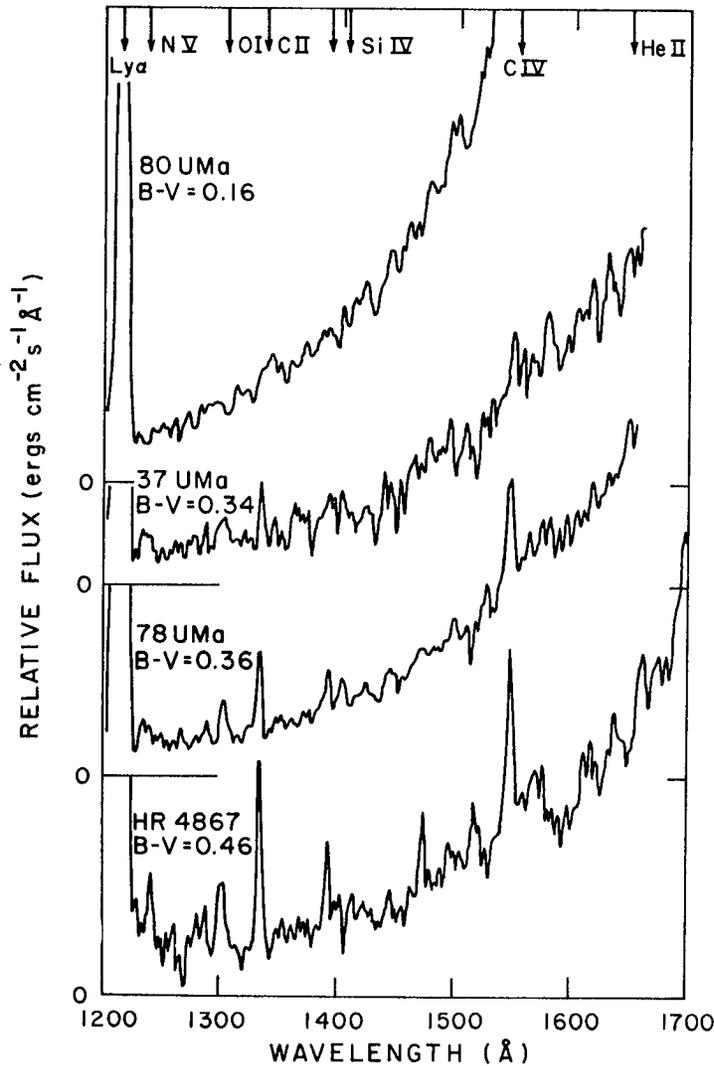


Fig. 3. Short wavelength IUE spectra of four members of the Ursa Major Cluster. The zero level is indicated for each spectrum, but the vertical scales are different for each. Strong chromospheric and transition region emission is visible in 78 UMa and HR 4867. Emission in the C IV (1550 Å) and C II (1335 Å) features is prominent in 37 UMa, but no emission, and possible absorption at O I and C II, are evident in 80 UMa (from Walter *et al.* 1984).

basis of radiative equilibrium, He I 10830 Å features, or line variability (Wolff 1983), mean that we cannot yet determine whether the A-type stars (except for the very coolest) have nonradiatively heated atmospheres. On the other hand, many Ap stars have strong magnetic fields so that there are many different ways in which nonradiative heating could occur in these stars.

As a result of extensive observations of ultraviolet spectra and the Ca II H and K lines, we have learned a great deal about the nonradiatively heated chromospheres and TRs of late-type stars. Since these results have been reviewed in detail by Brown (1983), Dupree (1982), and Linsky (1981c, 1982, 1983c), I list here some of the highlights of this work.

(1) Emission lines indicative of chromospheric plasmas generally are observed in all stars later than early F spectral type and of all luminosity classes. Evidence for TRs ( $10^5$  K plasma) generally is present in dwarf stars

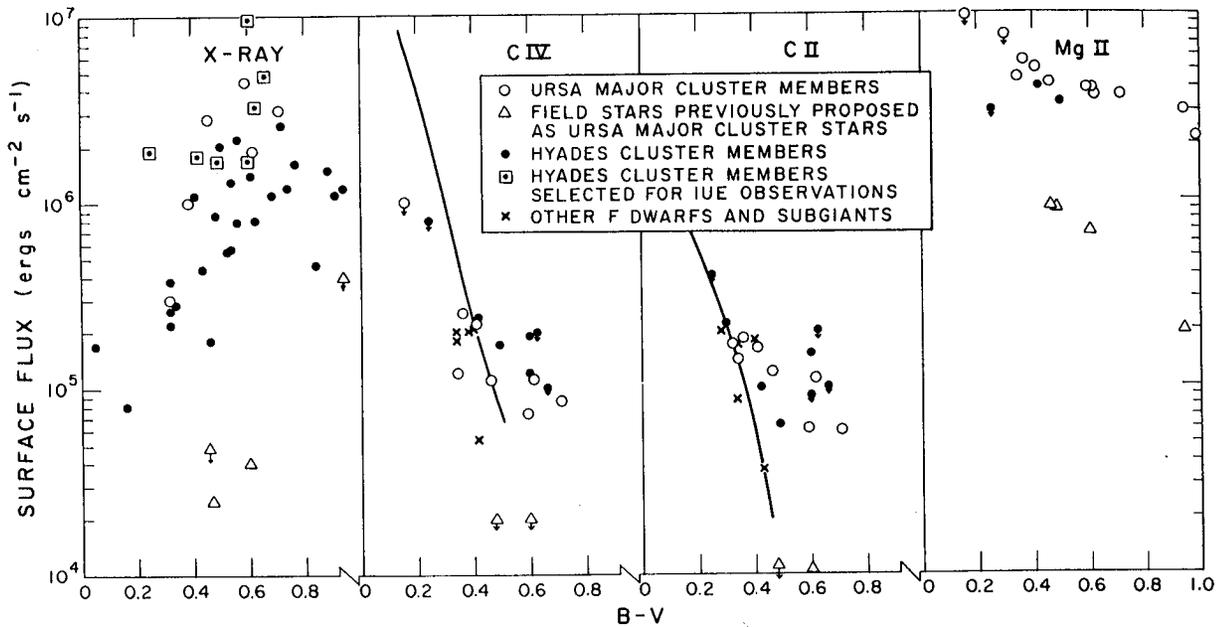


Fig. 4. Comparison of surface fluxes in soft X-rays, C IV 1550 Å, C II 1335 Å, and the Mg II 2800 Å doublet for Ursa Major Cluster members, probable field stars previously identified as Ursa Major members, Hyads, and selected field stars. X-ray surface fluxes of the ten Hyads that Zolcinski *et al.* (1982) selected for IUE observations are denoted by boxes, and upper limits are indicated by arrows. The solid lines indicate the photospheric continuum emission and scattered light (per 6 Å interval) at C IV 1550 Å and C II 1335 Å obtained by averaging the measured flux for Ursa Major stars in 20 Å bands on both sides of the C IV and C II lines (from Walter *et al.* 1984).

cooler than about F0 V, and in the giants and supergiants of spectral types F and G. Linsky and Haisch (1979) proposed and Simon, Linsky, and Stencel (1982) confirmed the existence of a dividing line in the HR diagram near spectral type K1 III such that TR lines are generally not observed in single stars to the right (cooler) of this boundary. Whether the existence of the dividing line is due to the true absence of any plasma at  $10^5$  K in these stars or merely to the rapid decrease in the emission measure of such plasma with decreasing effective temperature, cannot be determined at this time. However, upper limits to the C IV surface flux in  $\alpha$  Boo (K2 III) are already only 1% that of the quiet Sun (Ayres, Simon, and Linsky 1982). The location of the boundary in the HR diagram is the same as the X-ray boundary proposed by Ayres *et al.* (1981). The absence or small amount of  $10^5$  K plasma in the cooler giants could be a result of the rapid decrease in rotational velocity as giants evolve across these "boundaries" (Gray 1981), leading to weakened dynamo generation of magnetic fields and thus decreased heating and open magnetic field configurations.

(2) Stars cooler and more luminous than these boundaries typically have large mass loss rates (Cassinelli 1979) as inferred from circumstellar absorption features and infrared emission from dust among the M supergiants or asymmetric Ca II and Mg II emission lines (Stencel 1978; Stencel and Mullen 1980) in the K stars. Stencel et al. (1981) and Carpenter, Brown, and Stencel (1984) have used line ratios within the C II 2325 Å multiplet to estimate electron densities in the chromospheres of late-type giants and supergiants. They find that stars hotter than the boundary have high-density geometrically thin chromospheres, whereas stars cooler than the boundary have low density chromospheres that are geometrically extended (1-5 times the photospheric radius). Brown and Carpenter (1984) have derived chromospheric temperatures of 7000-9000 K for these stars from C II 1335 Å/2325 Å flux ratios.

(3) Hartmann, Dupree, and Raymond (1980, 1981) proposed a third class of stars, the hybrid stars, which show evidence for both strong mass loss and  $10^5$  K TR plasma. Prototypes of stars in this class are  $\alpha$  Aqr (G2 Ib) and  $\alpha$  TrA (K4 II). The hybrid nature of these stars has been explained by an Alfvén wave heated and accelerated wind (Hartmann et al. 1981), isolated hot flux tubes imbedded in a cool wind (Linsky 1982), shocks in an inhomogeneous wind (Mullan 1984b), or (in the particular case of  $\alpha$  TrA) a previously unknown F dwarf companion (Ayres 1984a). We do not yet know whether any of these proposed explanations is correct.

(4) Surface fluxes for such TR emission features as C IV 1550 Å vary greatly from one star to another. Stars with very large surface fluxes include the dMe stars (Linsky et al. 1982), RS CVn systems (Simon and Linsky 1980), young stars like those in the Hyades (Zolcinski et al. 1982), and pre-main sequence stars (Giampapa 1983b). There is a clear increase in surface fluxes, and thus nonradiative heating rates, with decreasing age on the main sequence (e.g., Simon and Boesgaard 1983; Barry et al. 1984), but the  $(\text{age})^{-1/2}$  dependence proposed by Skumanich (1972) to describe the behavior of Ca II fluxes appears not to be valid for stars younger than the Hyades (Duncan 1983). The surface fluxes also increase with increasing rotational velocity, and Hartmann et al. (1984) have proposed a functional dependence of the Mg II emission on the Rossby number, further strengthening the association of magnetic fields with the nonradiative heating process.

(5) The importance of magnetic fields in determining the geometric structure and energy balance in the chromospheres and transition regions of late-type stars has been summarized by Linsky (1983a). This evidence is of several types. First, the existence of individual solar-like active regions on stars is revealed by the modulation of UV emission lines at the rotational period, in phase with the dark starspots deduced from the optical light curves (Baliunas and Dupree 1982; Marstad et al. 1982; Linsky 1983c). Second, the large dispersion in heating rates for stars of the same spectral type, which can be explained readily only by different magnetic field strengths and geometries on these stars, is contrary to the predictions of purely acoustic wave heating (Linsky and Ayres 1978; Basri and Linsky 1979). Third, the empirical functional dependence of chromospheric heating rates on gravity and effective temperature strongly suggests heating by slow mode MHD waves (Stein 1981; Ulmschneider and Stein 1982). Fourth, the existence of flaring in dMe,

RS CVn, and T Tauri stars implies a rapid conversion of magnetic energy to heat as is presumed to occur in solar flares. Finally, the existence of systematic redshifts of  $10^4$ - $10^5$  K emission lines (Brown et al. 1984; Ayres et al. 1983; Ayres 1984b) likely is analogous to the downflows of hot plasma observed over solar active regions.

## VI. EVIDENCE FOR NONRADIATIVELY HEATED PHOTOSPHERES

We conclude this review with a brief summary of the evidence for non-radiative heating in stellar photospheres defined here as the layers located deeper than the temperature minimum. Evidence for such heating would consist of a derived temperature structure that is hotter than predicted on the basis of radiative equilibrium alone. Alternatively, one could consider as evidence photospheric emission in a spectral interval that is brighter than predicted on the basis of a radiative equilibrium photospheric model. Either type of evidence requires an accurate radiative equilibrium model. This is a difficult requirement for two reasons: (1) Such models require an accurate and reasonably complete description of line blanketing taking nonLTE effects into account, at least in the important opacity sources. (2) The solar photosphere is highly inhomogeneous and the existence of nonradiatively heated flux tubes and efficient cooling by CO in the nonmagnetic regions is a likely basis for thermal instability (Ayres 1981). Thus one-component radiative equilibrium models are not realistic physically for the Sun and, therefore, for late-type stars in general. We are thus left with the following quandary: Against what are we to compare an empirical photospheric temperature distribution in order to infer the existence of nonradiative heating at photospheric levels?

For the Sun, Chapman (1981) derived empirical temperature structures for spatially averaged plages (active regions) and has estimated temperature structures for isolated flux tubes by the analysis of the cores and wings of the Ca II, Mg II and Lyman alpha lines. These models are compared with quiet Sun models in Figure 5. Other models indicating photospheric temperature enhancements in magnetic regions have been computed by Vernazza, Avrett, and Loeser (1981), Morrison and Linsky (1978), and others. While such models are not directly compared to radiative equilibrium models, the systematic enhancement of the photospheric temperature structure in magnetic regions clearly suggests the presence of nonradiative heating, at least in the magnetic regions.

The extension of such arguments to late-type stars should be viewed with skepticism because of the difficulty of computing accurate radiative equilibrium models properly incorporating atmospheric inhomogeneity. Nevertheless, the models of dMe stars computed by Giampapa, Worden, and Linsky (1982) on the basis of the Ca II and H $\alpha$  lines have hotter temperatures in the temperature minimum region than dM stars of similar effective temperatures. A similar argument may be made for the active F-K dwarfs compared to the less active dwarfs (Kelch, Linsky, and Worden 1979) and the active subgiants in RS CVn systems compared to nonactive stars of similar spectral type (Simon and Linsky 1980; Baliunas et al. 1979). Additional work should be undertaken.

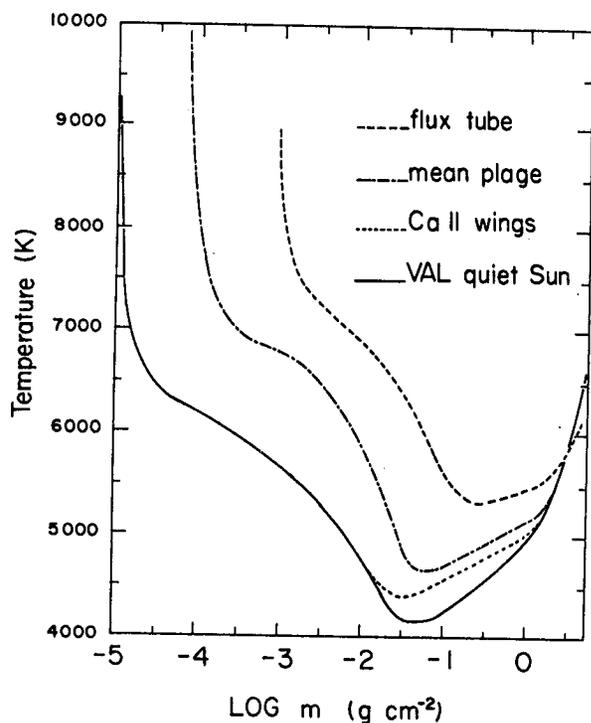


Fig. 5. Plage, flux tube, and quiet Sun models. The solid line is the VAL quiet Sun model (Vernazza, Avrett, and Loeser 1981). The short dashed lines (Ca II wings) represent a modification of the VAL designed to reproduce the Ca II H and K damping wings. The dash-dot curve is a plage model based on H I  $\text{L}\alpha$ , Ca II K, and Mg II k data obtained by the French (LPSP) experiment on OSO-8. The long dashed (higher) curve represents a flux tube model with a chromospheric portion matching the OSO-8 plage profiles with a 20% filling factor. The photospheric portion ( $m > 0.3 \text{ g cm}^{-2}$ ) is similar to the class of flux tube models advocated by Chapman (1977). From Chapman (1981), courtesy of Colorado Associated University Press.

The ultraviolet continua of A stars have been examined for evidence of temperatures in excess of those predicted by radiative equilibrium models. Praderie, Simonneau, and Snow (1975) proposed that emission in the short wavelength wing of the Lyman alpha line of Vega (A0 V) implies nonradiative heating, but Snijders (1977) and Hubeny (1981) have shown that this spectral feature is consistent with nonLTE radiative equilibrium models. Again, further observational and theoretical work is needed.

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#### DISCUSSION

Cassinelli: What physical process is starting to occur at A7 V that gives rise to the start of the late-star phenomena?

Linsky: It is generally presumed that the physical process is the onset of dynamo-generated magnetic fields with the onset of appreciable (whatever that means) convective-zone depth near spectral type F0. However, we should be most careful when parroting this conventional wisdom for the following reasons: (1) Magnetic fields can occur in hotter stars as is shown by the Am stars, and even such B stars as  $\sigma$  Ori E. Since strong fields do exist in stars for which dynamo field amplification should not occur (because of the absence of appreciable convective zone depth) the onset-of-a-dynamo argument must be wrong or at least inadequate. (2) All three commonly used techniques for determining the onset of the late-star phenomenon have observational problems, namely the optical and UV emission lines have to be measured against a very bright continuum in the A stars (loss of contrast), and the X-ray emission could come from unseen cool dwarf companions. (3) Conventional wisdom is usually wrong.

Praderie: I wish to present another view about the correlations between  $L_X$  and rotation. If we think of X-ray emission as the result of a magnetically heated corona,  $L_X$  should be related both to the rotation rate  $\Omega$  and to the properties of the convection zone, where differential motions and fluid helicity take place.

In a paper published by Mangeney and Praderie (1984 Astr. Ap., 130, 143), it is shown that  $L_X$  correlates with an effective Rossby number defined as  $(1/2)(V_c(\max)/L)(1/\Omega)$ , where  $V_c(\max)$  is the maximum value of the convective velocity, and  $L$  is the total depth of the convection zone. We obtain

$$L_X \sim R_o^{-1.2 \pm 0.1}$$

for a set of 44 mainsequence stars observed by the Einstein satellite. This relation holds from O stars to M stars. This suggests a common mechanism for the emergence of B to the surface and for the resulting coronal heating along the full main sequence.

Linsky: Your conclusion is very interesting. It is important to see if luminous stars also obey this relation because convective-zone parameters depend upon gravity in addition to effective temperature.

Underhill: Qualitatively it seems possible that one may develop dynamos in the outer layers of massive stars if there is a remnant of the primordial magnetic field present because the differential motion of the photosphere, driven by the rotation of the star, will surely develop some helical motion. How long dynamos created in this way may exist is very likely a function of the position of the outer  $He^+$  convection zone and its thickness.

Chan: It is very difficult for the outer convection zones of hot stars to do anything. Envelope models using mixing-length theory show no unstable ionization zone below the photospheres of stars earlier than B0. Two-dimensional calculations of the convection zones in mainsequence A5 and F0 stars indicate that the powers of the convection zones in hot stars are much weaker than predicted by the mixing-length theory.

Sreenivasan: Dynamos are considered possible in convective regions because of the implications of Ohm's law:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \lambda \nabla^2 \mathbf{B},$$

which states that if  $\mathbf{v} \neq 0$ ,  $|\mathbf{B}|$  will grow in time if the first term is larger than the second on the RHS. In a radiative region  $\langle \mathbf{v} \rangle = 0$ . Even then a realistic theory of a dynamo process is very difficult to work out, as we know from the literature. A couple of Crays, half a dozen bright theorists, and 5 years of guaranteed employment would help improve matters considerably. I do not know the prospects for working out a dynamo theory in purely radiative regions.

Linsky: In my opinion, major progress in our understanding of how magnetic fields are generated and dissipated in stars of all types is one of the most important tasks of theoretical astrophysics.

Underhill: In 1949 I published information showing that in stars with  $T_{\text{eff}} \sim 25000$  K, the radiative gradient exceeds the adiabatic gradient at depths in the photosphere where the visible continuum is formed. However, in later model-atmosphere work it was not necessary to take account of the possible convection zone, nor was it, indeed, practical to do so. Nevertheless, convection can occur in the  $\text{He}^+$  ionization zone of the deep photospheric layers of stars of types O9 - B2. If there is a primordial magnetic field, convective motion may create weak dynamos in these layers.

Uchida: Magnetic field can be strengthened without having convection. There is rotation which produces circulation, and therefore differential rotation. This strengthens the  $B_\phi$  component, though it gives no feed back to  $A_\phi$ , the latter being necessary for the regenerative, or oscillatory dynamo, in the case of the Sun. So, if there is a primordial field, we can expect strong fields, since the life of an early-type star is short compared with the decay time of the primordial magnetic field.

Linsky: Your suggestion appears interesting. Can it explain the strong bipolar magnetic fields measured in Ap stars and their B-star analogues?

Uchida: Yes. (See the discussion following the review by Uchida.)

# OBSERVATIONS OF NONTHERMAL RADIO EMISSION FROM EARLY-TYPE STARS

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## Abstract

As a part of a wider survey of radio emission from O, B, and Wolf-Rayet (WR) stars, we discovered five new stars whose radio emission is dominated by a nonthermal mechanism of unknown origin. From statistics of distance-limited samples of stars, we estimate that the minimum fraction of stars which are nonthermal emitters is 25% for the OB stars and 10% for the WR stars. The characteristics of this new class of nonthermal radio emitter are: (i) a high radio luminosity, typically  $10^{19}$  ergs  $s^{-1}$  Hz $^{-1}$ , (ii) a spectral index  $\alpha$  ranging from 0.0 to -0.7 (where  $S_\nu \propto \nu^\alpha$ ), (iii) lack of pronounced variability, and (iv) no measurable polarization. There is as yet no obvious characteristic which separates the nonthermal emitters from other early-type stars.

## I. INTRODUCTION

Nonthermal radio emission was first discovered from the two O-type stars 9 Sgr (O4 V) and Cyg OB2 No. 9 (O5f) (Abbott, Bieging and Churchwell 1984). We believe these stars represent a new class of nonthermal radio emitter. Recent observations indicate that the WR star HD 193793 (WC7+ Abs) is also a member of this class (Florkowski and Johnston 1984; White 1984).

The cause of the nonthermal emission is unknown. The observations do not fit existing stellar sources which are known to radiate nonthermally. Further, there is no information on how widespread this phenomenon is among the early-type stars. This is of crucial importance, because all radio data to date have been interpreted as thermal wind emission. To address these problems, we undertook a survey of radio continuum emission from distance-limited samples of OB and WR stars. We present here preliminary survey results describing the nonthermal emitters in our sample.

## II. SURVEY RESULTS

The WR sample included all 44 WR stars within 3 kpc and above declination  $\delta \geq -47^\circ$ . Of this total, 29 were detected, 23 by us and 6 by others (Dickel, Habing and Isaacman 1980; Florkowski 1982; Ho $\ddot{g}$ g 1982, 1984). The stars were selected from the Sixth Catalog of van der Hucht et al. (1981),

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using distance estimates from Lundstrom and Stenholm (1984) as well as Hidayat et al. (1984). The OB sample included all 25 OB stars within 2.5 kpc, with bolometric luminosity  $L_* \geq 10^6 L_\odot$ , and above the declination  $\delta \geq -47^\circ$ . It was selected from the catalogs compiled by Abbott (1982). Distances are estimated from cluster membership in all but a few cases, where absolute magnitude calibrations were employed (Humphreys 1978). Three WR stars and two OB stars were not observed for technical reasons. The stellar samples are complete out to the indicated distances.

The new observations were made at the NRAO<sup>4</sup> Very Large Array (VLA) during three observing periods in 1982 August, 1984 March and April. All stars were observed at 6 cm, and the stronger sources were re-observed at 6 cm and 2 cm. The 1982 August data were taken in the "C" configuration with a bandwidth of 50 MHz. The 1984 observations were taken in a "B-C Hybrid" configuration with an effective bandwidth of 100 MHz. All sources were observed to a sensitivity limit of  $\approx 0.1$  mJy, except where confusing sources imposed a higher limit. The visibility data were transformed to intensity maps using the Astronomical Image Processing System (AIPS) of the NRAO. All detected sources were unresolved. Table 1 gives the fluxes of the new sources which are "nonthermal" by the criteria discussed below. No detectable circular polarization was present in any source.

Table 1  
New Nonthermal Radio Emitters

Star	Spectral Type	Wavelength	Flux (mJy)	Date	Spectral Index	5 GHz Luminosity (ergs s <sup>-1</sup> Hz <sup>-1</sup> )
HD 168112	O5 III	6 cm	1.3±0.1	84 Mar 9		
		6 cm	1.3±0.1	84 Apr 4		
		2 cm	1.2±0.1	84 Apr 4	-0.1±0.2	6 × 10 <sup>18</sup>
Cyg OB2 No. 8A	O6Ib	6 cm	0.8±0.1	84 Mar 4		
		6 cm	0.7±0.1	84 Mar 9		
		2 cm	0.5±0.2	84 Mar 9	-0.4±0.4	3 × 10 <sup>18</sup>
HD 167971	O8I	6 cm	15.4±0.2	84 Mar 4		
		6 cm	13.9±0.2	84 Apr 4		
		2 cm	6.6±0.2	84 Apr 4	-0.7±0.1	
WR 147	WN7	6 cm	35.9±0.3	84 Apr 4	0.0±0.0 <sup>a</sup>	7 × 10 <sup>19</sup>
MR 93	WC7	6 cm	1.3±0.1	82 Aug 20		
		6 cm	1.5±0.1	84 Apr 4		
		2 cm	0.8±0.1	84 Apr 4	-0.6±0.2	7 × 10 <sup>18</sup>

<sup>a</sup>Based on a 20 cm flux of 35.8 mJy measured by Becker (1984).

<sup>4</sup>The National Radio Astronomy Observatory is operated by Associated Universities for Research in Astronomy, under contract with the National Science Foundation.

The most difficult task for interpreting our survey is to discriminate thermal wind emission from other mechanisms which we assume, following the discussion of Abbott, Biegling and Churchwell (1984), are nonthermal. We briefly describe below our designations for the radio emission and the criteria which define the categories:

1) "Definite Thermal Wind Emitters." This description applies to stars if: (i) their radio emission is resolved and agrees with thermal wind models (e.g. White and Becker 1982), or (ii) the radio flux has a spectrum obeying  $S_\nu \propto \nu^{0.6}$  and the total measured flux agrees with predictions from a thermal wind model using a well-determined mass loss rate independently measured by diagnostics at UV, optical, or IR wavelengths [ $\dot{M}$ (UV, optical, IR)].

2) "Probable Thermal Wind Emitters." Describes stars with no measured spectral index, but a 6 cm flux which agrees with well-determined  $\dot{M}$ (UV, optical, IR).

3) "Probable Not Thermal Wind Emission." Describes stars with no measured spectral index and either (i) a 6 cm flux which greatly exceeds predictions from  $\dot{M}$ (UV, optical, IR), or (ii) a 6 cm flux which is highly variable.

4) "Definite Nonthermal Wind Emission." Describes stars which meet criteria #3 and in addition exhibit either (i) a spectral index,  $S_\nu \propto \nu^\alpha$ , obeying  $\alpha \leq 0.0$ , (ii) radio emission unresolved by the VLA in the "A" configuration, or (iii) a positive detection of intrinsic polarization.

By applying these criteria to our survey observations, five new non-thermal radio emitters are identified. All are considered to be "nonthermal" based on their spectral index and their excessive radio flux.

### III. SUMMARY

By the criteria defined above, we characterize the radio emission of our survey stars in Table 2. It is clear that nonthermal radio emission is widespread. We find that 24% of the OB stars and 12% of the WR stars are nonthermal emitters. Because of the large number of stars for which the character of the emission is unknown, these fractions are minimum estimates only.

Our new sources are all characterized by a luminosity of  $\approx 10^{19}$  ergs  $s^{-1}$   $Hz^{-1}$ , a spectrum in the range  $-0.7 \leq \alpha \leq 0.0$ , and a lack of polarization. The 5 GHz fluxes of all sources varied by less than 10% over the interval of 1 month. These properties resemble those found previously for 9 Sgr and Cyg OB2 No. 9, and we conclude that these sources all represent one class of object. We have not yet found any stellar property which distinguishes the nonthermal from the thermal wind emitters. The lower percentage found for the WR stars may be a contrast effect, because the stars all have extremely dense winds which strongly emit thermal free-free radiation.

Table 2  
Summary of Survey Results

Category	# OB Stars	# WR Stars
1) Definite Thermal Wind Emission	6 (24%)	6 (14%)
2) Probable Thermal Wind Emission	4 (16%)	16 (36%)
3) Unknown, Undetected, or Not Observed	9 (37%)	17 (39%)
4) Probable Nonthermal Wind Emission	1 ( 3%)	2 ( 5%)
5) Definite Nonthermal Emission	5 (20%)	3 ( 7%)

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## DISCUSSION

Underhill: There are five points where your statements imply unacceptable interpretations of the observed radio fluxes: (1) Variation of the radio flux  $S_\nu$  as  $\nu^\alpha$  indicates only the presence of a density gradient in the emitting region (Seaquist 1976, Ap.J., 203, L35). The value  $\alpha = 0.7$  corresponds to one particular density dependence, that of a gas expanding with constant  $M$  and  $v$ , and radiating by bremsstrahlung. (2) You have assumed that all of the radio flux is due to bremsstrahlung; some may be due to gyroresonant radiation. (3) Agreement of the values of  $M$  estimated from the strengths of the  $H\alpha$  emission, the UV wind lines, and the radio fluxes may be purely coincidental given the uncertainties in the results. Each part of the theory makes use of a different part of the model for the mantle of the star and the parts are not linked by internally consistent physics. (4) I have pointed out that assuming dense winds for Wolf-Rayet stars leads to physically unrealistic models, see Underhill (1983, Ap.J., 265, 933). Another interpretation of the observed radio fluxes of WR stars is desirable than assuming that the radio fluxes are solely due to bremsstrahlung. I have provided one. (5) Lack of polarization of the radio flux may be due to the fact that one observes radiation from volumes containing magnetic fields pointing in a large number of different directions.

Abbott: Replying to (4), we derived a wind emission measure from optical recombination lines observed by workers at JILA. For the majority of WR stars, the observed radio fluxes are completely consistent with those expected from thermal emission from the wind emission measure inferred from the optical data.

Underhill: I have not seen the work to which you refer. If it is based on nebular theory, I doubt that it is relevant for interpreting the spectra of Wolf-Rayet stars.

Linsky: I would like to comment on the use of the term nonthermal to describe synchrotron or gyroresonant emission. It is probable that the synchrotron or gyroresonant opacity is large at centimeter wavelengths in the winds of many hot stars. If so, then the emission can be described by a Planck function at the coronal electron temperature (assuming that these electrons have a Maxwellian velocity distribution) with the emitting "surface" being that at which the optical depth is unity. In this case, the emission is thermal although not free-free. There are additional complications, however. The emitting surface will not be spherical because the synchrotron or gyroresonant emissivity is directional. Also the emission can be polarized, as is well known.

R.L. White: In the cases where the radio emission has been resolved, we know that the emitting regions are very large ( $\sim 10^2 - 10^3$  stellar radii), as predicted by the thermal free-free emission model. Thus, at least some winds (including some Wolf-Rayet stars) are thermal emitters and do have the inferred (large) mass-loss rates.

Underhill: It is not obvious to me that detection of radio emission from an area in the sky surrounding a star means that the radiating plasma is optically thick at the detected boundaries. Your interpretation of the cause of the radio emission is one possibility. There may be others.

Hearn: Your definition of the "probably thermal" class of radio emission from WR stars is that the rate of mass loss derived from the radio observations is in agreement with the result from other methods of determining mass loss. If the true mass-loss rate is much less than the value derived from the radio observations, one must explain why the other methods of measuring mass loss are also wrong. Would anyone like to comment on how reliable these mass-loss determinations are?

Abbott: There is general agreement between  $\dot{M}$  diagnostics in the IR, the UV, and from optical recombination lines. The accuracy of the  $\dot{M}$  diagnostics for WR stars is probably better than an order of magnitude.

Underhill: In many analyses adjustable parameters are fixed to make  $\dot{M}$  from two or more analyses be the same. Each type of theory relating  $\dot{M}$  to the observed feature ( $H\alpha$ , UV resonance line, or radio flux) deals with a different part of the model mantle. There is no physically consistent relationship between these different parts of the model mantles. Any agreement between the  $\dot{M}$  values deduced may be purely coincidence driven by the arbitrary choice for the several parameters in the theory. The theory which Abbott relies on is only one possible solution for the problem.

Sreenivasan: It is interesting that you find that most WR stars have thermal radio fluxes whereas most OB stars are thought to possess non-thermal fluxes. This is one of the contrasting aspects that requires understanding. Did you consider the fluxes to be thermal because the mass-loss rates as seen by ( $H\alpha$ , infrared, radio) indicators are comparable in analogy with stellar atmospheric nomenclature - (same temperature for several processes vis-a-vis different temperatures) for LTE vs. Non-LTE?

Abbott: This may be a contrast effect, because WR winds are much stronger thermal emitters than OB winds. All mass-loss indicators in hot stars are fairly insensitive to stellar temperature.

Cassinelli: At the IAU Symposium on WR stars, there was a great deal of discussion concerning the fact that all the stars have the same radio  $\dot{M}$  ( $\sim 2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ ) in spite of a wide range in stellar luminosity. Could this be caused by a combination of radio-emission mechanisms?

Abbott: I believe the radio emission from the majority of WR stars is thermal wind emission, and that the small range of observed mass-loss rates is real.

## NONRADIAL PULSATION AND MASS LOSS IN EARLY B STARS

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### I. Nonradial Pulsation in Early B Stars

In the last several years it has been fairly firmly established that NRP probably occurs in nearly all sharp-lined early B stars near the main sequence (Smith 1977). A recent breakthrough occurred with the discovery by Walker et al. (1979, 1981) of quasi emission/absorption "bumps" moving across the line profiles of the rapid rotators  $\zeta$  Oph and  $\alpha$  Vir, and the demonstration by Vogt and Penrod (1983) that an intermediate-1 ( $l=8$ ) NRP mode is responsible for these features in  $\zeta$  Oph. In his ongoing dissertation work, Penrod has monitored some 20 Be and Bn stars and found convincing evidence for NRP in 13 of them, and line profile variations suggestive of NRP in the other 7. Baade (1984) has also identified two NRP modes in  $\mu$  Cen. A search for line profile variables among moderate rotators has turned up NRP in  $\epsilon$  Per (Smith 1984) and  $\eta$  Lep, with  $v \sin i$ 's of 140 and 70 km/sec, respectively. It now seems that NRP can be present at all rotational velocities with equal frequency (near 100%). However, at most 20% of these stars exhibit detectable photometric variations.

Several investigators have found that many OB supergiants exhibit short-timescale photometric variations of a few percent, with periods that fall between the radial fundamental and rotational periods in nearly all cases, which suggests NRP. Smith and Ebbets (1981) offer circumstantial spectroscopic evidence for NRP in  $\rho$  Leo (B1Iab), and the line profile variations observed by Ebbets (1982) in a few other O9 to B0 supergiants are almost certainly caused by a number of simultaneous NRP modes. It appears that the number of NRP modes coexisting in OB supergiants make the detection and identification of the excited modes less straightforward than in the main-sequence stars.

### II. Periodic Moving Shells in the Circumstellar Environment

There is increasing evidence that all  $\beta$  Cep stars have an active radial mode, and that this mode triggers the recurrent temporary ejection of part of the star's atmosphere (Odgers 1955). The evolution of a typical shell feature has been described recently (Smith 1983). Briefly, an optically thick component first appears some 30 to 50 km/sec to the blue of the photospheric profile. The shell decelerates as it rises to 5 to 25% of a stellar radius, and becomes transparent as it diffuses in velocity space. It eventually returns and impacts the upward accelerating shell from the next cycle, creating a shock. In even the small amplitude  $\beta$  Cep stars, some  $10^{-8} M_{\odot}/\text{yr}$  is tossed into the CSE; nearly all of it is returned within hours. Although the maximum velocity of the shell is considerably less than the critical velocity of the radiative wind flow in B stars, there are indications that some (typically 1%) of the shell never returns to the star. For example, Burger et al. (1982) note persistent depressed blue wings of the UV C IV resonance lines of BW Vul, and use this to infer a mass loss rate of  $10^{-9} M_{\odot}/\text{yr}$ .

From the foregoing, it appears that mass loss can be expected to occur in any radially pulsating B star. We believe that a similar phenomenon occurs in nearly all early B stars as a result of NRP, resulting in pulsationally driven mass loss of  $10$  ( $-11$  to  $-9$ )  $M_{\odot}/\text{yr}$ . The velocity amplitudes of nonradially pulsating stars are quite similar to those of the Cep stars, and are locally radially directed. The mass tossing and ejection in an NRP star will occur preferentially from the equator, where the amplitude is largest, and will occur sequentially around the star's circumference. However, since any spectral features produced by this matter will be diffused in velocity space, this "lawn sprinkler" effect will be difficult to directly observe in optical spectral lines.

### III. A Tale of Two Stars - Mass Ejection Mechanisms

Some recent observations of  $\rho$  Leo (B1Iab) and  $\lambda$  Eri (B2IVe) have strengthened the suspicion of a link between NRP and mass injection into the CSE. In the first example, Smith and Ebbets (1981, hereafter SE) monitored the Si III triplet in  $\rho$  Leo and found occasional significant reductions in the strengths of these absorption lines, even in a few hours. The variations seemed to be correlated in time and strength with H-alpha emission events. SE argue that only a global photospheric change, in particular pulsation, could cause the observed variation of the Si line strengths. Their calculations show that a 1000 K reduction in the temperature of  $\rho$  Leo could cause the observed variation, and pointed out that if this thermal energy were converted into mass movement, it could drive the observed H-alpha shell over the observed time and distance. The implied mass loss rate lies in the range  $10$  ( $-9$  to  $-8$ )  $M_{\odot}/\text{yr}$ , which is larger than the rate for most B III-V stars, but 300 times less than the rate found in the presumably radiation driven wind of this supergiant (Lamers 1981). SE searched for line profile variations attributable to NRP in  $\rho$  Leo but could not find them. However, they pointed to the likelihood that many modes coexist in supergiants, so that no single mode could affect the profile greatly. They suggested that when several modes get into phase, the combined pulsation amplitude can become supersonic, and the resulting nonlinearities produce a shock strong enough to eject the upper atmosphere into the CSE.

A second example of pulsation driven mass ejection is furnished by Penrod's extensive monitoring of He I 6678 in  $\lambda$  Eri (B2IVe) between September 1983 and May 1984, during which a minor Be outburst occurred. During the pre-outburst phase, the star exhibited its usual periods of .70 and .27 days, corresponding to  $l=2$  and 8 modes. The approximate amplitudes were  $A_2=5-10$  km/sec and  $A_8=20$  km/sec. In October, an outburst had occurred which manifested itself in emission in the Balmer and He I lines. The emission reached its maximum in November, by which time the  $l=8$  amplitude had decreased to near invisibility ( $A_8$  8 km/sec), while  $A_2$  had decreased but slightly. The emission was declining by January and was absent by April. During this time,  $A_8$  was returning to its initial amplitude, while  $A_2$  declined to perhaps half its initial value. The  $l=8$  amplitude thus seems to correlate with the outbursts over short timescales, while the  $l=2$  amplitude responds more sluggishly.

Pulsation theory suggests that the  $l=2$  mode contains more energy (of order  $10^{42}$  ergs) than the higher- $l$  modes. Penrod's data suggest that low- $l$  modes occur more frequently in Be stars than in Bn stars of comparable  $v \sin i$ . This suggests that a low- $l$  mode is indispensable to outbursts (at least in some types of Be stars), and in particular that only this mode contains a sufficient reservoir of stored energy to feed the outbursts. We speculate that a hierarchy exists in which modes of increasing  $l$  are excited during an outburst at only a small energy cost to the low- $l$  parent mode. These daughter modes have relatively small amounts of energy but achieve large surface amplitudes because they exist only near the surface. The nonlinearities induced by the large amplitudes progress into shocks which eject perhaps  $10^{-10}$  to  $10^{-11}$   $M_{\odot}$  of the star's atmosphere into orbit. The NRP amplitudes diminish as a result of this expenditure of energy, to grow again in time once the outburst ceases. The relatively more rapid decline and subsequent return of the  $l=8$  mode in  $\lambda$  Eri simply reflects the lower energy content of this mode.

This mechanism would allow B stars to be "normal" or "Be" at different times during their main-sequence lifetimes, as an accident of their mode structure at a given epoch, and would explain the erratic nature of the outbursts. The embarrassing presence of flattened equatorial disks around many Be stars which are not rotating near the break-up velocity has a natural explanation in the highly equatorial geometry of high-order sectorial modes.

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## DISCUSSION

Praderie: Could you convince me that a profile, obtained from a non-spatially resolved disk, is able to "feel" oscillations with order  $\ell$  as high as 20? How sensitive is such a profile to the exact value of  $\ell$ ?

M.A. Smith: First let me say that the observational evidence for modes with  $\ell > 20$  is less than a month old, although it has been confirmed by observations from a second spectrograph, and it has been observed by Penrod for a second star. Line profiles contain doppler-imaged information from the entire stellar disk. Therefore, for a NRP model to work requires first that the instantaneous velocity fields be correct over the disk and, further, that the velocity field progress around the disk in time in a prescribed way. When a model works it should be seen as a great success. It takes only a short time for erroneous model parameters to expose their failure.

Since the Vogt and Penrod paper, observational advances have been coming in rapidly. This is because it is always desirable instrumentally to go to a lower spectroscopic resolution in exchange for a higher signal-to-noise ratio. This circumstance has encouraged the study of NRP in the rapid rotators because the models for their stellar disks contain many resolution elements in velocity space. Now when one gets to values of  $\ell$  as high as 20, one sees 10 wave crests and troughs on the hemisphere, and these contribute to 5 travelling bumps on the line profile (one-to-one mapping from stellar disk position to wavelength on the profile).

The higher the  $v_{\text{rot}} \sin i$ , the greater will be the spectroscopic visibility of a high- $\ell$  mode, the higher the  $\ell$ , the more closely spaced will be the bumps on the profile. At the same time, ever fewer grid points on the model disk will contribute to a given velocity, and hence to a particular wavelength. This will cause the bump contrast to diminish, and the detection threshold of a high- $\ell$  mode will rise. Although I have not modeled these modes yet, I would guess that the velocity-amplitude detection threshold for a  $\ell = 20$  or 25 mode is between 15 and 20  $\text{km s}^{-1}$ , assuming a reasonable trough-to-crest temperature difference and assuming an equatorial aspect for the observer. The bump contrast is approximately linear with all of these factors ( $\ell$ ,  $v_{\text{rot}} \sin i$ ,  $\Delta T$ ). If a single mode is present, I estimate its  $\ell$ -value can be determined with a precision of about  $\pm 15\%$ .

# NARROW ABSORPTION COMPONENTS IN Be STAR WINDS

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## I. Introduction and Historical Review

Narrow absorption components with  $\text{FWHM} \approx 100\text{--}300 \text{ km s}^{-1}$  are frequently observed superposed on UV P Cygni profiles in early type stars (Snow, 1977). In Snow's *Copernicus* data, most of the observed line profile variation appeared to be associated with the narrow components. A survey of 26 O stars by Lamers *et al.* (1982) yielded observations of narrow absorption components in 16 of the stars. Typical centroid radial velocities of the components were  $0.6\text{--}0.9v_{\infty}$ . The optical depths of the components and the centroid radial velocities were found to be inversely related. The ionization stages of the narrow components were found to be systematically higher than those of the underlying P Cygni profiles. Henrichs (1984) reported that the presence of narrow absorption components is observed in 56 percent of a sample of 85 stars brighter than  $M_{\text{bol}} = -7.5$ . No correlation in luminosity class,  $v \sin i$  or with  $f$ ,  $(f)$ , or  $((f))$  designation was found.

Studying narrow absorption components in O stars has its drawbacks, since many of the UV P Cygni profiles in O stars are close to saturation. The presence of narrow absorption components becomes difficult to detect under these circumstances, particularly at low velocities. If narrow absorption components, their time history, and their relation to the underlying P Cygni profiles are to be studied, stars with unsaturated P Cygni profiles and showing short-term UV line profile variability are required. As noted by Snow and Morton (1976), early Be stars have detectable stellar winds and unsaturated UV resonance lines of the species which have shown the presence of narrow absorption components. Henrichs *et al.* (1983) found that the resonance lines of N V, C IV, and Si IV in  $\gamma$  Cas frequently show a single narrow absorption component at high velocity superimposed on a quiescent P Cygni profile. As in the case of the O stars studied by Lamers, *et al.* (1982), the component centroid radial velocity is inversely related to the optical depth of the line.

## II. Observations

A limited number of other UV active Be stars with detected narrow absorption components have been monitored sufficiently with *IUE* to permit analysis of the behavior of the narrow components. The stars I will discuss are  $\omega$  Ori (B2 IIIe), 66 Oph (B2 IVe), and 59 Cyg (B1.5 IVe). One question to be explored is the extent to which the narrow absorption components in these Be stars differ from narrow components in the O stars and  $\gamma$  Cas.

The UV resonance lines of C IV, Si IV, and Si III in  $\omega$  Ori (Sonneborn, *et al.* 1984) show a strong absorption component at high radial velocities. The centroid radial velocity of the component is inversely related to the optical depth of the component. There are suggestions of the presence of weaker absorption components at lower radial velocities, but these are not resolved. The weaker components are ephemeral. The behavior of this star similar to that of  $\xi$  Per (Henrichs, 1984) with the largest amplitude line profile variability observed at radial velocities smaller than the component centroid velocity. Sonneborn, *et al.* (1984) have shown that the UV line profile variation is uncorrelated with either visual continuum linear polarization or with H $\alpha$  emission strength. Significant UV wind line profile variation occurs on timescales as short as a few hours and is observed with equal amplitude during both low and high polarization phases.

Unlike  $\gamma$  Cas, the UV line profiles have never been observed without the presence of at least one narrow absorption component.

The UV resonance lines of Si IV and C IV in 66 Oph (Fig. 1) are characterized by the presence of multiple resolved and partially resolved absorption components which are highly variable in number, strength, and distribution in radial velocity. No quiescent Si IV or C IV line profiles are observed. This differs significantly from the behavior of the more luminous O stars and early Be stars, since the entire wind contribution to both the Si IV and C IV line profiles is variable and ephemeral. No underlying P Cygni profile of the type familiar in the O stars is observed. The strongest narrow absorption component observed in this star is observed at the low radial velocity of  $-200 \text{ km s}^{-1}$ . Variations in optical depth with no accompanying changes in radial velocity differ significantly from the behavior of the strong high velocity narrow absorption components in  $\gamma$  Cas, or even in  $\omega$  Ori. The behavior of the higher velocity and partially resolved components is similar to the behavior of the weak absorption components in  $\omega$  Ori. Significant changes in the line profile shape may occur without similar changes in the total profile absorption equivalent width. Similar line profile strength, and variation is observed in periods of both low (Peters, 1982) and high linear polarization (Hayes, 1983).

The UV resonance lines of C IV (Fig. 2) and N V in 59 Cygni also show narrow absorption components and significant line profile variation. N V absorption in this star, when observable, is present as a single displaced absorption component observed anywhere in the range 0 to  $-1400 \text{ km s}^{-1}$ . The C IV profile typically has two or more resolved narrow absorption components present, which may be observed anywhere from zero radial velocity to the violet edge of the line profile. A frequent profile shape consists of weak low velocity absorption, minimal absorption at intermediate velocities, and strong broad absorption at high velocities. This profile shape is similar to that reported by Massa, *et al.* (1984) for BD -41 °7719 (B1 V) for which no history of Be activity is known. Massa, *et al.* (1984) were able to fit the line profile by adopting a non-standard velocity law, without invoking a more complex wind structure. C IV line profiles having strong absorption at low velocity and weaker absorption at high velocity are also observed in 59 Cyg, as are profiles with approximately uniform absorption over a wide range in radial velocity and profiles with multiple resolved narrow absorption components. Si IV and Si III in this star, during the epoch covered by the IUE observations, are symmetric and show no evidence of wind absorption. This contrasts with the significant wind absorption observed in both lines during the 1972 and 1974-1975 shell episodes reported by Marlborough and Snow (1980). Both the N V and C IV profiles are dominated by the component absorption, and it is not possible to identify any quiescent line profile (either wind or photospheric). The behavior of the C IV line profiles in 59 Cyg resembles 66 Oph, rather than the more luminous O and very early Be stars.

### III. Discussion

Any models or mechanisms for the formation of narrow absorption features in the UV resonance lines of Be star spectra must account for the presence of multiple narrow absorption features which are variable in number, radial velocity, and strength. Suitable mechanisms must produce features which, for the stars with the strongest mass loss rates, have higher ionization than the bulk of the wind material. For stars with smaller mass loss rates, the narrow absorption components apparently dominate the wind absorption. In either case, suitable mechanisms must be capable of producing significant UV line profile variation on timescales of hours to days during episodes of both low and high linear polarization (66 Oph and  $\omega$  Ori) and during both B-shell and Be phases (59 Cyg). If the finding of Henrichs (1984) is confirmed, that for stars less luminous than  $M_{\text{Bol}} = -7.5$  only Be stars show narrow absorption components, this may suggest that one and the same mechanism may be responsible for both Be phenomena and narrow absorption components. However, it will need to be shown that narrow absorption components are common in Be stars before such a suggestion may be accepted.

A number of models for the formation of narrow absorption components in O stars have been proposed (summarized by Lamers, *et al.* 1982). Some of these may be excluded for the Be stars as a result of the observed line profile variation. The models which do not seem to be especially plausible for the Be stars considered in this paper are the presence of a plateau in the velocity law, the presence of an ionisation maximum at intermediate velocities in the wind acceleration zone producing an optical depth minimum at intermediate radial velocity, and models producing a stationary shell in the wind acceleration zone.

A number of other models have been proposed to explain some of the features of the line profiles in these stars. Temporary mass loss from bipolar magnetic loops attached to the stellar photosphere, and hence coupled to the stellar rotation (Underhill and Fahey, 1984), have also been proposed to explain narrow absorption components in stellar winds. This model has difficulty with the lack of correlation of the presence of narrow absorption components with  $v \sin i$  reported by Henrichs (1984). However, this model does not restrict narrow absorption components to high radial velocities. Models predicting a high and low density structure to the stellar wind caused by instabilities in a flow driven by radiation pressure or by variable mass loss may be more successful in describing the behavior of winds in early Be stars. These models appear to be capable of producing single absorption components in the velocity range observed for O stars and very early Be stars. In these models, the presence of a correlation of component radial velocity and column density is expected since the same radiation pressure is available to accelerate wind material at all times, and lower density material is expected to be accelerated to higher velocities than high density material. Such models do not predict multiple resolved narrow absorption components, nor do they predict that low velocity absorption components may be regularly observed in some stars. An important observational test for these models is the high time resolution evolution of the line profiles. Such models predict that enhanced absorption should initially appear at low radial velocity and within a few hours move to high velocity before gradually decaying.

More observational and theoretical work is needed on this topic. High time resolution observations are needed for a larger sample of early Be stars which have shown variable line profiles. More data is needed on B stars with properties similar to the better studied Be stars. In particular, Henrichs' (1984) claim that narrow components are associated only with Be stars and not with B stars should be confirmed, especially in view of the C IV profile observed by Massa, *et al.* (1984). The role of non-radial pulsations which have been reported in one Be star (Vogt and Penrod, 1983) in affecting the properties of the wind should be further explored.

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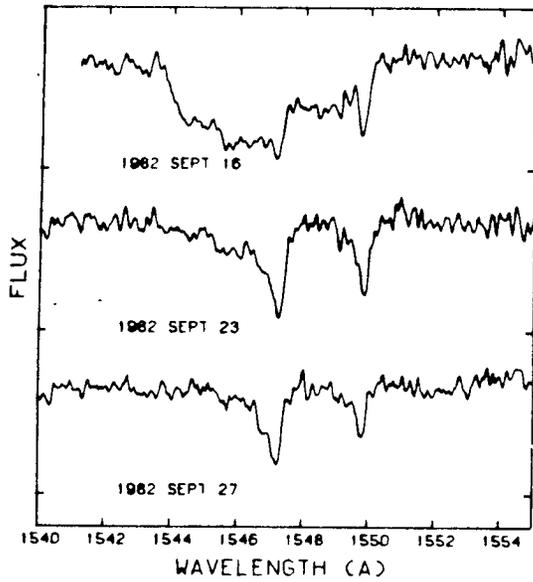


Figure 1: (Left) C IV profiles for 66 Oph for 1982 Sept 16-27. The low velocity narrow absorption component persists despite the drastic weakening of the high velocity absorption between Sept 16 and Sept 23.

RELATIVE FLUX

**59 CYGNI  
C IV 1548, 1550**

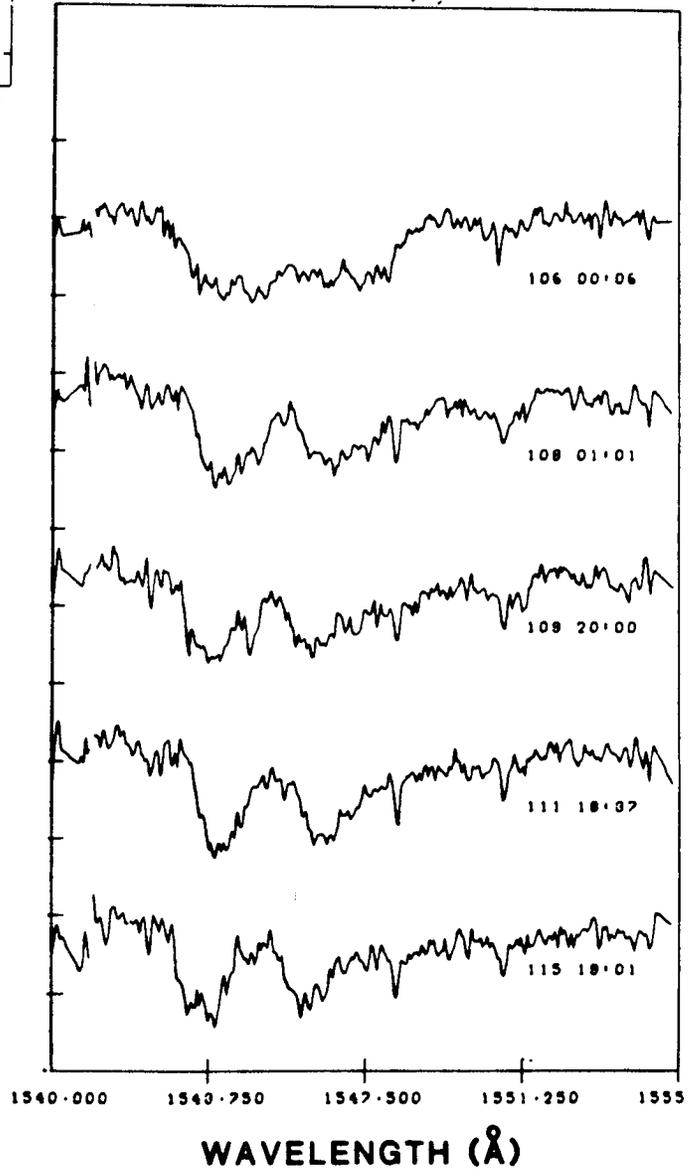


Figure 2(Right): CIV profiles in 59 Cyg for 1981 April. Each line profile is offset from the others by 1.4 times the continuum flux. Multiple narrow absorption components are particularly well resolved on days 111 and 115.

## DISCUSSION

Underhill: A long series of IUE observations of  $\theta$  CrB, a B6e star, exists. I am presently analysing these data. The strengths of the discrete components change from time to time, but the displacements are small and constant so far as they can be measured. Doazan, *et al.* (1983, *Astr. Ap.*) have published a description of some of this material. However, I do not agree with all of their deductions. You may find the paper by Underhill and Fahey (1984, *Ap.J.*, **280**, 712) useful for interpreting the behaviour of the discrete components in Be stars.

Mullan: Are some of your stars pole-on? If so, why would equatorially-confined non-radial oscillations have visible effects?

Grady: The stars 66 Oph and  $\omega$  Ori have been described as "pole-on" based on the low values of  $v_{\text{rot}} \sin i$  (160 and 240  $\text{km s}^{-1}$ , respectively (Slettebak 1982)), and the assumption that  $v_{\text{eq}}$  is 400-500  $\text{km s}^{-1}$ . The latter assumption is questionable. At this point, insufficient data exist to derive independently the inclination angle.

Cassinelli: The Be stars show superionization of C IV as late as B9. This is later than expected under the usual Auger explanation. Perhaps some other heating is involved. Any ideas?

Grady: At present no, but it will be very interesting to explore the connection between phenomena such as the presence of narrow absorption components, non-radial oscillations, and superionization.

# LIGHT VARIATIONS OF THE B-TYPE STAR HD 160202

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## ABSTRACT

Light variations of the B-type star HD 160202 in the galactic cluster M6 are presented. A flare type increase in brightness by about three magnitudes in a time interval of 40 minutes has been recorded.

## I. INTRODUCTION

For a number of years the Astronomy Department of Northwestern University operated a field station in Las Cruces, N.M. for the purpose of evaluating the image orthicon system as a photometric instrument. Between 1962 and 1965 I observed a number of galactic clusters for the purpose of a photometric evaluation of the system. At the same time a search was conducted for short-period light variations among the cluster members. The advantage of the image orthicon tube is in its capacity to accumulate the amount of light falling on the photocathode in a preset period of time thus reaching faint stars in a relatively short time interval. A scan of the photocathode displayed the field on a TV screen which in turn was photographed with a camera. The advantage of the system can be judged from the fact that in 8 sec integration time stars of magnitude 16 were recorded by means of a 12-inch telescope. The disadvantage of the whole process was in its last step, the photographic recording of stellar brightness which introduced the problems associated with photographic photometry. Nevertheless tests have shown that the brightness of a star can be measured with an accuracy of about 0.1 mag (Hynek et al., 1966).

## II. OBSERVATIONS AND REDUCTION

The observations of M 6 started in 1962 and continued until 1965. During this period of time 21 nights were devoted to the cluster and the observations per night, in some cases, extended for five hours. In the course of reduction the diameters of a number of stars were measured by means of a linear comparator. A calibration curve was constructed for each night using the V photoelectric observations of Rohlfs et al. (1959) for the magnitude scale. Among the stars measured a particular interest aroused the star No. 32 in Rohlfs et al. Catalogue. As check stars two other stars, No. 20 and 70 were also investigated. It was found that comparison stars remained constant within  $\pm 0.05$  mag during the time intervals involved. On the other hand, star 32 appeared to be variable. The variable star can be easily identified at the upper right hand arm of the V-shaped configuration in Fig. 1a. Its change in brightness has been plotted in Fig. 1b. As the diagram indicates the star was at its expected brightness only once in the early part of 1962 (the first point in Fig. 1b). From there on its brightness gradually declined to mag 9. On July 3, 1965 we witnessed a series of increases of

brightness the last one being about 3 mag above the average brightness for the night. Another small increase in brightness occurred on July 15. These observations have been collected in Table I.

The star was reobserved photoelectrically a few years later. The measured brightness was  $6.74 \pm 0.01$  in 1968 (average of 11 nights) and  $6.73 \pm 0.03$  (average of 9 nights) and in 1970. From these observations it appears that the star regained its original brightness in about six years. A report about the flare was also published elsewhere (Bakos, 1969, 1970).

### III. DISCUSSION AND CONCLUSION

It is reasonable to assume that the gradual decline in brightness of star 32 was due to a formation of a shell or some kind of an envelope around the star. Such envelopes are unstable and in a time interval of months or years they are blown off. Pleione is a good example or a star in NGC 6913 observed by myself (Bakos, 1973). The unusual feature about the flare in M 6 is the short time scale of the event. The observations of July 3, 1965 (J.D. 8944) started while the flare was in progress. The observation preceding this one was two months earlier (J.D. 8881) when the star was close to its minimum brightness. The question is: when did the rise to maximum occur? If soon after J.D. 8881, then on J.D. 8894 we were observing the tail-end of the flare. Although it appears that the flaring process ended abruptly it seems likely that the decline to minimum brightness was gradual as indicated by the increased brightness on July 15 (J.D. 8956).

It could also be argued that the decline to minimum brightness was not outside the range of expected brightness for the star. The maximum brightness is an extrapolation of the calibration curve for that particular night. If the event is scaled down by about a magnitude the brightness of the star is within the range before and after the shell episode in 1962 and 1968.

If on the other hand the event was of a short duration (few hours) it is hard to imagine a shell-dissipating process responsible for about tenfold increase in brightness. In such a case one would have to assume a non-radioactive heating process associated with the magnetic field of the star. Such processes are responsible for solar flares and a scaled up version could apply to the B-type stars. It is unfortunate that the observations presented here do not give a clear indication of the time scale of these events in the star.

In summary, it has been shown that a B-type star in the galactic cluster M 6 went through the process of shell formation and a flare type increase in brightness in a time interval of three years. Similar cases associated with B-type stars were reported in the past; however they represent sporadic and accidental observations. The observations presented here show, for the first time a flare-type event with a resolution of five minutes.

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TABLE I  
 Variations of Brightness of Star HD 160202

J.D. - 243 0000	V mag	No. of frames
7794.833	6.8	4
7879.720	7.8	5
8198.783	7.7	7
8212.878	7.6	1
8224.783	8.0	1
8523.947	8.7	18
8524.894	9.0	23
8525.878	9.1	25
8536.927	8.8	6
8576.677	8.6	6
8607.654	8.8	3
8614.642	8.5	9
8879.846	8.2	16
8880.885	8.2	35
8881.882	8.2	30
8944.756	8.2	49
8956.743	7.7	33
8970.715	8.9	5
8972.660	8.4	16
8985.656	8.7	10
8993.705	8.5	10

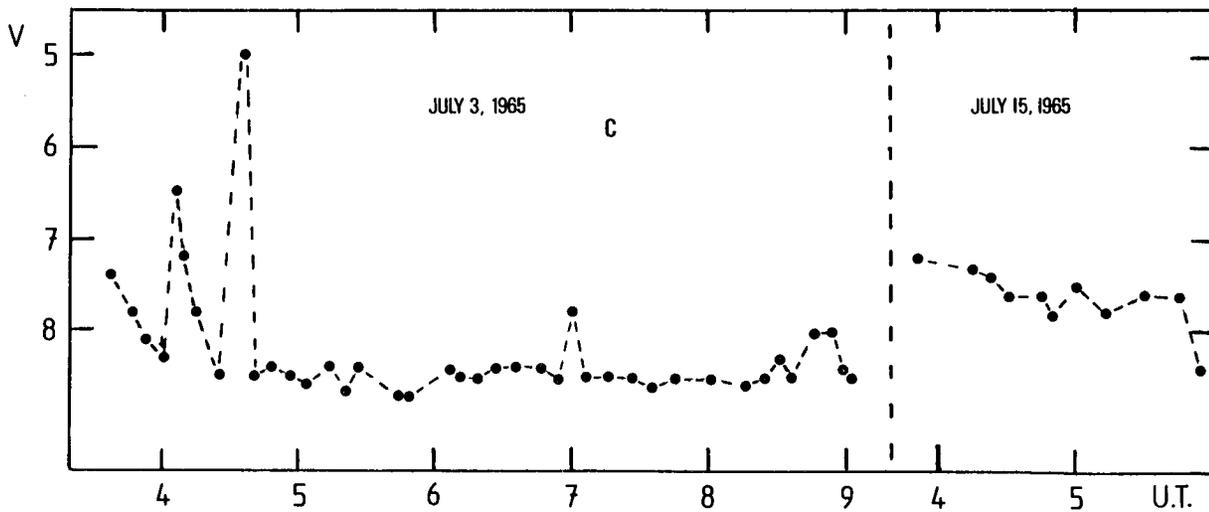
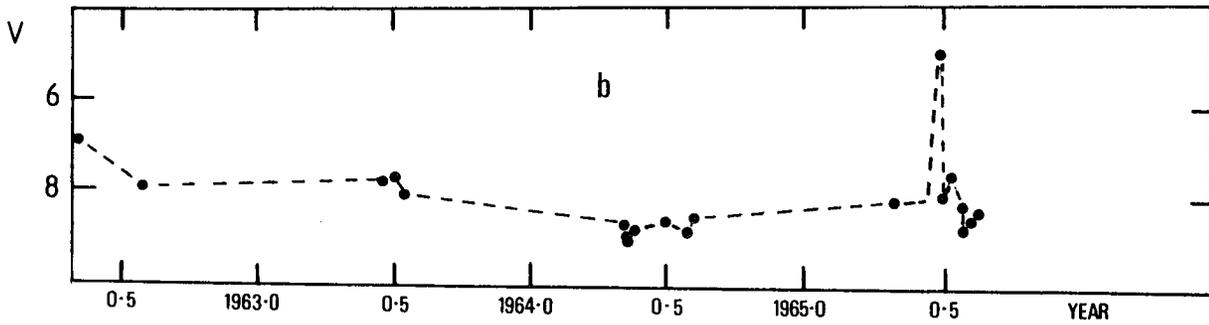
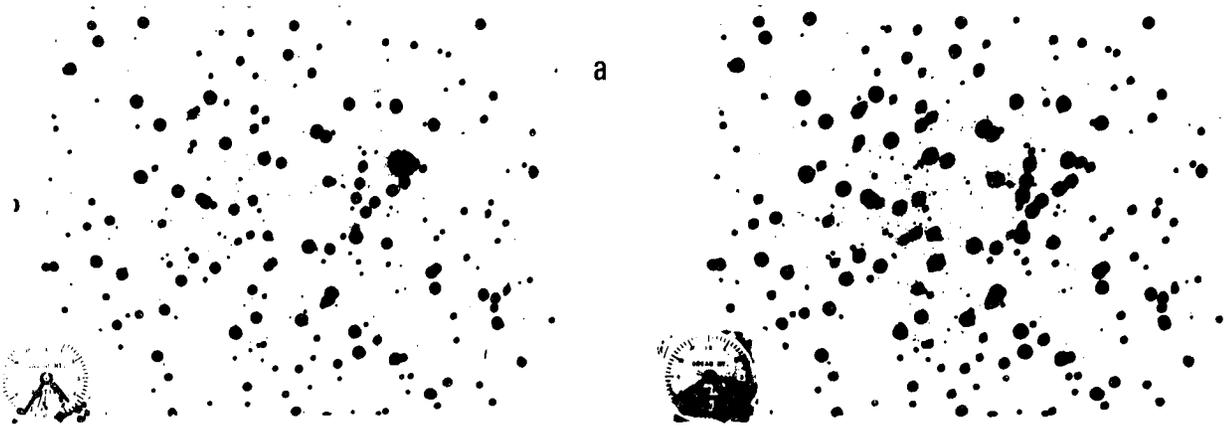


Fig. 1a. The field of variable No. 32.

Fig. 1b. The light variations of the variable in 1962 - 1965.

Fig. 1c. Five minute resolution of the light curve on two nights in 1965.

# ULTRAVIOLET SPECTRAL MORPHOLOGY OF O-TYPE STELLAR WINDS

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The prominent stellar wind profiles in ultraviolet O-type spectra display strong systematic trends, and a high degree of correlation with the optical spectral types, among the majority of normal stars. True or false? Such a question is susceptible to empirical investigation, independently of theories about the origin of stellar winds; indeed, a pure morphological approach is preferable initially, in order that the description of the phenomena not be made subject to the inevitable, time-dependent uncertainties associated with physical measurements, calibrations, and models, or be convolved with interpretative concepts. Of course, only physical analysis can lead to ultimate understanding, but an accurate and complete image of the phenomena addressed is an essential prerequisite. Moreover, morphology can either strongly support or eliminate physical hypotheses, and provide vital guidance toward their development.

The opening question above has been investigated in collaboration with Robert J. Panek and Joy N. Heckathorn, by means of an extensive survey based upon the unprecedented sample of high-resolution data provided by the International Ultraviolet Explorer archives. Short-wavelength (1200-1900 Å) observations of 120 stars with accurate optical classifications were rebinned to a constant wavelength resolution of 0.25 Å, normalized (not dereddened), and plotted at 10 Å/cm, permitting effective intercomparisons of numerous objects. The results will be presented in the form of a comprehensive spectral atlas, to be published by NASA, and some of them are described here. They demonstrate that the answer to the opening question is a resounding true!

Along the main sequence, the resonance doublets N V  $\lambda\lambda$ 1239,1243 and C IV  $\lambda\lambda$ 1548,1551 have strong, saturated P Cygni profiles from O3 through O6, which begin to decline at O7 toward absorption troughs alone by O9. Thereafter, the C IV wind troughs continue to decline toward pure photospheric (plus interstellar) absorption at B1 V (Henize, Wray, and Parsons 1981; Walborn and Panek 1984a). Interestingly, the subordinate transition N IV  $\lambda$ 1718, while unsaturated, shows a behavior analogous to that of the N V and C IV.

In contrast, the Si IV  $\lambda\lambda$ 1394,1403 resonance doublet shows no stellar wind effect anywhere on the main sequence. Rather, the Si IV stellar wind effect displays a remarkable luminosity dependence, developing gradually from a moderate absorption trough in the giants to a full P Cygni profile in the most luminous supergiants (Walborn and

Panek 1984b).

A very important point (unfortunately recognized too late for inclusion in the preceding reference) follows from the Copernicus data presented by Snow and Morton (1976): the C III  $\lambda 1176$  multiplet shows a luminosity-dependent stellar wind effect strikingly similar to that of the Si IV. This C III feature is not a resonance transition, but the C III ionization potential (48 eV) is almost the same as that of Si IV (45 eV); on the other hand, the ionization potentials of C IV, N IV, and N V are significantly higher (64, 78, and 98 eV, respectively). The contrasting behaviors of the stellar wind effects may provide directly observable evidence of ionization and velocity gradients, such that the higher ionization features form further out, but the C III and Si IV are formed nearer to the star, where the flow has not yet begun on the main sequence and gradually picks up with increasing luminosity.

Thus, the normal ultraviolet spectra provide an empirical, two-dimensional reference frame relative to which peculiar objects can be recognized and described. For instance,  $\theta^1$  Orionis C in the Orion Nebula Trapezium has weak (and variable) wind features for its spectral type; there is strong external evidence that it may be a very young O star. Conversely, the optical standard  $\tau$  Scorpii (B0.2 V) has highly unusual, enhanced ultraviolet wind features, including asymmetrical Si IV absorptions. HD 36879, O7 V(n) - presumably a rapid rotator - has peculiar, narrow Si IV emission features which varied significantly in strength between two observations obtained 4 days apart.

Another peculiar category of particular interest to me is that of the ON and OC spectra, so classified on the basis of optical absorption-line criteria. A number of them show striking anomalies in their ultraviolet wind features, relative to the normal spectra. For instance, the ON dwarfs HD 12323, 14633 (Abbott, Bohlin, and Savage 1982), 48279, and 201345 and the ON supergiants HD 105056 and 123008 all have enhanced N V wind profiles and/or deficient C IV, while the OC supergiants HD 152249 and 152424 have just the opposite. The opposite deviations of the C and N features in each spectrum strongly suggest an abundance anomaly hypothesis (Walborn and Panek 1984c).

Finally, I would like to mention the narrow-line WN (WN-A) spectra, which bear strong relationships to those of the hottest Of stars. In the ultraviolet, as in the optical, they constitute a highly homogeneous and peculiar category. Their N V and C IV P Cygni profiles are quite similar to those in Of spectra; however, the Si IV shows peculiar wind profiles with saturated shortward absorption troughs and weak emission, while He II  $\lambda 1640$  and N IV  $\lambda 1718$  show just the opposite, namely weak absorption and very strong emission. Detailed modeling of these peculiar profiles will surely yield substantial new information about

the geometry and physical conditions of the envelopes in which they are formed.

The highly systematic behavior of the stellar wind features among the majority of O-type spectra, and their strong correlations with the well-calibrated optical spectral types, are consistent with those wind models which incorporate a structural dependence on the fundamental stellar parameters. On the contrary, wind models which postulate a predominance of random rotational or magnetic effects, unrelated to the fundamental stellar parameters, are not supported by the ultraviolet spectral morphology; rather, such effects may contribute to the observed properties of some of the exceptional peculiar objects.

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#### DISCUSSION

Hearn: Have you looked at the Copernicus results to see what the O VI line is doing? If not, this would be worth doing.

Walborn: Not yet, but I am planning to do so in collaboration with Ralph Bohlin. There are several lines, including the O VI lines and C III 1176 shortward of the IUE wavelength limit which are of interest in the present context.

M.A. Smith: I agree with Castor that these systematics are indicative of the probable importance of radiation pressure in driving the winds, particularly among the supergiants. However, near the main sequence the situation may be different. In one of the few comprehensive papers on mass loss in near-main-sequence stars (on Be stars), Snow (1981, Ap.J., 252, 139) found a lack of correlation between mass loss and the physical parameters of stars. It was just this circumstance that led him to suggest that another parameter aside from radiation pressure must be important in these stars. We may be seeing the beginning of mapping out the turfs on the HR diagram of radiation pressure and nonradial pulsations.

Walborn: I would emphasize the importance of not projecting the properties of peculiar objects onto the interpretation of the normal spectra. Certainly the rotational velocity is a significant third parameter in the case of the Be stars. The morphology of the normal spectra must be established first, and then the behaviour of peculiar objects or categories can be recognized and described relative to the reference frame.

Underhill: The breakdown of the Eddington-Barbier relation in an expanding/contracting model atmosphere prevents one from inferring from the spectra of hot stars with winds meaningful, single-valued relationships between velocity of outflow, or level of excitation and ionization, with distance from the center of the star. Any inference concerning the relative abundances of two or more elements from the relative equivalent widths of lines is impossible until an adequate statistical equilibrium solution has been done to take care of "NLTE" effects accurately in the mantle of the star. The line-profile must be calculated using an appropriately detailed theory of the formation of lines in a mantle. Until these steps are taken, it is misleading to talk of "abundance" differences when referring to the apparent differing line strengths in the spectra of stars which are similar in many respects.

Walborn: In both cases I referred to empirical hypotheses suggested by the spectral morphology. Since the C III and Si IV profiles are at zero velocity in the main-sequence spectra, while the C IV, N IV, and N V profiles reach high negative velocities, intuition indicates that the former would arise interior to the latter, higher ionization features. In the ON and OC spectra, the opposite deviations of the N and C features relative to the normal spectra indicate the abundances as the most plausible responsible physical parameters.

Underhill: The relevant N and C energy level populations could react differently to the ambient "NLTE" situation.

Castor: Almost all the variation of UV line strengths for normal stars can be accounted for in terms of the mass-loss rate of the wind; it is probably best, for now, not to use these features for spectral types. The correlation with spectral type says something about the dependence of the rate of mass loss on stellar parameters.

Walborn: Certainly, the higher wind densities of the more luminous stars are relevant to, if not entirely responsible for, the Si IV effect. However, there are some objects with lower terminal velocities and/or higher wind densities than typical, which nevertheless follow the normal morphology of the wind profiles. All spectral types I showed are optical; the good correlation with the Si IV profiles indicates that the latter will be a useful UV criterion. Any spectral feature which is well behaved can be used for empirical classification, regardless of the physical mechanism responsible for its origin.

Cassinelli: In the later O stars, say O7, the difference in Si IV from the main sequence to supergiants can be explained from the large differences in mass loss. In the O3 V stars you might expect the Si IV lines to be strong because of the large mass-loss rates. However, the temperatures are also higher and Si IV tends to disappear at temperatures of the order of 50000 K or higher.

# NONTHERMAL RADIO EMISSION AND THE HR DIAGRAM

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Perhaps the most reliable indicator of non-radiative heating/momentum in a stellar atmosphere is the presence of nonthermal radio emission. To date, 77 normal stellar objects<sup>2</sup> have been detected and identified as nonthermal sources.<sup>3</sup> We list them in Table 1: 59 are incoherent emitters, 9 are coherent, and 9 have exhibited both types of emission. With the exception of the RS CVn binaries 39 Cet and V711 Tau, all of the coherent emitters can be identified with dMe (flare) stars. Of the sample, 42 are close (interacting) binaries, and 35 are single stars or wide binaries in which the radio emitting component has not yet been identified. Most of the close binaries (33) are listed in the updated version of the Hall Catalog of RS CVn Binary Star Systems.<sup>4</sup> Of the remainder, all have components similar to the "active" components in RS CVn systems or to dMe stars. The single stars include 8 very-hot, mass-loss stars, 3 red giants and supergiants, 2 (post) T Tauri stars, and 21 dMe (flare) stars.

Despite the fact that a reasonably complete, luminosity-limited catalog of nonthermal radio stars has yet to be compiled, it is apparent that nonthermal radio emission is not ubiquitous across the HR diagram. This is clearly the case for the single stars; it is not as clear for the binaries unless we associate the radio emission with their late-type components. Choosing to make this association, I plot the single stars and the late-type components together (see Fig. 1). The following picture emerges:

1) There are four locations on the HR diagram where nonthermal radio stars are found: A - the WR/05 region; B - the M3II region; C - the KOIV region; and D - the dM region. The magnetic B star,  $\sigma$  Ori E (B2Vp), is at present unique. The large "gap" in spectral types B, A, F appears to be real.

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<sup>2</sup>I exclude pulsars and objects such as X-ray binaries (e.g. Sco X-1) where the radio emission probably has its origin in an accretion disk rather than a stellar atmosphere.

<sup>3</sup>Gibson (1983) has provided criteria for identifying stellar radio emission as thermal or nonthermal (coherent or incoherent). See also Abbott, Biegging, and Churchwell, this volume.

<sup>4</sup>Edited by D. S. Hall, M. Zeilik, and E. R. Nelson; available from M. Zeilik, Dept. of Phys. and Astron., U. of New Mexico.

Table 1. "NORMAL" STARS EXHIBITING NONTHERMAL RADIO EMISSION

Name	HR	HD	Gliese	Sp	log L <sub>R</sub> <sup>a</sup>	Ref.	C <sup>b</sup>	Ref.	Notes <sup>*</sup>
39 Cet	373	7672		wd+G5III	16.9	37	C	37	
UV Psc		7700		G2IV-V+K3IV-V	17.4	43			
L726-8A			65A	dM5.5e	14.0	13	C	13	
UV Cet			65B	dM6e	13.3	18	C	13	
Algol	936	19356		B8V+G5III	17.6	21			*
UX Ari		21242	14.1	G5V+K0IV	(17.9) <sub>10</sub>	11			
V711 Tau	1099	22468		G5IV+K1IV	18.0	12	C	4	*
V471 Tau		26337		wd+K7Ve	15.3	34			
		26961		G5IV+?	16.3	30			
b Per	1324	26961		A2IV+G	(16.5) <sub>8</sub>	23			
V410 Tau				K3V-IVe	17.7	6			*
RZ Eri		30050		A5Vn+G8IV	(16.7) <sub>8</sub>	32			
V1005 Ori			182	dM0.5e	(15.4) <sub>15</sub>	33			*
12 Cam	1623	32357		K0III+?	16.8	8			
V371 Ori			207.1	dM3e			C	41	
σ Ori E	1932	37497		B2Vp	17.9	5			
		37847		F+G8III	16.9	39			
χ <sup>1</sup> Ori AB	2047	39587	222AB	GOV+dM	14.1	28			
α Ori	2061	39801		M2Iab	(18.7) <sub>15</sub>	25			
π Aur	2091	40239		M3II	(18.0) <sub>10</sub>	36			
		51268		K2IIIp+?	18.1	39			
AR Mon		57364		G8III+K2-3III	17.5	30			
YY Gem			278C	dM1.5e+dM1.5e	15.6	15			
σ Gem	2973	62044		K1III+?	16.9	22			
YZ CMi			265	dM4.5e	15.0	16	C	16	
54 Cam	3119	65626		GOV+G2V	16.3	43			
RX Pup		69190		(Symbiotic)	---	35			*
TY Pyx		77137		G2IV+K0IV	16.0	32			
		81410		F5V+K0III	18.1	39			
AD Leo			388	dM2.5e	(15.4) <sub>1.4</sub>	27	C	27	
DM Uma				G8V-IV+?	16.8	30			
CN Leo			406	dM8e			C	31	*
o Hya	4494	101379		AOV+K3III	17.8	7			
Ross 128			447	dM5			C	31	
DK Dra	4665	106677		K0III+K0III	16.5	30			
Wolf 424			473	dM5.5e			C	44	
RS CVn		114519	501.1	F4IV-V+K0IV	17.2	19			
BH CVn	5110	118216		F2IV+KIV	(18.1) <sub>10</sub>	11			
Proxima Cen			551	dM5e	13.8	40			
RV Lib		128171		G2-5+K5	17.3	30			
BD+16°2708			569	dM0e			C	31	
		137164		K1IV+K2IV	16.9	29			
σ <sup>2</sup> CrB	6064	146361	615.2A	F8V+GOV	(16.5) <sub>15</sub>	22			*
DoAr 21				dGe	18.1	10			
WW Dra		150708		G2IV+K0IV	17.1	26			
Wolf 630 AB		152751	644AB	dM4e+dM4e	15.0	18	C	31	
		155638		G8IV+?	16.1	30			
29 Dra		160538		K0-2III+?	18.0	8			
9 Sgr	6736	164794		O4V	18.8	2			
AM Her				wd+dM4	15.6	9	C	9	
		167971		O8If	19.8	1			
		168112		O5III	18.7	1			
V1216 Sgr			729	dM4.5e			C	31	
V1285 Aql			735	dM2e			C	31	
R Aql		177940		gM5e-8e	(18.8) <sub>10</sub>	39			
MR 93				WC7	18.8	1			
		185510		K0IV-III+?	16.4	8			
VW Cep				G6V+K1V	15.0	24			
		193793		WC7	19.6	14			
Cyg OB2 No. 9				O5F	19.5	2			
Cyg OB2 No. 8A				O6Ib	18.7	1			
WR 147				WN7	20.1	1			
AT Mic		196982	799AB	dM4.5e+dM4.5e	15.2	42			
AU Mic		197481	803	dM1.6e	15.3	18			
FF Aqr				sdOB+G8III	17.7	8			
RT Lac		209318		G9IV+K1IV	17.8	20			
HK Lac		209813		F1V+K0III	(17.8) <sub>10</sub>	11			
AR Lac		210334		G2IV+K0IV	(17.9) <sub>10</sub>	11			
V350 Lac	8575	213389		K2IV-IIIp+?	(17.1) <sub>10</sub>	11			
DM-21°6267AB			867AB	dM2e+dM4e			C	31	
EV Lac			873	dM4.5e			C	29	
IM Peg	8703	216489		K1IV-IIIp+?	18.2	43			
SZ Psc		219113		F8V+K1IV	(18.1) <sub>10</sub>	32			
EQ Peg A			896A	dM3.5e	(14.1) <sub>15</sub>	18	C	31	
EQ Peg B			896B	dM4.5e	13.3	45			
λ And	8961	222107		G8IV-III+?	16.6	3			
II Peg		224085		K2-3V-IV+?	(17.4) <sub>10</sub>	11			

2) The peak incoherent 5 GHz luminosities  $L_R$  (ergs  $s^{-1}$  Hz $^{-1}$ ; see Table 1; also indicated by the size of the "bubble" in Fig. 1) show a surprisingly small range for stars within each class. In addition, the  $L_R$ 's seem to "pile up" near the maximum  $L_R$  among stars within each class. This further strengthens my association of the radio emission with the late-type active component in binaries containing both hot and cool stars.

3) The fraction of stellar energy that escapes as radio emission can be estimated by comparing the integrated maximum radio luminosity  $L_R^*$  to the bolometric luminosity. We form  $L_R^*$  by multiplying  $L_R$  by an "effective" bandwidth of 15 GHz, assuming the radio emission is broadband and the spectrum is relatively flat. Typical ratios of  $L_R^*/L_{bol}$  for each of the stellar classes are:

Class :	A	B	C	D
$L_R^*/L_{bol}$ :	$\sim 10^{-10}$	$\sim 10^{-9}$	$\sim 10^{-7}$	$\sim 10^{-7}$

That RS CVn and dMe stars comprise the bulk of the detected nonthermal stars would seem to be a reflection of their relatively high  $L_R^*/L_{bol}$  ratios. The same stars also have relatively high ratios of  $L_x/L_{bol}$ .

4) There are no apparent differences in  $L_R$  between binaries with two cool components, binaries with one hot and one cool component, and single stars for classes C and D. (All the stars in classes A and B are apparently single.) This suggests that flares need not be triggered and sustained by interacting magnetospheres (cf. Simon *et al.* 1980; Uchida and Sakurai 1983) but rather are intrinsic to the active component(s).

5) The late-type stars (Classes B, C, and D) are located in parts of the HR diagram where there is good reason to suspect that the surfaces of the stars are being "braked" -- magnetically, by strong winds, or by angular momentum transfer due to recent post-main sequence expansion -- with respect to their interiors. It remains to be evaluated whether radial differential rotation is a necessary (though not sufficient) condition for the presence of nonthermal radio emission in late-type stars.

Footnotes to Table 1:

<sup>a</sup> $L_R$  is the maximum observed 5 GHz incoherent radio luminosity of the star (ergs  $s^{-1}$  Hz $^{-1}$ ).  $L_R$ 's measured at other frequencies are indicated in parentheses with the frequency (in GHz) indicated as a subscript.

<sup>b</sup>C indicates the star has been detected as a coherent emitter.

\*Notes:

Algol (=  $\beta$  Per); 5 GHz max interpolated

V711 Tau; max interpolated

V410 Tau; a T Tau or post T Tau star

V1005 Ori; uncertain whether event was incoherent

RX Pup; the distance is quite uncertain;  $S_{8.7}^{\max} = 50$  mJy; if  $d = 1$  kpc,  $\log L_R = 19.7$

CN Leo; the ID is somewhat questionable because the field is heavily confused

DoAr 21 (= 10 Oph); a T Tau or post T Tau star in the Rho Oph cloud

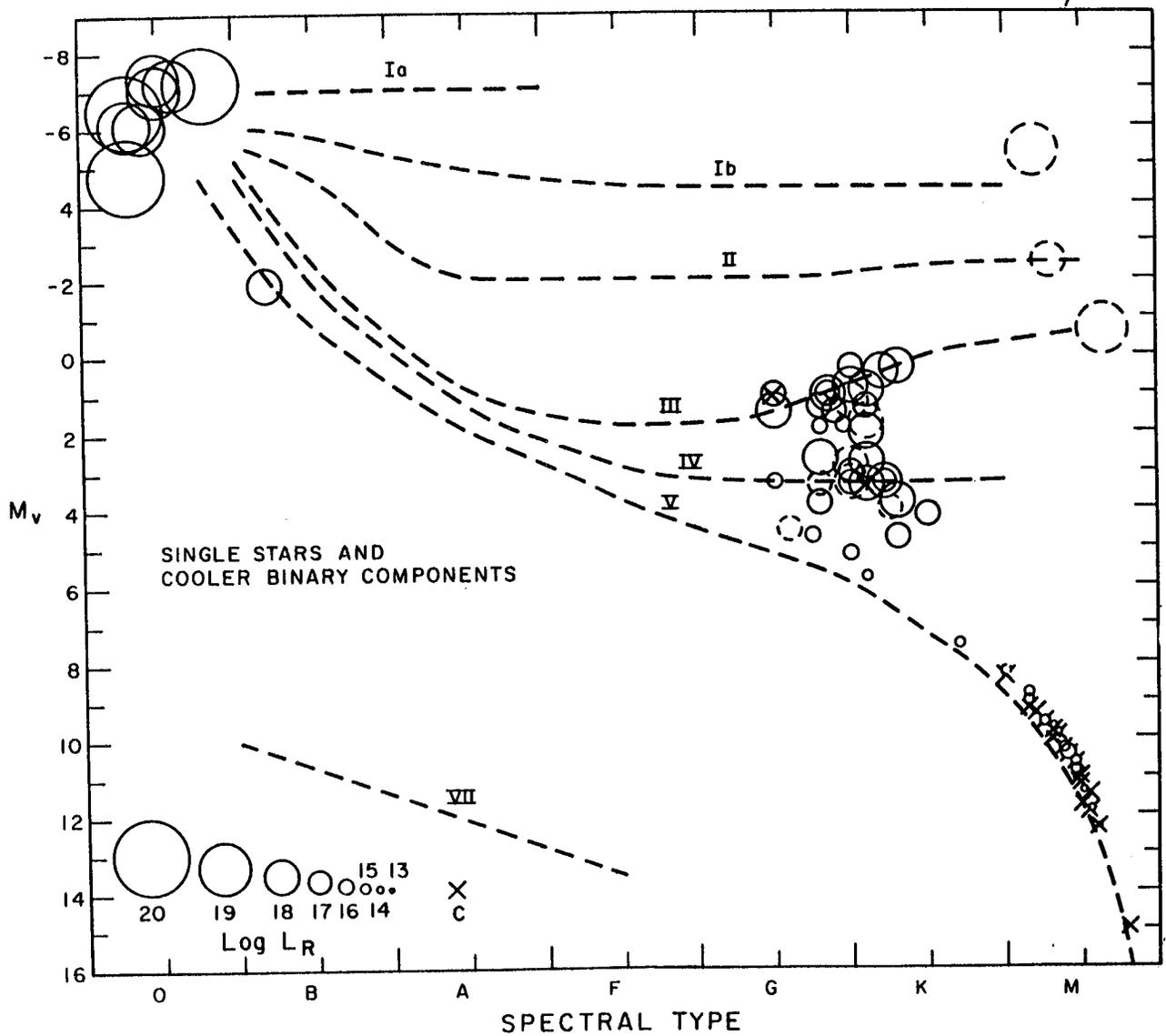


Fig. 1. The HR diagram for normal nonthermal radio stars combining single stars with the late-type components of binary systems. The range of luminosities for each "bubble" is +0.3 to -0.6 in the log. Coherent emitters are indicated by an x. Dashed circles indicate  $L_R$  was determined at a frequency other than 5 GHz (see Table 1).

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# X-RAY ACTIVITY IN PRE-MAIN SEQUENCE STARS

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## I. INTRODUCTION

Low mass ( $M \sim 1 M_{\odot}$ ) pre-main sequence (PMS) stars are traditionally characterized by emission line optical spectra, aperiodic photometric variability, infrared and ultraviolet excesses, absolute luminosities  $2^m$  to  $5^m$  above the ZAMS, and proximity to dense dark clouds. Most of these stars, frequently called T Tauri stars, have been found in H $\alpha$  objective prism surveys, variable star searches, or near-infrared surveys. It is well accepted that such stars have commenced nuclear burning and are descending to the main sequence on timescales of  $10^6$  years. Their spectral peculiarities are attributed primarily to stellar winds of order  $10^{-8} M_{\odot}/\text{yr}$ . The presence of winds is confirmed by P Cygni profiles and thermal radio emission seen in some T Tauri stars. There is also considerable evidence involving Herbig-Haro objects, bipolar molecular flows, and emission line jets indicating that the mass ejection from these young stars can be anisotropic. (These and other new results are discussed in the symposium published in Rev. Mexicana Astron. Astrof. 7, 1983.)

A new method for discovering and studying PMS stars has emerged in recent years: high resolution imagery in soft X-rays made possible by the Einstein X-ray Observatory. Although X-ray images of random regions of the galactic plane show only  $\sim 0.3$  source/sq. deg. at fluxes around  $10^{-13}$  erg/cm<sup>2</sup> (Hertz and Grindlay 1984), images of star formation regions reveal dozens of X-ray sources/sq. deg. In some cases they are coincident with classical T Tauri stars and in other cases with stars that are demonstrably PMS but without strong winds. The level of X-ray emission is  $10^3$ - $10^4$  times that of ordinary main sequence stars. I will summarize here these X-ray findings and their interpretation with respect to winds and surface activity. Readers are referred to Feigelson (1984) for a more comprehensive review and complete references. Some recent optical and radio observations supporting the X-ray evidence for giant flares on PMS stars are discussed in section IV.

## II. X-RAY OBSERVATIONS OF PMS STARS

X-ray studies of pre-main sequence stars have to date concentrated on three nearby star formation regions: the Orion nebula, the  $\rho$  Ophiuchi cloud, and the Taurus-Auriga cloud complex. Studies of various other regions, including rich fields such as the Cone nebula and Chamaeleon I cloud, are forthcoming. Approximately 60 X-ray sources with 0.5-4.5 keV luminosities between 1 and  $5 \times 10^{31}$  erg/s have been seen in the central degree of the Orion nebula (Ku et al. 1982). All are coincident with optical stars, but only 5 appear in Herbig and Rao's (1972) catalog of spectroscopically identified PMS stars. Evidence from X-ray images displaced from the center

of the nebula suggests that a complete deep survey of the cloud with a sensitivity of  $L_x \gtrsim 10^{30}$  erg/s would show some hundreds of X-ray luminous PMS stars.

The  $\rho$  Ophiuchi star formation cloud has been studied in detail including multi-epoch temporal coverage (Montmerle *et al.* 1983). Fifty to seventy (depending on the statistical significance) X-ray sources were found in the  $2^\circ \times 2^\circ$  cloud, virtual all with optical counterparts ranging from  $5^m$  to  $18^m$ . Again, many were not identified in spectroscopic or infrared surveys as PMS stars. Of great importance is the finding that at least 2/3 of the stars vary on timescales of days, and all vary within 2 years. One X-ray source, designated ROX20 and associated with a previously unnoticed visual binary system of weak-H $\alpha$  PMS stars, exhibited the most rapid variability. It declined from  $2 \times 10^{31}$  erg/s to a 'quiescent' level of  $8 \times 10^{29}$  erg/s in 2 hours. A well-known T Tauri star, A5205, lying a few degrees from the  $\rho$  Oph cloud also exhibited rapid variability, as shown in Figure 1 (Walter and Kuhi 1984).

The Taurus-Auriga complex covers several hundred square degrees, so only portions of special interest were targets of X-ray images. A dozen emission line T Tauri stars were detected with  $5 \times 10^{29} \lesssim L_x \lesssim 8 \times 10^{30}$  erg/s, but a comparable number were not detected at these levels. One of these T Tauri stars, DG Tau, has the fastest X-ray variation yet seen (Figure 2; Feigelson and DeCampli 1981). Five X-ray luminous stars not previously identified have been intensively studied (e.g. Mundt *et al.* 1983). They have high lithium abundance indicating stellar youth, weak H $\alpha$  emission, low level quasi- or aperiodic photometric variability, and moderately rapid rotation. These optical properties clearly indicate they are PMS stars without strong winds, but probably possessing star spots and strong chromospheres.

A final aspect of the phenomenology is the X-ray spectra of PMS stars. Though the Einstein IPC detector does not have very high spectral resolution, analysis of the brighter PMS sources consistently indicated that the spectrum is fairly hard. It must be either nonthermal in origin, or thermal with  $T \gtrsim 15 \times 10^6$  K. Soft spectra ( $T \lesssim 5 \times 10^6$  K) are excluded, even if high column densities of absorbing material are assumed to be present.

### III. INTERPRETATION OF THE X-RAY EMISSION

It is clear that, despite predictions to the contrary (e.g. Bisnovaty-Kogan and Lamzin 1977), T Tauri winds are not the cause of high levels of X-ray emission. This is deduced from the facts that many X-ray luminous PMS stars have weak or absent optical emission lines, exhibit rapid variations requiring densities present only close to the stellar surface, and X-ray spectrum harder than achievable by thermalization of the  $V \lesssim 300$  km/s T Tauri winds. The large X-ray variations on timescales of minutes and hours point instead to events similar to solar flares. PMS stars join the ranks of dMe flare stars and RS CVn binaries as classes of late-type stars with enhanced surface activity. All three classes exhibit similar rise and fall timescales but the energy released in PMS and RS CVn flares are  $10^4$  times that seen in flare stars such as Prox Cen or in strong solar flares.

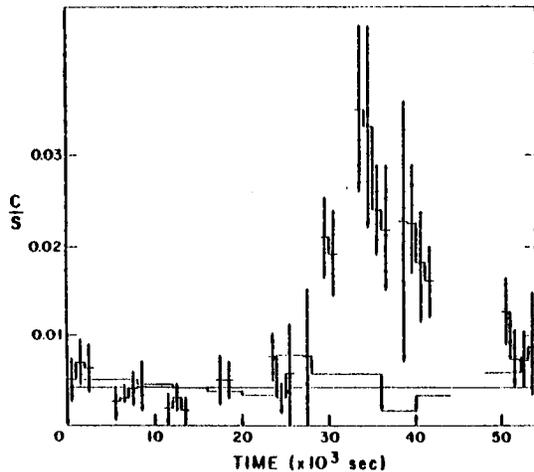


Figure 1: X-ray flare from the T Tauri star AS205 (Walter and Kuhi 1984).

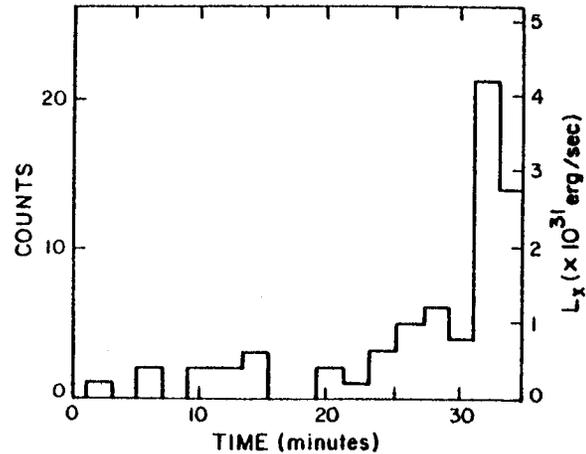


Figure 2: X-ray flare from DG Tau (Feigelson and DeCampi 1981).

The high level of X-ray activity in PMS stars is in reasonably good accord with the well-established correlations between stellar youth, chromospheric activity and rotation rate (Skumanich 1972). Generally, speaking, local disk stars have X-ray luminosities around  $10^{27}$ - $10^{28}$  erg/s, Hyades cluster stars are  $\sim 30$  times stronger and PMS stars are  $\sim 30$  times stronger again. Although there is some evidence for an X-ray/rotation correlation is available (Smith *et al.* 1983), detailed studies are limited by the extreme X-ray variability and uncertainties in PMS stellar ages.

It is important to recognize that strong X-ray emission is not limited to a small fraction of PMS stars as, for example, RS CVn activity is limited to stars in tidally locked binary systems. Source counts in clouds typically show more X-ray stars than classical T Tauri stars, indicating that the enhanced flaring state is more common and/or longer lived than the enhanced wind state. Efforts to uncover a PMS population exhibiting neither winds nor X-rays, based on proper motion (Jones and Herbig 1979) and optical spectroscopy (Feigelson and Kriss 1983) surveys, have found only modest numbers of 'hidden' PMS stars. We can thus probably conclude that most, and possibly all, low mass stars exhibit their highest level of surface activity during the PMS phase.

#### IV. NON X-RAY EVIDENCE FOR PMS FLARING

The X-ray findings are not at all the first indications for flaring PMS stars. For over 25 years, Haro (1968), Gershberg (1978) and Gurzadyan (1980) have been calling attention to the optical similarities between T Tauri and flare stars. Very rapid faint U band flickering has been seen in several T Tauri stars and interpreted as the product of many superposed flares (Worden *et al.* 1981). The Ca II infrared triplet in T Tauri stars is

saturated, unlike main sequence stars (Herbig and Soderblom 1980). IUE spectra of some T Tauri stars resembles those of RS CVn systems (Giampapa et al. 1981), though others show P Cygni profiles indicating a wind origin. Cool (Rydgren and Vrba 1983) and hot (Schaefer 1983) star spots have been inferred to be present on selected PMS stars from periodic photometric variations. And finally, theoretical stellar atmosphere models based on a "deep chromosphere" have had considerable success in explaining the continuum and line emission in those T Tauri stars which do not have extremely dense winds (Calvet et al. 1983).

One distinction between X-ray and IR/optical/UV investigations is that the latter tend to detect the integrated effects of enhanced chromospheric activity, while the former is sensitive to individual flare events. I would like to describe two recent investigations that suggest that, with sufficient luck and patience, individual flares can be detected outside of the X-ray band. First, during a coordinated EXOSAT/IUE/optical monitoring campaign of several PMS stars (F. Walter et al., in preparation) we observed an event in the star SU Aur at Penn State's Black Moshannon Observatory (Brungardt, Campbell and Feigelson, in preparation). The Ca II triplet, seen repeatedly in absorption, went into emission simultaneously with a considerable brightening of the continuum. The timescale of the event was  $\approx$  40 minutes. The star was observed several times over the following weeks, but no similar variation occurred. The literature has numerous similar incidences of rapid but occasional spectroscopic variations (Mundt and Giampapa 1982, and references therein).

The second example occurred in the radio band. A considerable number of T Tauri stars have faint radio emission due probably to free-free emission in their ionized winds (e.g. Cohen, Bieging and Schwartz 1982). We conducted a multi-epoch radio continuum survey of the  $\rho$  Ophiuchi cloud specifically to look for radio variations from the 60 X-ray flaring stars. One such star, DoAr 21 = ROX 8 = Oph 10, was found (Feigelson and Montmerle, in preparation). The radio emission increased from 3 to 48 mJy at 5 GHz in 1 day, with changes of 15 mJy in 2 1/2 hours. The spectrum was extremely inverted ( $\alpha \approx +1.5$ ), inconsistent with a thermal wind. Again follow-up observations proved exasperating, showing flux densities lower than 5 mJy. Curiously, the star in question was a strong emission line T Tauri optical spectrum 20-40 years ago, after which the wind disappeared.

## V. CONCLUDING REMARKS

In some ways, the description of pre-main sequence stars given here serves as a metaphor for the discussion of OB stars elsewhere in this volume. The unusual properties of PMS/T Tauri stars were for many years primarily attributed to their strong winds. I have outlined numerous lines of evidence indicating that PMS stars also have enhanced surface activity, including extremely strong individual flares. From a philosophical point of view, we do not need a rejection of the wind paradigm as much as an assimilation of two separate paradigms--'winds' and 'flares'--to the same class of objects. Given our current knowledge, I do not think PMS stars can be readily divided (either as a classificatory or evolutionary sequence) into separate 'wind'

and 'flare' groups. The X-ray discovered PMS stars do appear to be purely 'flare' objects. Some of the strongest wind T Tauri stars, such as RW Aur and RU Lup, are deficient in X-rays, but this could well be due to absorption of X-rays in the wind. Hence we are observationally prevented from confirming a class of purely 'wind' objects. Two of the most rapidly variable X-ray emitters, DG Tau and AS205, are classical T Tauri stars, indicating that winds and flares can occur simultaneously. Finally, we have DoAr 21 which lost its wind, leaving a flaring state to persist. It seems probable that, as in the Sun, these two characteristics coexist in PMS stars and are interrelated in complex ways.

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#### DISCUSSION

Roman: You said that almost all pre-main-sequence stars are strong in X rays. Since you use X rays to identify the pre-main-sequence stars, how do you allow for the selection effect?

Feigelson: We are confident that the X-ray identified PMS stars are in fact young because of their high  $L_X/L_{\text{Bol}}$  ratio and the fact that several have confirmed high lithium abundances, rapid rotation and other characteristics of youth. But it is difficult to know when the entire PMS population has been found. Objective-prism, optical-variability, near and far infrared, X-ray, spectroscopic, and proper-motion surveys have all been made of a few nearby star-formation clouds, for instance, L1551. They yield different, but overlapping, PMS populations. An educated guess would be that the total PMS population in the Taurus clouds is about twice the classical T Tauri population (Feigelson and Kriss, 1983, A.J.), but the population is considerably larger in the Orion and  $\rho$  Ophiuchi clouds.

Bookbinder: A quickie - for the radio flare, did you obtain polarization measurements?

Feigelson: No linear or circular polarization was detected during flare; the quiescent emission is too weak to detect polarization.

Underhill: The fluxes received in X-ray and radio wavelengths give information about the physical state of very hot plasma. Such plasma radiates few or no lines in the optical range from  $10^3$  to  $10^4$  Å. Consequently there are no diagnostics in the optical range that can give information about the presence of very hot plasma. One would not expect to locate stars with very hot plasma in their mantles using observations made in the optical range. This provides a fundamental physical reason for the lack of correlation between stars known to show T-Tauri type spectra and those observed to have very hot plasma ( $T \sim 10^7 - 10^8$  K) in their mantles.

Feigelson: Yes, that is correct. There are two aspects of the relationship between X-ray emission and T-Tauri emission-line spectra. First, the presence of high X-ray levels does not require the presence of T-Tauri lines. Second, some of the T-Tauri stars with the strongest lines (RW Aur, RU Lup) are not seen in X rays. This could be due to absorption of X rays produced close to the stellar surface by the dense winds (see Gahm 1980, Walter and Kuhl 1981).

Davila: One model for the bipolar molecular winds observed in PMS stars requires a steady state, hot wind. Is there evidence for steady X-ray emission from these stars?

Feigelson: Any quiescent level of PMS X-ray emission would have  $L_X < \sim 10^{29}$  erg s<sup>-1</sup>. The  $\rho$  Ophiuchus star ROX20, for example, was seen several times at  $L_X \sim 8 \times 10^{29}$  erg s<sup>-1</sup> in addition to its flare to  $> 8 \times 10^{31}$  erg s<sup>-1</sup>. For most PMS stars, there is not sufficient data to confirm such an effect.

Mullan: What are the terminal velocities of T-Tauri stars? How are they known?

Feigelson: Typically  $100 - 300$  km s<sup>-1</sup>, as measured by the widths of optical emission lines and/or P-Cygni profiles.

## ACTIVE PHENOMENA IN THE PRE-MAIN SEQUENCE STAR AB AUR

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### ABSTRACT

The Herbig Ae star AB Aur presents short time scale variability in the Mg II and Ca II resonance lines. A qualitative model of the expanding envelope, involving fast and slow streams in a corotating structure, is proposed to explain the Mg II spectral variability.

### INTRODUCTION

In contrast with main sequence A type stars, pre-main sequence stars of this spectral type exhibit observational indications of the presence of chromospheres and winds (Praderie et al., 1982; Tjin A Djie et al., 1982; Talavera et al., 1982; Felenbok et al., 1982; Catala and Talavera, 1984). In AB Aur (HD 31293, A0ep) spectral variations with a characteristic time scale of less than one day were found in the Ca II resonance lines; longer time scale variabilities (years, months) are also known in visible light, in the hydrogen Balmer lines (Praderie et al., 1982 and references therein; Finkenzeller, 1983) and in the UV Mg II and Fe II resonance lines (Praderie et al., 1984).

It is the purpose of this note to report results of a systematic search for line variability in a short time scale (hour) in the star AB Aur, and to infer a model of this star's envelope.

### OBSERVATIONS

A coordinated campaign of observations was organized in October 1982, involving the IUE satellite as the major instrument, the CFHT 3.60m telescope, the 1.50m telescope of the Observatoire de Haute Provence (OHP), as well as two photometric telescopes (see Praderie et al., 1983). Fourty hours continuous observation with IUE allowed us to obtain a series of 29 high resolution spectra, well exposed for the Mg II and Fe II resonance lines. During the same period, thirty three spectra of the Ca II resonance lines were obtained over 5 nights at OHP, and 7 spectra at CFHT.

The "base" time of 40 hours was chosen as an estimate of the rotation period of the star, derived from its projected rotational velocity  $v \sin i$  ( $90 \text{ km s}^{-1}$ ) and an assumed radius of  $3 R_{\odot}$ .

Two questions were addressed during the October 1982 campaign : (i) does rotation modulate emission features in AB Aur, as it does in active solar type dwarfs (Vaughan et al., 1981)? (ii) does the star present flares?

## RESUME OF RESULTS

1. Mg II over 40 hours. The profile shape in reduced units varies with time, while the continuum level seems to be quite stable. The blue wing velocity of  $\lambda$  2795, i.e. the maximum velocity reached by Mg II ions on the line of sight hitting the stellar core, varies between  $-395$  and  $-515$   $\text{km s}^{-1}$  (Figs. 1 and 2). The emission equivalent width  $W_{\text{em}}$  of  $\lambda$  2802 varies between  $0.94$  and  $1.68$   $\text{\AA}$ . There is a tendency in the blue wing velocity  $V_s$  to vary sinusoidally with time with a period close to 40 hours. This trend is hardly detectable in the plot of  $W_{\text{em}}$  versus time, although a slight anti-correlation might be present between  $W_{\text{em}}$  and  $V_s$ .

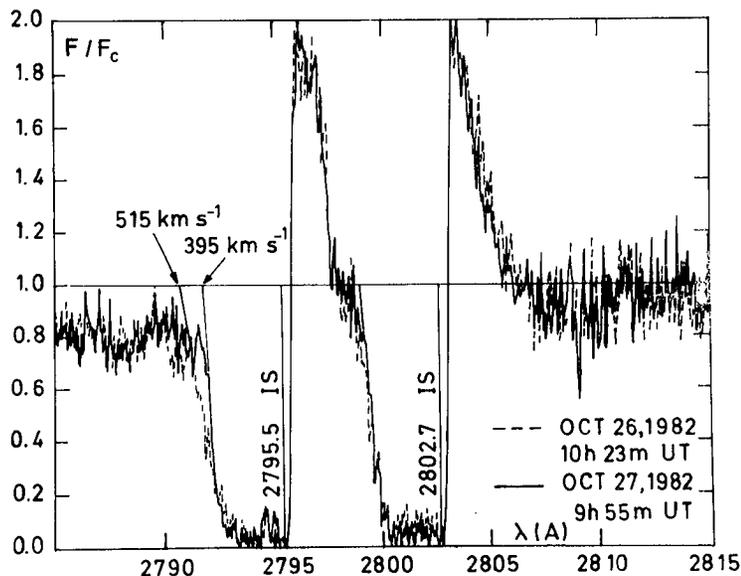


Fig.1 The Mg II resonance lines from two IUE spectra (LWR 14494 and 14511). The blue wing velocity  $V_s$  is indicated for  $\lambda$  2795, as well as the position of the interstellar lines.

2. Fe II resonance lines over 40 hours. The Fe II resonance multiplets show lines splitted in 3 components. Their velocity shift and intensities do not vary at all during the 40 hours of observation. The bluest component velocity is  $-150$   $\text{km s}^{-1}$ , a smaller value than  $V_s$  (Mg II).

3. Ca II K line over 40 hours and over 5 days. The Ca II K line is highly and seemingly randomly variable (see Praderie et al., 1983). When simultaneity was achieved with Mg II observations, the profile showed a redward emission wing (velocity  $+170$   $\text{km s}^{-1}$ ) and 3 blue shifted absorption components (velocities  $-190, -260, -350$   $\text{km s}^{-1}$ ). Later on, during the campaign, the shape of the profile changed, with variable asymmetry, and variable red emission and blue shifted components. We could not find, empirically or by numerical methods, any regular pattern in the available set of data. Compared to the Mg II data, the Ca II ones suffer from gaps, and from a less favorable and

irregular time sampling.

No flares were observed in any of the lines studied during this campaign.

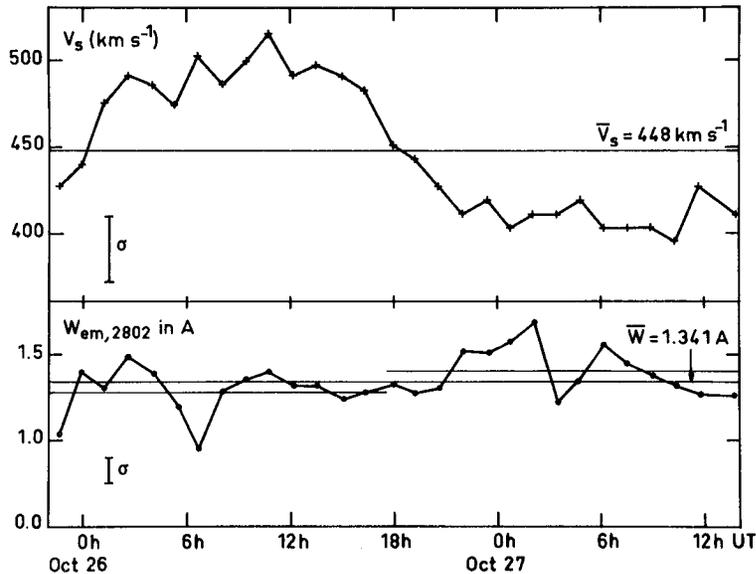


Fig.2 Top : Mg II terminal velocity  $V_s$  in  $\lambda$  2795 versus time; Bottom: emission equivalent width  $W_{em}$  in  $\lambda$  2802 versus time. The average value of  $W_{em}$  is indicated (1.34Å), so are the averages of the first 20 hours of observations and for the 20 consecutive ones.

#### A QUALITATIVE MODEL FOR THE ENVELOPE OF AB AUR

The velocities and velocity variations exhibited by the three sets of lines studied suggest that binarity is not the cause of the observed phenomena. Firstly, no periodic velocity variations are found in the photospheric spectrum (Finkenzeller, 1983). Secondly, the lines we observed behave very differently each from the other, and the quasi sinusoidal variation of  $V_s$  (Mg II) has no counterpart in Ca II or in Fe II resonance lines.

As to their formation in the wind of the star, the lines studied are stratified (Catala et al., 1984), with Ca II of chromospheric origin (1-2  $R_*$ ), Mg II formed over a vast region (from 1 to 20  $R_*$ ), and Fe II most likely originating in a decelerated region located further away than the Mg II region.

That  $V_s$  (Mg II) presents a quasi sinusoidal variation with a 40 hr period, which is our present estimate of the rotation period of the star, suggests that rotation is modulating the flow velocity up to far enough distances from the photosphere (20  $R_*$ ). If this is the case, then the expanding envelope of AB Aur cannot be spherically symmetric. We suggest a qualitative picture of the Mg II forming region, composed of corotating fast and slow streams, which are best traced by the Mg II lines. Namely Ca II does not offer a clear support for such a model, although its resonance lines should probe the deepest parts

of the chromosphere ; we believe the reason is related to the more spaced and irregular sampling of the data. At larger distances in the envelope than the Mg II forming regions, the Fe II lines, which do not vary over 40 hr, indicate that the streams have merged ; the heterogeneity in the envelope, attested by several components in the Fe II lines, has most likely changed of nature.

In the Mg II forming region, the fast streams would correspond to open magnetic field lines, the slow streams to closed magnetic field loops. This picture is proposed in analogy with the solar coronal holes and active regions, it is supported by velocity variations more than by emission variations. Observation of enhanced emission features during periods when the Mg II line of sight wind velocity is low, and diminished features when the velocity is high, would tend to confirm this picture.

Further elaboration on these results will be presented in a forthcoming paper. Repeated observations covering several rotation periods of the star (instead of one) are planned in November 1984.

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## DISCUSSION

Cassinelli: The P-Cygni profiles of Mg II look odd. Lucy (1982) found that a non-monotonic wind velocity could lead to flat bottom-sharp emission profiles like those you have shown. Could you comment on X-ray emission from these stars?

Praderie: In the Mg II P-Cygni profile which I showed, the absorption core is saturated. The line synthesis performed by Catala (see Catala et al. 1984, Astr. Ap., 134, 402) reproduces the observed profile by adding a Doppler velocity of  $45 \text{ km s}^{-1}$  to the thermal velocity. This seemingly ad hoc velocity can, indeed, be understood in a phenomenological model with slow and fast streams which are not so long lived as in the Sun, and which disappear at a certain radius, developing turbulence. One can show that the scale of this turbulence is smaller than the photon path in the conditions of the AB Aur expanding envelope (Catala, 1984 4th European IUE Conf.). No X-ray emission was observed for AB Aur by the Einstein Observatory. To my knowledge, only one Herbig star in Orion was observed by Pravdo et al.

Mullan: The wind must be cool. How do you know that variations in the wind are occurring very far out (at  $r > 10 R_*$ )?

Praderie: The variations reported over 40 hours in AB Aur were in both the deepest parts of the expanding envelope (as shown by the emission in  $\lambda 2802$ ) and the most remote parts of the Mg II line-forming region (terminal velocity in  $\lambda 2795$ ). The wind is not cool everywhere. I pointed out that a chromosphere at  $T \sim 15000 - 18000 \text{ K}$  is needed to synthesize properly the emission in the Mg II lines. It is located at  $1 - 2 R_*$ ; further out, the temperature drops (see Catala et al., 1984, Astr. Ap.).

# Coronal Temperatures

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The Solid State Spectrometer (SSS) on the Einstein Observatory (HEAO 2) was sensitive in the energy range 0.5-4.5 keV to fluxes as low as  $4 \times 10^{-12}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ . Good spectra were obtained for 19 stars, including Algol (White et al. 1980), 7 RS CVn systems (Holt et al. 1979; Swank et al. 1981; Agrawal, Riegler, and White 1981), 2 dMe stars (Swank and Johnson 1982), 2 W UMa binaries (Crudace and Dupree 1984), 1 GV single star, and 3 OB supergiants (Cassinelli and Swank 1983), 2 BV stars and 1 O7 binary. This is a very incomplete survey of stellar coronae, but it does include coverage of several late and early types and usually more than 1 sample of the class.

The results for these stars suggest two generalizations despite the small numbers: (1) There is a broad variety of X-ray spectra of stellar coronae and (2) there probably are X-ray spectral types. The first point seems obvious in view of the  $2-3 \times 10^6$  K average temperature of the solar corona and RS CVn quiescent temperatures more than ten times hotter. The SSS began to explore the variations in between these extremes. By the second point I mean that the X-ray coronae of stars of similar other properties have similar temperatures. It could be that the temperature structures only depend on a subset of the other properties.

SSS stellar spectra have not generally been well fit with isothermal models, but two temperatures have been adequate. There has been a question of whether certain types of distributions of emission measure with temperature would fit as well. The answer in some cases is no. I will discuss this new evidence that some distributions are indeed bimodal.

Finally, I will make some remarks on the spectra of the early type stars and constraints on the presence of very high temperatures ( $10^7-10^8$  K).

The range of coronal temperatures seen with the SSS is clear in Figure

1. The SSS on the Einstein Observatory had a resolution of about 160 eV, which cannot resolve most of the lines contributing about half of the flux, especially the Fe L-shell lines below 1 keV. (Present day solid state detectors have a resolution twice as good and can resolve major line complexes in such spectra.) Nevertheless, since the assumption of collisional ionization equilibrium implies specific weighting of the lines of a given element, the data is very sensitive to the input temperatures. The three spectra of late type stars shown in Fig. 1 all require two components to fit the data acceptably, one at  $4-6 \times 10^6$  K, and the other above  $2 \times 10^7$  K. The most obvious difference in these

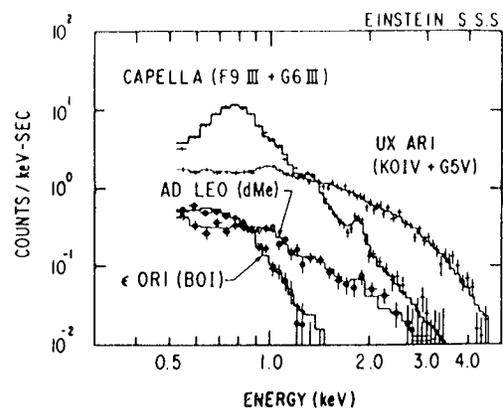


Fig. 1 - SSS pulse height spectra of 4 stars. The histograms are the predictions of best fit models.

spectra is in the relative emission measures of these components, or, alternatively, the relative fluxes. For UX Ari the low to high temperature fluxes are about 1:1, for Capella 10:1, for AD Leo 3:1. For  $\epsilon$  Ori no high temperature component is required. These spectra also differ at low energies and the dominant low temperatures are indeed slightly different, as I will summarize later.

I turn now to the evidence that stars of similar type have similar X-ray spectra. Of the two dMe stars observed with the SSS, AD Leo is dM3.5e and the blended image of the visual binary Wolf 630AB is also dM3.5e. Their X-ray spectra are not identical, but the low temperatures are close, as are the proportions of high temperature emission measure (Jensen and Swank 1984). Cruddace and Dupree (1984) found that VW Cep and 44i Boo, W UMa binaries with periods 0.278 and 0.268 days, have very similar spectra. At the other end of the stellar mass scale are the Orion supergiants,  $\epsilon$ ,  $\zeta$ , and  $\delta$  Ori, with X-ray spectra practically indistinguishable. (See Cassinelli, this volume.)

RS CVn binaries are represented in Fig. 1 by both Capella and UX Ari, which look substantially different. Qualitatively the RS CVn group divides into two, according to whether their X-ray spectra are similar to spectra of UX Ari or of Capella, although the numbers are too small to define the transition well. In all the UX Ari-like cases, the active star is a KIV secondary, while for Capella, it is an F9III star, for  $\sigma$  Cr B F8V, and for  $\lambda$  And G8III-IV. The binary periods of these three are 104, 1.2, and 20.5 days, and their rotation periods 12, 1.2, and 50 days, so that the X-ray spectral difference is not a correlation with rotation.

Walter (1981) found a difference between  $L_x/L_{B01}$  for F8-G5 stars compared to G8-K2 of the same period, regardless of binarity. The SSS had no observation of a single K star. The one GV star observed was  $\pi^1$  U Ma, which has a rotation period of 5 days. Figure 2 shows the spectrum. The peak around 0.8 keV due to FeXVII is characteristic of  $(4.0 \pm 0.1) \times 10^6$  K (which gives  $L_x = 2.3 \times 10^{29}$  ergs  $s^{-1}$ ). The temperature is the same as the lowest measured for Capella. The data is not sensitive to a high temperature component in the same ratio as that of Capella. This case suggests that the luminosity class is not influencing the coronal temperature.

On the other hand, the BOV  $\tau$  Sco and the O9.5V  $\zeta$  Oph (See Cassinelli, this volume) look different from the Orion supergiants, although similar to each other. All of the stars the SSS detected had a  $3-8 \times 10^6$  K component. Figure 3 shows the temperatures of just this component and its emission measure. The dispersion is largest in what I have called the F-G group. Otherwise, the groupings are apparent even for this component.

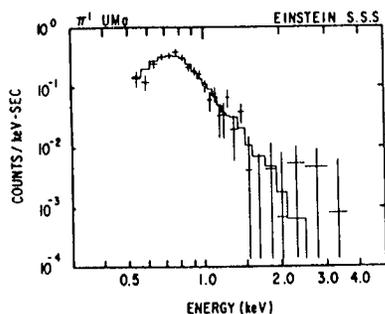


Fig. 2 - SSS spectrum of  $\pi^1$  UMa with a  $4 \times 10^6$  K isothermal model.

I have been referring to two temperature components as if it were clear that the emission distributions are bimodal. For some of the RS CVn spectra, especially Capella, two temperatures give a good fit only for abundances around a factor of two different from solar. It seemed possible that this only reflected the presence of a more complex distribution of temperature. However, we found rather strong upper limits (Swank and White 1980) to emission measures at intermediate temperatures. Veddar and

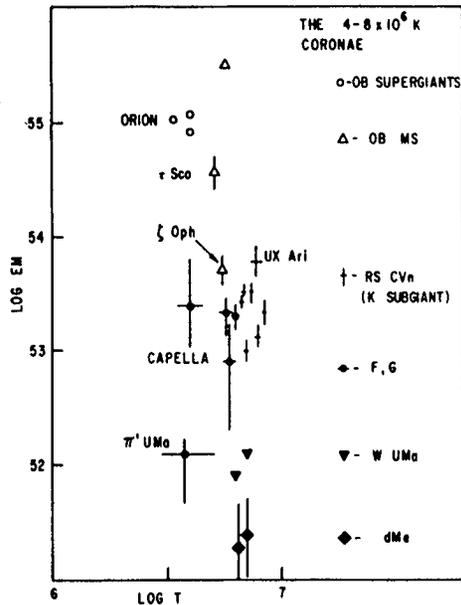


Fig. 3 - Log EM vs. log T for the low temperature components in fits to SSS data.

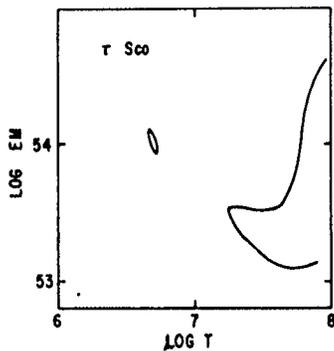


Fig. 4. - 90% confidence contours for two temperature fits to the  $\tau$  Sco spectrum.

Canizares (1982) found that a distribution  $\propto T^{-0.9}$  fit their Einstein Focal Plane Crystal Spectrometer data for 3 lines (FeXVII, FeXX, and OVIII) and they suggested that two temperature fits were an approximation to such a distribution.

Doschek and Cowan (1984) see such a distribution in the solar spectrum and point out theoretical support. The predictions are quite different, in fact, and even with the SSS resolution can be distinguished for the relatively bright sources. I have fit the data to the form  $EM = C(T/T_b)^{a1}$  for  $T < T_b$  and  $C(T/T_b)^{a2}$  for  $T_b < T < T_m$ . For Capella, the best  $\chi^2$  for this form was 500 as compared with 90 for the two temperatures. For UX Ari, it was 100 as compared with 65. On the other hand low temperature isothermal components are indistinguishable from rather sharply peaked distributions for that component alone. In the case of the dMe spectra a distribution was indistinguishable from the the two temperature fits (Jensen and Swank 1984).

The  $\tau$  Sco and  $\zeta$  Oph spectra discussed by Cassinelli could be fit with a dominant component at  $5-6 \times 10^6$  K plus  $2-6 \times 10^{30}$  ergs  $s^{-1}$  at  $50-100 \times 10^6$  K. For those stars the wind column densities (with O and heavier elements not ionized) are not high,  $< 2 \times 10^{21}$   $cm^{-2}$ . Considering the interstellar medium contribution and remaining calibration uncertainties, the SSS data cannot distinguish whether the spectrum was formed at the base of the wind or above it. The constraints on the two components for  $\tau$  Sco are shown in Figure 4. A second component at only a few times  $10^7$  K would give a high fraction of low energy emission, around 1-2 keV, which is not observed. There could be more of a

component at  $10^8$  which would explain the 2-4 keV counts without predicting much low energy line emission, but there is some possibility that these high energy counts are due to noise. The Si feature in the  $\tau$  Sco spectrum is very significant, but is from gas at  $< 10^7$  K (if in collisional equilibrium).

The dominant temperature is hotter than for the Orion supergiants and not naturally explained in the shock model developed by Lucy (1982). It would take the full terminal velocities to produce shocks at 5-20 times higher temperatures. Such shocks of high velocity material have not appeared a good model for the bulk of the X-rays from early-type stars (Harnden et al. 1979; Fabian and Stewart 1981), although they have not been ruled out of giving some contribution. Because of these difficulties in understanding the X-ray production of early-type stars, other explanations seem to deserve careful consideration.

Acknowledgments: The results I have reviewed here reflect the efforts of many who have worked on the SSS or who used it to observe stars. Those of A. Szymkowiak, K. Jensen, F. Seward and J. Cassinelli were especially pertinent to this paper.

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## DISCUSSION

Cassinelli: With regard to the possibility of shocks in the outer parts of the wind, Mullan's CIR model (stream-stream interactions) could explain shocks in the outer parts of winds.

Linsky: Could you comment on whether the SSS data for hot stars, the dMe stars, and RS CVn systems rule out the possibility of nonthermal electrons? I wonder whether the hard X rays observed by the SSS could be explained by nonthermal electrons rather than by a  $50 - 100 \times 10^6$  K thermal plasma?

Swank: The SSS can not distinguish between high-temperature thermal emission ( $T > 40 \times 10^6$  K) and power-law or non-thermal emission. The HEAO 1 A2 medium energy detector "sees" UX Ari, HR 1099, Algol, and AR Lac and puts upper limits on temperatures (or limits on the power law). I think the limits on the Fe K-line emission that would serve as witness to thermal emission are not severe. HEAO 1 A2 did observe a bright flare, probably from a dMe star or pair, in which Fe K-line emission is very significant.

Waldron: You mentioned that you had to change abundances to fit the SSS X-ray data. Was this necessary for many of the stars you fitted?

Swank: The abundances required for fits were all within a factor of 2 of solar, usually much closer. For Capella, which was the brightest source, metal abundances nearly a factor of 2 higher than solar are required in fits with just two temperatures. We have not found a distribution of emission measure with temperature that fits with solar abundances, although there may be one.

R.L. White: For SSS observations of supernova remnants, the X-ray emitting gas is known to be out of ionization equilibrium, which leads to problems when fitting equilibrium spectra to the observations. Might ionization non-equilibrium also be important for interpreting the spectra of stars? For instance, if the X rays come from gas cooling behind shocks, the electron temperatures and ionization temperatures might differ.

Swank: In the RS CVn stars, the time scales of variability affecting our observations were longer than about 1/2 day, and at the densities expected ionization equilibrium should have had time to be established. I have not considered the effect in the shock model for the early-type stars. If, for either type of star, a steady-state, non-equilibrium picture holds, it should be considered.

Mullan: The ratio of  $EM(T_1)/EM(T_2)$  is  $\sim 1$  in RS CVn stars. Is it  $\ll 1$  in OB stars? If so, is there a qualitative difference between coronae in OB stars and those in RS CVn stars?

Swank:  $EM(T_1)/EM(T_2) < 0.1$  in OB stars, while  $\sim 1$  in the RS CVn stars with K subgiant active components. It is  $\sim 0.1$  for Capella and only a little larger for  $\sigma$  CrB.

# BIPOLAR EJECTION OF MATTER FROM HOT STARS

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## INTRODUCTION

A general program on the internal velocities in H II regions is carried out within the past decade at our observatories by the use of photographic Fabry-Pérot interferometry, in the H $\alpha$  line and lately also in the [N II] $\lambda$ 6584 line. Among the score of objects studied three H II regions and one planetary nebula possess pronounced symmetry around their ionizing stars. Our velocity data combined with morphological properties suggest strongly that the nebulae were formed essentially by matter ejected from the central star and that ejection has occurred preferentially from diametrically opposite regions on the star, that is, in a bi-polar fashion (for a summary see Pişmiş 1979). I shall comment briefly on the individual nebulae and will present a model towards an interpretation of the observations.

### NGC 6164-6165

The overall image of the nebula shows a striking symmetry. In particular the two brightest regions symmetrically located with respect to the central O6f star, HD 148937, are receding from it with a projected line of sight velocity of  $30 \text{ km s}^{-1}$ . (Catchpole and Feast 1970; Pişmiş 1974). The velocity field from two interferograms in H $\alpha$  and [N II] $\lambda$ 6584 and the morphological details are consistent with the following model (Pişmiş 1974): the nebula is formed essentially by ejection preferentially from active spots located at opposite hemispheres, at the extremities of a diameter on a fast rotating star; this diameter, the direction of bipolar outflow, is oblique to the rotation axis of the star. The orientation of the axis of rotation and that of the bipolar outflow, ( $10^\circ$  from the rotation axis) are close to the plane of the sky (see Figure 1). The time elapsed since the beginning of the outflow is around  $4.4 \times 10^3$  years for a distance of 1.5 kpc for the nebula. The symmetrical fainter emission regions closer to the star are presumably ejected at a later time. There is also indication that ejection has occurred in blobs.

In a study of the H II complex surrounding NGC 6164-5 using narrow pass-band filters Bruhweiler et al. (1981) conclude that their data give support to our model.

### NGC 2359

This H II region sometimes called a "ring nebula" has in fact two rings surrounding the ionizing star HD 56925 (WN5). The rings are within an extended H II region. We have measured radial velocities at about 300 points covering the overall nebula. For want of space an image of only NGC 2359 is repro-

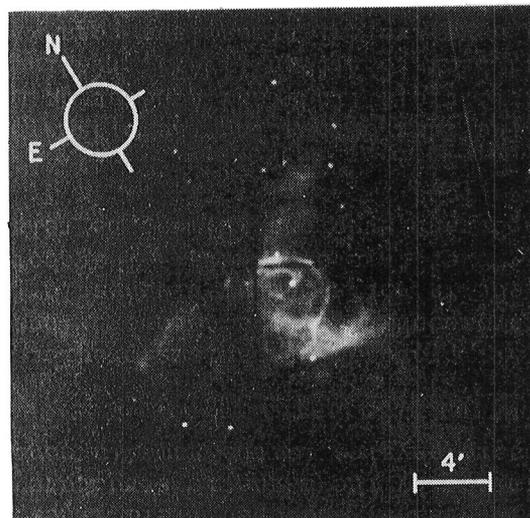
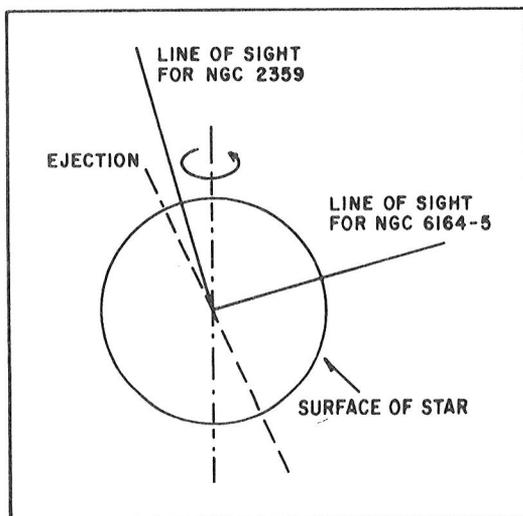


Figure 1. A sketch of the model of bi-polar ejection proposed to account for the observations of NGC 6164-5 and of NGC 2359.

duced in the present communication (Fig. 2). To avoid spurious velocities the interference pattern was oriented orthogonally to the rings of the nebula. Thus the velocities in the rings are free of convolution effects and are reliable. They show clearly that the outer ring is receding from (by  $13 \text{ km s}^{-1}$ ) and the inner ring approaching (by  $15 \text{ km s}^{-1}$ ) the observer relative to the systemic motion of the H II region. This is indication that the ring structure is formed by ejection from the central WN5 star and that ejection has not been isotropic but bi-polar, for if isotropic the rings should be the projections of a spherical shell and therefore would show the same velocity as the whole complex.

The same model of collimated bi-polar outflow from a fastly rotating star, as proposed for NGC 6164-5, can explain the relative velocities of the rings. In the case of NGC 2359 the angle between the rotation axis and the ejecting direction is estimated to be  $30^\circ$ . Figure 1 shows the orientation of the model with respect to the observer. The age of the rings is around  $2.1 \times 10^5$  years. (For details see Pişmiş et al. 1977).

MI-67

This H II region classified as a planetary by some has a morphology which suggests strongly that it is mainly the result of directional outflow from the central WN7 star, 209 BAC. The outer regions show arm-like features delineated

by H II blobs. We have detected an expansion of  $30 \text{ km s}^{-1}$  in the region surrounding the central star (Pişmiş and Recillas-Cruz 1979); this value is in agreement with a later determination by Chu and Treffers (1981). It appears however that our FP velocities in the arm-like features are somewhat vitiated by convolution effects. The scanning FP velocities by Chu and Treffers, are free of such effects; they show a general tendency of approach towards the observer of the southern and eastern extensions suggesting that an outflow has produced them; the northwestern region is too faint for reliable velocity data but it is conceivable that it might show a relative recessions supporting perhaps the picture of a bi-polar outflow. It should be rewarding to obtain a complete velocity coverage of MI-67 including the fainter regions.

S 650-1

This is a planetary nebula worth including in the present discussion. Its morphology exhibits a striking bi-symmetry. Our FP radial velocities together with data from two previous studies (Taylor 1979; Sabbadin and Hamzaoglu 1981) are consistent with our model of bi-polar ejection from the central star. (Recillas-Cruz and Pişmiş 1984). However, no significant vestige of a rotation is detected in this nebula.

#### DISCUSSION

A bi-polar mode of ejection from the parent star appears to satisfy all four of the nebulae mentioned above. We have proposed earlier (Pişmiş 1974 and summarized in Pişmiş 1979) that the agent funneling the ejecta is a magnetic field associated with the symmetrically located ejecting regions, active spots, of the parent star. A *dipole* along the diameter joining such spots may represent the assumed magnetic field. The outflow will then preferentially take place along the lines of force in the region of the magnetic poles. A milder outflow across the lines of force in all directions is not excluded since all four nebulae are within more or less amorphous nebulosity. It will be necessary to carry out polarization measurements to check our hypothesis of the existence of magnetic fields.

The central stars of the three H II regions, namely NGC 6164-5 (O6f), NGC 2359 (WN5) and MI-67 are losing mass at present through their winds. We therefore go on to suggest that if mass loss from the central stars has been directional in the past and not isotropic, we may expect that their present mass loss in the form of winds takes place in a similar fashion. Thus I re-emphasize the suggestion I have made earlier (Pişmiş 1979) that winds in such stars may have structure resembling a bi-polar configuration. It would be interesting to construct synthetic profiles of spectral lines from a rotating star with active spots on it and compare it with observed ones. The variation in the spectral lines of some WR stars may well be explained in this way.

It is worth mentioning that a discussion of  $\zeta$  Puppis, Moffat and Michaud (1981) conclude that the periodic variation of the  $H\alpha$  profile can best be explained by a magnetic field, a multipole, associated with the star.

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## DISCUSSION

Lafon: If you observe a torus expanding in a plane that is not perpendicular to the axis of rotation, i.e. a precessing torus, from some point you see much more matter on two symmetric lines of sight, which may be considered as "blobs" (enhanced column density compared to the other parts of the torus). May such an effect be a possible explanation for what you described?

Pişmiş: A torus as you describe may perhaps account for the two symmetrical "blobs" of NGC 6164-5, as due to enhanced column density at the extremities of an inclined torus, but it fails completely to explain the velocity field. I showed in my talk that the two symmetrical bright regions of this nebula (NGC 6164-5) exhibit expanding motions relative to one another amounting to  $60 \text{ km s}^{-1}$ . Even if the torus were expanding, the outward motions of the "blobs" in the torus would have their velocity vectors nearly perpendicular to the line of sight and hence their observed relative radial velocities would be very small. As regards NGC 2359, the double-ring nebula, neither the velocity field nor the morphology can be explained by an expanding torus.

STELLAR WINDS; OBSERVATIONAL EVIDENCE FOR A  
HOT-COOL STAR CONNECTION

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ABSTRACT

Stellar wind data has been collected for a total of 272 stars representing all spectral types including Wolf-Rayet stars. Two significant correlations are found relating the wind luminosity ( $L_w = \frac{1}{2}\dot{M}v_\infty^2$ ) to the bolometric luminosity and the terminal velocity ( $v_\infty$ ) of the stellar wind to the stellar effective temperature. Least-squared fits to the data suggest that  $L_w \sim L_{\text{Bol}}^2$  and  $v_\infty \sim T_{\text{eff}}^{1.8}$ . The surprising result is that all spectral types throughout the HR diagram are represented in these correlations.

INTRODUCTION

During the past decade it has become very clear that practically all stars throughout the HR diagram exhibit stellar wind behavior. The possible exceptions are the late main sequence stars. However, the existence of the solar wind suggests that other late main sequence stars may also have stellar winds that are presently undetectable. Therefore, one may surmise that the stellar wind phenomenon is a common feature among all spectral types. This poses an interesting question. Is there a common factor which is responsible for stellar winds throughout the HR diagram?

Various correlations between stellar wind ( $\dot{M}$ ,  $v_\infty$ ) and other stellar parameters ( $L_{\text{Bol}}$ ,  $T_{\text{eff}}$ , mass, radius, and surface gravity) have been obtained separately for early and late-type stars in order to investigate the nature of stellar winds. For the early-type stars, relationships between  $\dot{M}$  and  $L_{\text{Bol}}$  (Abbott et al. 1980, Carmany et al. 1981), or between  $\dot{M}$  and combinations of  $L_{\text{Bol}}$ , mass, and radius (Lamers 1981, Chiosi 1981) have been found. Concerning  $v_\infty$ , Abbott (1978) and Hutchings and von Rudloff (1980) found a relation between  $v_\infty$  and the stellar escape speed, while Cassinelli and Abbott (1981) and Underhill (1983) found a relation between  $v_\infty$  and  $T_{\text{eff}}$ . For the late-type stars, Reimers (1977, 1978) found that  $v_\infty$  is proportional to the square of the stellar escape speed, and  $\dot{M}$  is correlated with a combination of  $L_{\text{Bol}}$ , surface gravity, and radius.

The purpose here is to present a collection of observational data representing all spectral types and look for the possible existence of general correlations. In particular, a wind quantity which has previously not been tested is the kinetic power of the wind or wind luminosity ( $L_w = \frac{1}{2}\dot{M}v_\infty^2$ ), which is essentially a measure of the rate of energy input required by a star to maintain a stellar wind. The results surprisingly seem to support the idea of a hot-cool star connection in regards to their stellar wind properties.

## STELLAR DATA

Stellar ( $L_{\text{Bol}}$ ,  $T_{\text{eff}}$ ,  $\dot{M}$ ,  $v_{\infty}$ ) data has been collected for 272 stars representing all spectral types including Wolf-Rayet stars. Because of the large amount of data, the data will not be presented here (the data are available upon request). For many of the stars, multiple values of  $L_{\text{Bol}}$ ,  $T_{\text{eff}}$ ,  $\dot{M}$ , and  $v_{\infty}$  were quoted among the literature. To ensure an unbiased approach to the data, all quoted values were assumed to be equally weighted, and the adopted values for use in this analysis were obtained by an averaging process. Substantial scatter was noted in the quoted values of  $\dot{M}$  (factors of 10 for early-type and 10-100 for late-type). However, the stars showing this large scatter represent only about 10% of the total sample, and, in general, the typical scatter in all the stellar quantities is 10-20%.

## EMPIRICAL CORRELATIONS

Two strong correlations have been found from the present available data. Figure 1 shows the relation between  $L_w$  and  $L_{\text{Bol}}$  (both in  $\text{ergs s}^{-1}$ ) for 168 stars, and Figure 2 shows the relation between  $v_{\infty}$  ( $\text{km s}^{-1}$ ) and  $T_{\text{eff}}$  for 249 stars. The least-squared fit lines to the data are given by

$$\log L_w = 25.13 + 1.96 \log ( L_{\text{Bol}}/L_{\odot} ) \quad \text{ergs s}^{-1} \quad (1)$$

$$\log v_{\infty} = 1.97 + 1.77 \log ( T_{\text{eff}}/T_{\odot} ) \quad \text{km s}^{-1} \quad (2)$$

The corresponding linear correlation coefficients are respectively 0.95 and 0.97, implying that these relations are statistically very significant. From the definition of  $L_w$ , one can obtain an empirical relation for  $\dot{M}$  given by

$$\log \dot{M} = -14.30 + 1.07 \log ( L_{\text{Bol}}/L_{\odot} ) + 1.77 \log ( R^*/R_{\odot} ) \quad M_{\odot} \text{ yr}^{-1}$$

The Wolf-Rayet stars in Figure 1 are included to illustrate that the  $L_w$ - $L_{\text{Bol}}$  correlation also fails to predict the wind properties of these stars. Biéging et al. (1982) found a similar discrepancy in comparing Wolf-Rayet values of  $\dot{M}$  with the  $\dot{M}$ - $L_{\text{Bol}}$  relation for OB stars. However, the Wolf-Rayet values of  $v_{\infty}$  do follow the  $v_{\infty}$ - $T_{\text{eff}}$  correlation (Figure 2).

The solar values ( $L_w \sim 10^{26.75}$ ,  $v_{\infty} \sim 300$ ) were included in the least-squared fits and in both correlations, these solar values fall above the lines within the observable scatter ( $L_w$  of Sun not shown in Figure 1). This is not surprising, since, the solar wind values are determined directly, whereas, the wind values for other stars are determined spectroscopically. It is also unclear as to whether the quoted values of  $v_{\infty}$  for the late stars represent terminal velocities or lower limit shell components (Mullan 1978).

## DISCUSSION

The most surprising result of these correlations is that all spectral types are represented with the exception of late main sequence stars. These relations are presently hard to understand since the general consensus is that totally different mechanisms are responsible for stellar winds throughout the HR diagram.

The obvious question which emerges from the present analysis is where is the distinction between hot and cool star winds? The results indicate that no distinction is evident, and, in fact, the stellar flux ( $F_* \sim T_{\text{eff}}^4$ ) may be the fundamental quantity in the determination of stellar winds. This can be shown by rewriting the relations as  $\dot{M} \sim R_*^4 F_*$  and  $v_\infty \sim F_*^{1/2}$ . Qualitatively this dependence suggests that for a fixed value of  $F_*$ , larger values of  $\dot{M}$  can be obtained by increasing  $R_*$ , since the depth of the stellar gravitational well decreases making it easier for mass to escape the star. Correspondingly, as  $\dot{M}$  increases linearly with  $F_*$ , the flow speed of the wind begins to level off because it becomes harder to push the increasing mass of the wind to higher speeds.

Obviously, other stellar properties may also be important in the determination of wind structures (i.e., rotation, coronal structure), but the correlations found in this analysis suggest that the stellar flux may be the dominant factor. This is expected for hot stars, but not for cool stars. Further observational data are needed to test the significance of these relations.

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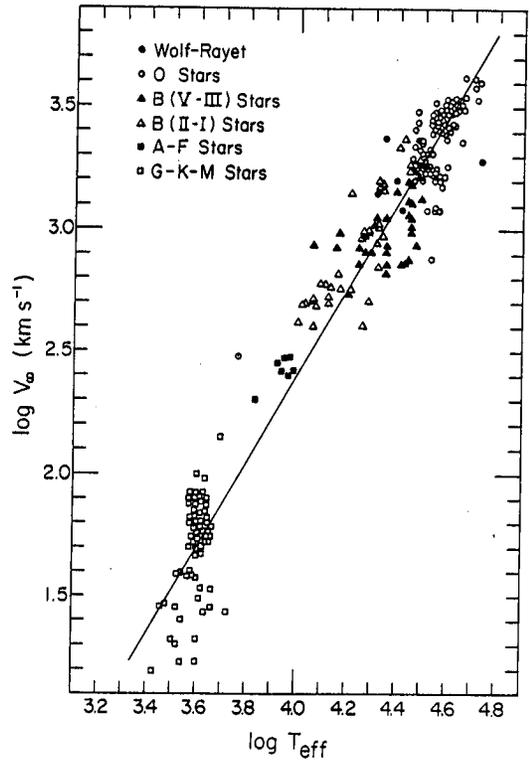
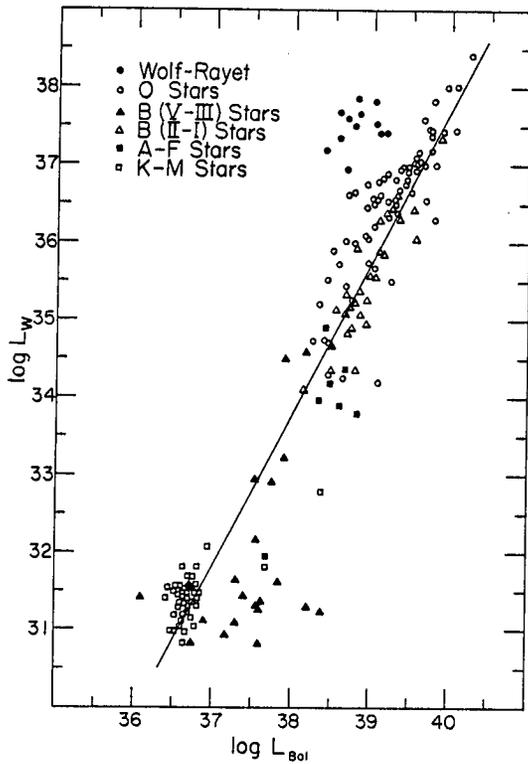


Figure 1. The correlation between wind luminosity ( $L_W$ ) and bolometric luminosity (both in  $\text{ergs s}^{-1}$ ). The A-M stars represent luminosity classes I-III. The value of  $L_W$  for the Sun is not shown.

Figure 2. The correlation between the terminal velocity ( $\text{km s}^{-1}$ ) and stellar effective temperature. The A-M stars represent luminosity classes I-III. The value of  $v_\infty$  for the Sun is indicated.

## DISCUSSION

Underhill: The dispersion about your empirical relations appears to be real. That is, it reflects more than the observational uncertainties in your empirical data. I have pointed out (1983 Ap.J. (Letters)) that the dispersion in  $v_{\infty}$  at fixed  $T_{\text{eff}}$  implies the action of more than one accelerating force. In the case of supergiants, one should recall that stars of the same mass and luminosity may have widely different values for  $T_{\text{eff}}$ , for instance, about 25000 K or 8000 K. There appears to be no single mechanism for the acceleration of the material in a wind, nor for regulating how much material above each element of surface may be "released" so that it can be accelerated to escape from the star at a finite velocity. The fact that the Sun shows high-velocity and low-velocity streams is just one example of this.

Waldron: It is quite possible that the observed dispersion is real and may be related to secondary effects (coronal structure, stellar cycles), however the results indicate that the primary accelerating mechanism is related to  $T_{\text{eff}}$ .

Abbott: Given your sample of stars, it is not possible to distinguish between a correlation with  $T_{\text{eff}}$  and a correlation with gravity (or terminal velocity), so I think your correlation of  $v_{\infty}$  with  $T_{\text{eff}}$  also implies that  $v_{\infty}$  is correlated with  $g$ . This may be understood because no matter what the mechanism adding momentum, you still have to raise material out of the gravitational potential well, so a natural scaling between  $v_{\infty}$  and  $g$  occurs independent of mechanism. For example, both a Parker thermal wind and a radiation driven wind predict  $v_{\infty}$  varying as  $g$ .

Waldron: In the correlation of  $v_{\infty}$  with  $T_{\text{eff}}$ , there are B V - B Ia stars which have essentially the same  $T_{\text{eff}}$  and  $v_{\infty}$ , but which would have a large spread in gravity, so based on the available data, it is not evident that  $v_{\infty}$  varies as  $T_{\text{eff}}$  implies  $v_{\infty}$  varies as  $g$ .

Linsky: Could you comment on whether the Sun fits your empirical scaling laws?

Waldron: The Sun does not fit the  $L_W - L_{\text{B01}}$  relation (about a factor of 30 too large) or the  $v_{\infty} - T_{\text{eff}}$  relation (about a factor of 3 too large). This discrepancy may be related to the fact that the Sun's wind properties are determined directly, whereas for other stars, the wind properties are determined spectroscopically.

Owocki: It is true that  $v_{\infty}$  tends to scale with  $v_{\text{esc}}$  for all stars, and is thus independent of the driving mechanism. The same is not true for  $\dot{M}$ , which differs by a factor of  $10^{10}$  between early-type stars and the Sun, reflecting the much stronger driving mechanism (for example, by radiation) in hot stars.

Waldron: Yes, it is true that  $v_{\infty}$  tends to scale with  $v_{\text{esc}}$ . However, the nature of the scaling is different throughout the HR diagram. It is also not obvious that  $v_{\infty}$  varying as  $v_{\text{esc}}$  implies that  $v_{\infty}$  is independent of the driving force. For example, in hot stars, you may deduce  $v_{\infty} \sim 3 v_{\text{esc}}$ ; this result is

very dependent on the form adopted for the radiation-pressure force.

Sreenivasan: The question of whether or not a local accelerating mechanism increases the rate of mass loss,  $\dot{M} = 4\pi r^2 \rho(r)v(r)$ , depends upon whether  $\rho(r)$  and  $v(r)$  are affected at a given distance  $r$  from the star in the same fashion or not. What happens depends on whether  $\rho(r)v(r)$ , the momentum density, increases or remains constant at a given  $r$ , and on where the accelerating mechanism is operative.

## HEATING IN THE SOLAR MANTLE

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### ABSTRACT

In the case of the solar chromosphere and corona, that is, the solar mantle, the primary energy source is the mechanical energy from photospheric motions. Plenty of energy is available; the problem is to transfer the needed amount of energy to the proper place to account for the observations. In this talk the global problem is reviewed from the point of view of the generation and transmission of energy, the intermediate storage of energy, and the release of energy in such a way that the observed features are generated.

The distribution of heat in the solar corona is very inhomogeneous. Loops, threads, and open field lines are recognized. The geometry is determined by the magnetic structure of the corona. We explore the idea that the basic physics is the same in configurations of loops and of open field lines.

All proposed mechanisms predict a very steep temperature gradient from the chromosphere to the corona. Thus the presence of a steep temperature gradient is not a useful diagnostic for establishing the validity of one theory over that of others. The choice of sensitive diagnostic features is an important step and it must be related to the possible errors of the observations.

The idea of heating the plasma of the solar mantle by shaking the magnetic field lines and generating magnetohydrodynamic (MHD) waves can be traced back to Alfvén (1947), Piddington (1956) and Osterbrock (1960). Events which have typical times less than  $\ell/v_A$  can be treated by theories involving AC currents. In this category one considers the actions of MHD waves, specially Alfvén waves. Events with timescales greater than  $\ell/v_A$  can be treated using the theory of DC currents. The physical mechanism for changing DC currents into heat is not clear at this time.

There are three sorts of MHD waves which are discussed: slow waves, a type of wave which carries little energy; fast waves, a type which may have problems with total reflection; and Alfvén waves. The latter waves appear to be the most useful form for transporting energy to the solar corona. Some theoretical difficulty is experienced with transporting energy across the observed steep temperature gradient between the chromosphere and the corona.

Longitudinal and lateral inhomogeneities exist in the solar mantle. Hollweg (1984) has presented an analytical study of the effects of longitudinal structure showing how one may transport energy across the transition region. The magnetic loops act as filters with peak transmission at resonant frequencies. A study of the effects of the dissipation of waves

shows how energy may enter the loops even when the transmission factor is less than unity. The fraction of available energy turns out to be independent of the details of the dissipative mechanisms.

Lateral inhomogeneities have been studied by Heyvaerts and Priest (1983). The presence of lateral inhomogeneities leads to phase mixing which is a key factor in the damping of Alfvén waves. The theory of Heyvaerts and Priest is most useful for open structures. In another paper Heyvaerts and Priest (1984) study the problem of finding the amount of energy which will be available if DC currents are present. An important question is how much of the available energy is accessible. The reconnection time is important in such situations. If the reconnection time is very small, no heating occurs. The accumulation of stresses over an interval of time, followed by a sudden release of energy, is relevant to flare theory, see Gold and Hoyle (1960).

The various theories which deal with particular MHD effects in the solar corona have been unified into one conceptual picture by Ionson (1984). The theories of the solar corona which have been reviewed demonstrate that the presence of small magnetic fields is very important for controlling the physical state of the solar mantle. This will probably also be true in the mantles of stars.

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(Prepared by A.B. Underhill from notes taken at the conference.)

## DISCUSSION

Zirker: What are the prospects for better diagnostics to discriminate among the different proposed mechanisms?

Chiuderi: In general terms, I am not very optimistic. If you consider the problem from the point of view of Ionson's theory, you see that all information on mechanisms is contained in the electrodynamic coupling efficiency. Therefore, one should be able to compute this quantity at different points and compare with the observations. I believe that it would be difficult to discriminate between the various mechanisms, unless one can pinpoint very peculiar observational signatures.

Golub: Jim Ionson and I have been looking at this very question. The main problem is that the observational signatures which you predict from the various proposed heating theories are in general not yet observable. For instance, some theories predict large microturbulent velocities in the corona which scale in anticorrelation with  $B$ . However, the observations are not available to test the theory; similarly with other theories. The scaling laws, as you have said, are thermodynamic and so smooth out much of the detailed physics.

Linsky: I would like to comment on the very appealing nature of the Ionson phenomenological theory. You pointed out at the beginning of your talk that all acceptable theories must be global. In the Sun the turbulent energy available in the photosphere does not change appreciably with position across the surface, whereas the coronal heating changes greatly from point to point. Therefore, the large variations in coronal heating from point to point depends on the coupling efficiency which must depend on the properties of the coronal magnetic field.

Underhill: Magnetic fields present a phenomenon which is ubiquitous. The theory which has just been reviewed shows how very important small magnetic fields may be for controlling the physical state of a low density, ionized plasma such as we have in the mantles of hot stars. Indeed, it appears that we cannot afford to ignore the effects of magnetic fields when we are modeling the mantles of stars of any type.

Mullan: In the Sun, Ionson's model cannot be tested too much because the convection zone properties are always the same. However, in other stars convection time scales can be very different. I have used this to interpret X-ray data in the dwarfs in terms of a resonance-impedance matching between convection time scales and coronal loop time scales (Ap.J. July 1, 1984 in press).

Chiuderi: This is another advantage of the phenomenological approach. It can be applied to other stars since, if the basic picture remains the same, namely the link between material motions and energy deposition, all you have to do is simply to put in the relevant values of the various  $\tau$ 's.

Hearn: The work of Ionson and others has been directed towards the heating of coronal loops. Is the mechanism also responsible for heating coronal holes?

Chiuderi: A phenomenological theory is not available for coronal holes. Specific mechanisms have, however, been worked out (Hollweg for Alfvén waves, Heyvaerts and Priest for phase-mixing in open field configurations) and these mechanisms seem to indicate that the physical processes are operating equally well in that case. The different response is due to the different magnetic and thermal structure.

Owociki: Global seems too strong a requirement for models since models need not be global in the sense that dissipation in a corona has little effect on conditions in the photosphere.

Chiuderi: I agree, maybe global is too strong a word. I used it to point out the link between photosphere and corona. Parker's theory fits with Ionson's unified description; it corresponds to the case  $\tau_{\text{diss}} \ll \tau_A, \tau_{\text{phase}}, \tau_{\text{leak}}$ .

Linsky: You dismissed slow-mode MHD waves as a heating mechanism. I presume that you were only referring to the corona because there is evidence that the chromosphere is heated by slow-mode waves. Also, the energy required to heat the chromosphere is much larger than that needed to heat the corona. Therefore, a truly global theory should account for slow-mode heating in the chromosphere and Alfvén heating in the corona.

Chiuderi: Correct; slow waves (and acoustic waves as well) are important for chromospheric heating. The neglect of the chromosphere can be a serious omission. What is implied here is that the flux in Alfvén waves produced by the photospheric motions does not suffer absorption or reflection in the chromosphere, so that it is justified to concentrate only on the effect of the transition regions.

Sreenivasan: The phenomenological approach you have described is very useful for gaining some insight about what is happening globally. But the fundamental approach cannot be abandoned because it helps you to understand the physics and leads to predictions which must be verified. We know that above ~ 2000 km from the limb, the electromagnetic theories of heating using Alfvén waves etc. are effective. This leaves the problem of heating the chromosphere. The role of the mechanical energy flux generated in the hydrogen convection zone of the Sun cannot be discounted for the chromosphere.

The Gold-Hoyle theory and J.B. Taylor's work that you referred to employ force-free magnetic fields and the twisting of the feet of the flux tubes by photospheric motions. The consequence of this twisting above 2000 km (at the top of the arches over closed loops and the other end of it above coronal holes) produces effects which can result in the turbulence that you alluded to. Generation of Alfvén waves and the "phase-mixing" that you referred to can be seen as a consequence of what is happening at the roots of these flux tubes. This way you can have a global, horizontally inhomogeneous phenomenon.

The energetics of all of this should include spicules which can soak up a

large part of the energy flux arriving at the photosphere from below. The mass flux and energy flux associated with spicules should be included in global fundamental theories. Sweeping things under the rug, in the way that you indicated occurs in phenomenological descriptions, is not wise because the hidden things will return to haunt us.

Chiuderi: A truly "global" theory should indeed include all the aspects you indicate (and possibly others). However, we are limited by our inability to include such a variety of effects and still calculate something. The approach described is a first sensible step towards globality. I would also add that there is nothing wrong about sweeping things under the rug until you are aware of it.

## THEORY TESTED BY MEANS OF THE STARS

L. Golub/Harvard-Smithsonian Center for Astrophysics

### I. Introduction

Until recently, this talk would have consisted of general statements about the usefulness of stellar data in the testing of theories. I would have pointed out that:

- (i) Stellar data allow us to explore a broader range of parameters than do strictly solar observations, thus providing a more stringent test of theories which were derived within the solar context (viz., Golub, 1980); also that
- (ii) The future development of the stellar portion of the "Solar-stellar connection" should not be a reiteration of the development of Solar physics, but should instead build upon that knowledge and search for ways to match the detailed information from the Sun to the large number of cases available from stars; and so on. Such statements have indeed been made in the past by myself and by others, in talks such as this one.

We are now in a position to do better than to discuss generalities. It has become possible to perform specific, directed tests which can provide significant checks on our solar-derived ideas and which can help us in understanding the stellar situation. Because the title of this talk is too broad for such a discussion, I will narrow it down to one well-defined area: an examination of the viability of the "standard"  $\alpha$ - $\omega$  dynamo model. We will do so by examining extreme stellar cases, which should show specific types of deviation from solar behavior. We will be looking for ways to disprove current ideas, since no additional evidence ever proves a theory. However, if we find consistency, it will strengthen our trust in the solar dynamo models.

I will use recent studies being carried out at the CfA utilizing EINSTEIN Observatory X-ray data. This is done mostly for convenience, because I am most familiar with this work. Similar examples could be drawn from other space experiments—most notably the IUE—and from the recent and the older ground-based data, such as the Wilson CaK observations.

The theoretical base which we need to consider has two parts, only one of which will be of direct interest to us:

1. the relation between surface magnetic fields and the heating of the corona, and
2. the use of surface magnetic fields as a tracer of dynamo properties.

These are two quite distinct theoretical areas, which happen to be linked due to observational necessity of observing  $\tilde{B}$  through its effects on the atmosphere, rather than by direct measurement; in the stellar case especially it is only now becoming possible in a few exceptional cases to measure  $\tilde{B}$  directly. In general we need to detect the field by its impact on activity-related observables and then work through an intermediate modelling step to obtain estimates of  $\tilde{B}$ . Such a procedure is fraught with uncertainties and it is fortunate for us that there exist measurements which show such clear signatures that we can derive some theoretical benefit from them.

## II. Plan of Attack

A vast body of Solar observations is available from which properties of the Solar dynamo may be deduced. The dynamo itself is not directly accessible to observation so we must rely on observing samples of the field that are brought up to the surface by buoyancy and convection. The Solar data (summarized in Golub et al. 1981) indicate that the magnetic field is being generated primarily at or near the base of the convection zone. Evidence for this view comes from the properties of large-scale magnetic fields on the surface, from theoretical arguments showing that locating the dynamo between a convecting and a stably stratified layer facilitates flux amplification (Bullard and Gubbins 1977) and from calculations indicating that residence times in such a region are enhanced, thereby allowing sufficient time for the necessary field amplification to occur (Galloway and Weiss 1980; Parker 1979).

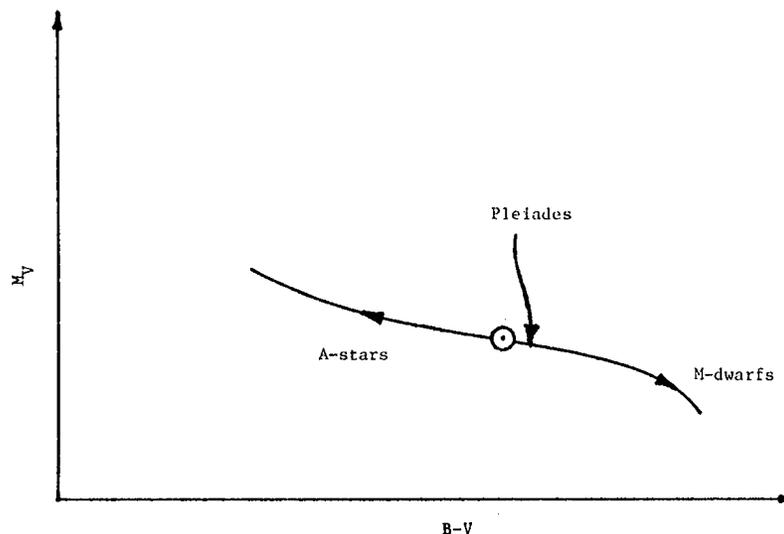
The necessity for having such an interface region with mild convective overshoot carries with it strong observation implications when we extend our range of observations to include stars other than the Sun. Such comparisons have always been hampered by the nonlinearity of the dynamo equations, which preclude simple estimates of dynamo behavior; however, we will examine situations in which the qualitative behavior of the dynamo is so different from the solar pattern that the test becomes significant. We examine three separate but related studies:

1. Main-sequence stars with shallow convective zones (Schmitt et al. 1984). We will refer to this study by the slightly inaccurate title "Onset of Convection";

2. Fully convective M-dwarfs (Bookbinder et al. 1984), referring to the low mass main-sequence dwarf stars, which stellar structure theory predicts to be fully convective;

3. Pleiades X-ray survey (Micela et al. 1984), which we will refer to as "Approach to the main sequence."

Our plan is therefore to define, through observations, the extent of Solar-type dynamo activity along the main sequence (Fig. 1) and to see whether the expected departures from Solar behavior actually occur:



### III. Onset of Convection

Schmitt *et al.* (1984) have completed an X-ray survey of late A and early F stars on the main sequence. Stellar structure theory predicts the appearance of subphotospheric convection zones below  $M_* \sim 1.6M_\odot$  or below  $T_{\text{eff}} \sim 8,000$  K (Gilman 1980). Theoretical determinations of the stellar structure in this regime depend strongly on the ratio of mixing length to pressure scale height ( $\Xi\alpha$ ) and also on the opacities used. If the existence of an outer convective zone is necessary for the existence of solar-type coronal activity (via the intermediary of dynamo activity), then the detection of a hot envelope around late A stars would serve as indirect evidence for the existence of convection zones; in view of the uncertainties in the theoretical calculations, the direct coronal observations might provide the most sensitive means of determining convective onset. In the most favorable case, a sudden increase in coronal emission would indicate a precise location for the onset of convection.

The major result of the survey is shown in Figures 2 and 3. Figure 2 gives the integral ("log N - log S") X-ray luminosity functions for stars in the color range  $0.1 \leq B-V \leq 0.5$ , corresponding to  $\sim$  A5 to  $\sim$  A7. The three curves show the distribution of X-ray luminosities for (from left to right) the single stars in the sample, the total sample and the multiple stars in the sample. The single and multiple star distributions are significantly different, with  $\log L_x$  (single) =  $28.3 \pm 0.1$  and  $\log L_x$  (mult.) =  $28.8^{+0.3}_{-0.1}$ . The latter value can be satisfactorily explained by convolving the single A-star luminosity function with the known (Rosner *et al.* 1981) M-dwarf luminosity function, thereby creating an artificial binary A-star sample which agrees quite well with the observed sample.

Figure 3 shows the further crucial subdivision of the data into "early" and "late" categories,  $0.1 \leq B-V < 0.3$  vs.  $0.3 \leq B-V \leq 0.5$ , using only single stars. We point out that the method employed permits the use of upper limits as well as detections. There are 26 detections and 60 upper limits in the sample; only four of the detections are in the 0.1 - 0.3 range in B-V.

It is clear that the X-ray luminosity function for the earlier stars lies far below that of the other group. A strict statistical test (Schmitt 1984) assigns 95% confidence to this conclusion. When we consider the presence of X-ray emission from the A7 dwarf Altair and the F0 dwarf  $\alpha$  Hyi and the absence of X-ray emission from the A0 dwarfs, Sirius A and Vega (Schmitt *et al.* 1984), we conclude that convection zones and magnetic fields are present in the former but not the latter. However, the claim that magnetic dynamos exist in stars as early as A7 contradicts the conventional wisdom that such dynamos cannot be sustained in stars earlier than  $\sim$  F6 (e.g., Durney and Latour 1978). Moreover, the apparent lack of correlation between X-ray emission and stellar rotation rate for F-stars (Pallavicini *et al.* 1981) contrasts with the strong correlation observed in G-, K- and M-stars.

The resolution of this difficulty may lie in the proper choice of correlators, in this case the Rossby number rather than the stellar rotation rate, vs. level of activity. The Rossby number is the ratio of the rotation

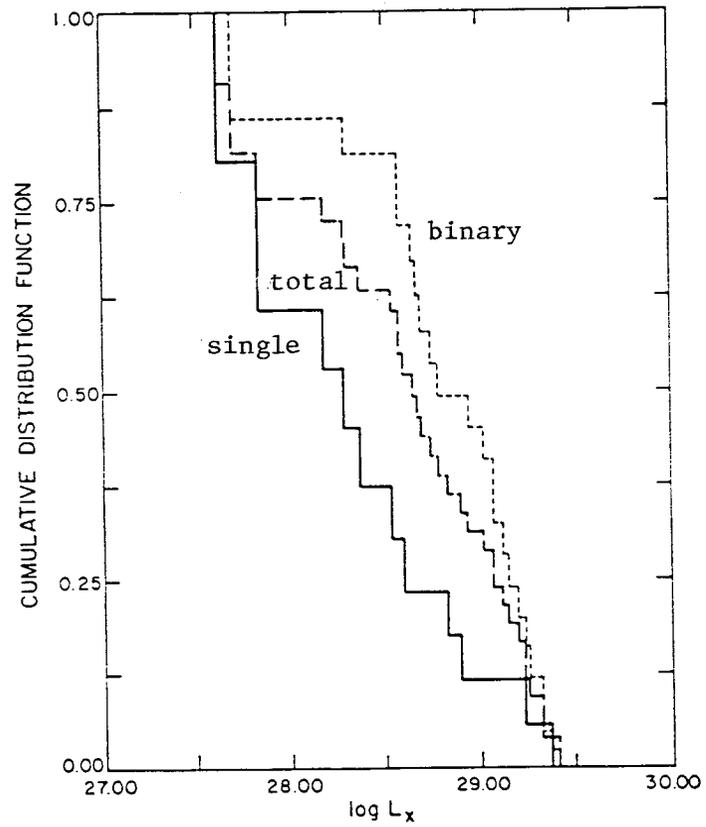


Figure 2. X-ray luminosity functions for stars in the color range  $0.1 - 0.5$  ( $B-V$ ).

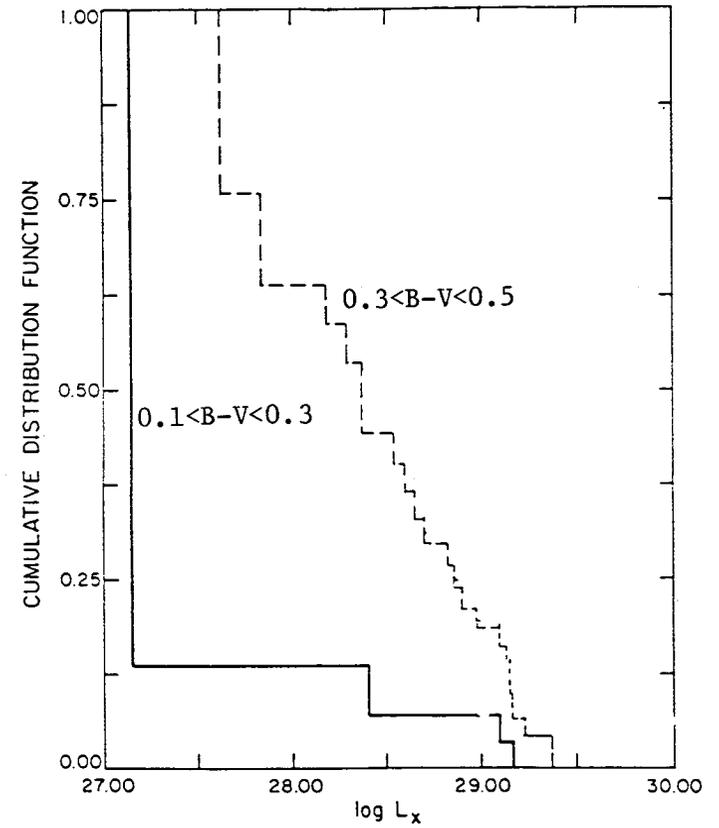


Figure 3. X-ray luminosity functions for single stars, divided into early and late subsamples.

period to the convective turnover time, which is also related to the so-called dynamo number:

$$R = \frac{\tau_{\text{rot}}}{\tau_{\text{conv}}} = N_D^{-1/2}$$

Figure 4 shows a plot of X-ray luminosity vs. Rossby number for the sample of late-A to late-F stars. Considering the sensitivity of computed convective turnover times to small errors in stellar mass and the questionable use of mixing length theory in stars with shallow convective zones, the correlation between  $L_x$  and  $R$  is very good. Note especially that the lowest point is Altair, which shows a very poor comparison between  $L_x$  and  $v \sin i$ .

Two final points about this figure: first, the best-fit relation  $\log L_x = 29 - 2 \log R$  which is shown on the figure, reduces to exactly the  $L_x$  vs.  $V_{\text{rot}}$  relation found by Pallavicini *et al.* for stars later than  $\sim F6$ , mainly because stellar radii and convective turnover times change very little along the main sequence after F6 and so drop out of the correlation. Second, it is part of the conventional wisdom that dynamos become efficient at  $N_D \gtrsim 1$ , which corresponds to  $\log R \lesssim 0$ . This is precisely the point in Figure 4 at which the effect of the onset of convection ceases to influence the data and the behavior previously observed for solar-type stars becomes dominant.

#### IV. M-Dwarf X-ray Emission

Bookbinder *et al.* (1984) have recently completed a survey of X-ray emission from M-dwarf stars; this paper extends the results reported earlier by Golub (1983). The new survey consists of a volume-limited (25 pc) sample of all M-dwarfs listed in the Wooley catalog which fell within EINSTEIN Observatory IPC fields accessible to us for analysis. The search resulted in 34 detections of M-dwarfs and 62 upper limits. The average sensitivity limit was  $\sim 5 \times 10^{27}$  erg s<sup>-1</sup>, although in some cases the threshold for detection was as low as  $1 \times 10^{25}$  erg s<sup>-1</sup>.

The major result of the survey is shown in Figure 5, giving X-ray luminosity vs. B-V color index. The most prominent feature in this diagram is the abrupt disappearance of high luminosity M-dwarfs later than  $B-V \gtrsim +1.6$ . Bookbinder *et al.* conclude that for a sample of single M-dwarfs and with the inclusion of upper limits (rather than just detections), the mean X-ray luminosity of stars later than M5 is less than  $10^{26.0}$  ergs<sup>-1</sup>. This drop in activity level has major consequences in areas as diverse as the soft X-ray background and sources of the interstellar medium. We will concentrate here on the possible implications of the observations for theories of stellar interiors in M-dwarfs. However, we will first discuss the reasons for believing that the drop in X-ray luminosity is real, rather than some type of observational selection effect due to bias in the selection of targets.

Bookbinder *et al.* have performed tests which place upper bounds on the fraction of very late ( $B-V > +1.6$ ) M-dwarfs which could exist undetected in the survey. The first test involves comparison with the EINSTEIN Observatory medium-sensitivity (Maccacaro and Gioia 1984) and deep (Primini 1984) surveys. The latter studies found and identified X-ray sources in the sky independent

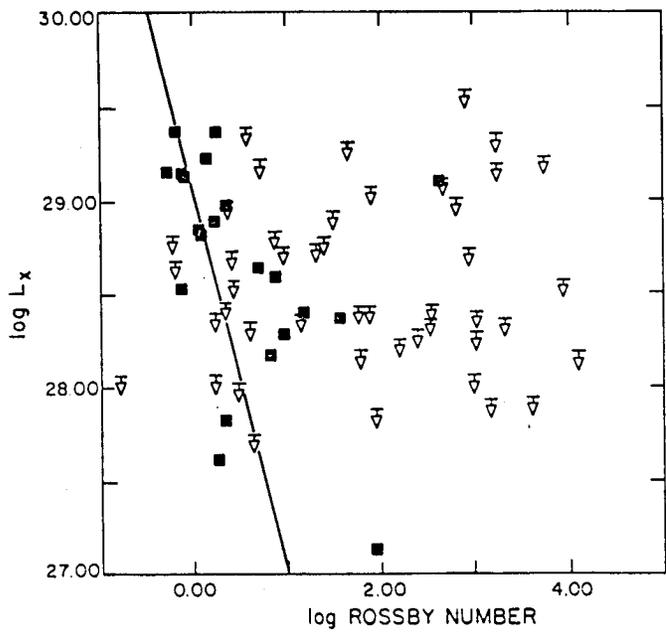


Figure 4. X-ray luminosity of late-A and early-F stars vs. Rossby number, including detections and upper limits.

M DWARF X-RAY LUMINOSITIES

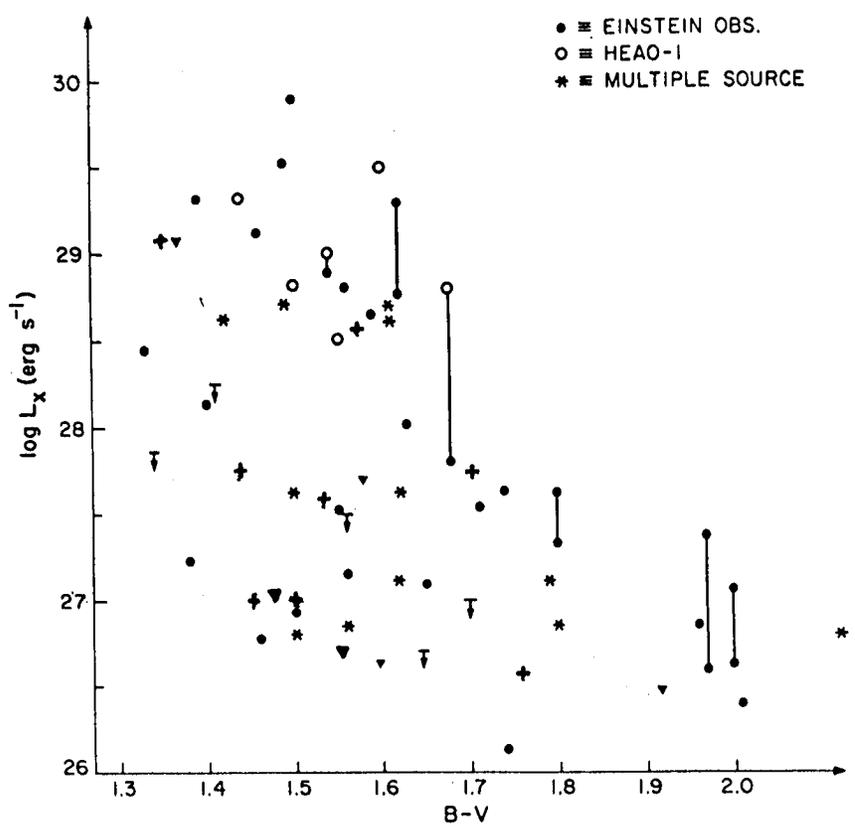


Figure 5. (right) Survey of M-dwarf x-ray luminosities --updated from Golub (1983).

of their type; some of them were found to be M-dwarfs. The number of M-dwarfs seen in those surveys may be compared directly to the observed X-ray luminosity function and the space density (which is not well known). Under the assumption that the space density of the very late M-dwarfs is flat, the results of the medium and deep surveys are reproduced exactly, using the drastic drop in X-ray level. A more sophisticated version of this test, using the standard galaxy model of Bahcall (1980), gives the same result. If instead, we assume that the X-ray level for  $B-V > +1.6$  is actually the same as that of the earlier M-dwarfs, we find that ten times as many stars should have been seen in the X-ray surveys or we are forced to assume that the late M-dwarf number density drops by a factor of ten.

The conclusion is thus that the drop in  $L_x$  is real. However, it is well known that the bolometric luminosity for M-dwarfs is a sharply decreasing function of spectral type, so that we need to ask whether  $L_x/L_{bol}$  also decreases. The answer depends upon the difficult determination of  $L_{bol}$ , but our preliminary results for a small subset of the total sample are shown in Figure 6. We see that the major features remain; in particular, the drop in emission is still present and shows itself as a disappearance of the high level emitters.

A contrary conclusion has been reached by Rucinski (1984), who claims that  $L_x/L_{bol}$  shows no significant change from M0 to M6. The sample used is similar to that shown in Figure 6 but does not show the drop in level after  $\sim M5$ . Both of these studies suffer from incompleteness and from not including the large number of upper limits available; this will be corrected in Bookbinder *et al.* by using the complete volume-limited sample.

The importance of a drop in X-ray emission at  $\sim dM5$  is that this is the point along the main sequence at which we expect stars to become fully convective. As we have discussed, a solar-type dynamo should operate near the base of the convective zone; thus there would be no room for the  $\omega$ -effect to operate.

#### IVa. Magnetic Field Calculations

We may use the observed X-ray flux and temperature values to calculate magnetic field strengths, based on solar-type loop models. The method has been described by Golub (1983) and involves the two formulae for B and filling factor (note that the stellar gravity factor was incorrectly shown in that paper):

$$B_{em} = 1.2 \times 10^{-8} \left[ T \left( \frac{g}{g_{\odot}} \right) \right]^{1/2} \left( \frac{v}{v_{\odot}} \right)^{-1}$$

$$f = \frac{3.4 \times 10^{-9}}{p(T)} F_x \left[ T^3 \left( \frac{g}{g_{\odot}} \right) \right]^{-1}$$

The total magnetic flux on the star, which is of interest in determining whether the B-field is measurable, is just  $\Phi = 4\pi R^2 B = 4\pi R^2 B_{em} f$ .

A graphical representation of the calculated B values for late-type stars is shown in Figure 7. The spectral types for which fields have been calcu-

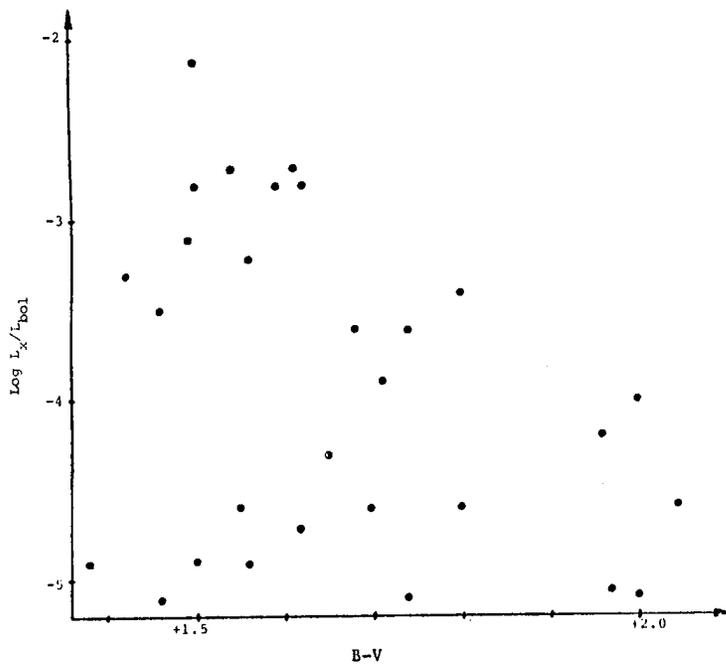
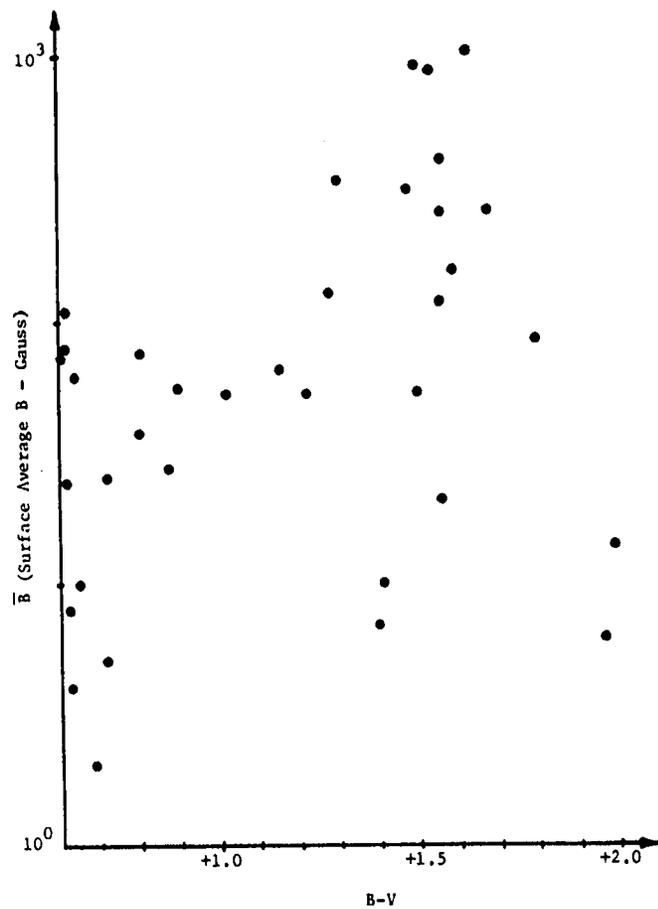


Figure 6. (top)  
 $L_x/L_{\text{bol}}$  for a sample  
of M-dwarf stars vs.  
color index  $B-V$ .

Figure 7. (right)  
Calculated average magnetic  
field values for detected  
G-, K- and M-dwarfs; see text  
for details.



lated run from  $\sim G0$  to  $\sim M6$ ; note that the Sun on this graph has  $\bar{B} \sim 10$  gauss. The most prominent feature is the peak in average B at around  $B-V = +1.5$ , corresponding to the BY Draconis variables and flare stars. The peak is followed by a sharp drop in field strength, down to solar levels.

Thus we predict that the most easily detected dwarf star magnetic fields will be found on the late-K to early-M BY Draconis stars. Also, that the drop in coronal emission after  $\sim M5$  comes from a drop in the average magnetic field, but only down to about solar values.

## V. Pleiades Survey

Micela *et al.* (1984) have reported the results of an X-ray survey of the Pleiades. Two  $1^\circ \times 1^\circ$  fields of the Pleiades region, containing 78 cluster members within a limiting magnitude of  $14^m$  and centered on two of the most luminous stars of the cluster (20 Tau and 17 Tau) were observed with the EINSTEIN (HEAO-2) Observatory Imaging Proportional Counter. The exposure times ( $\sim 3-4 \times 10^3$  sec) and background level give, at the Pleiades distance of  $\sim 127$  pc, a mean detection threshold of  $10^{29.5}$  erg  $\text{sec}^{-1}$ . They detected 1 (out of 8) B stars, 1 (out of 13) A stars, 2 (out of 10) F stars, 11 (out of 21) G stars and 6 (out of  $>26$ ) K stars. The brightest X-ray source is Hz II 253 (G1), with  $L_x \sim 10^{30.3}$  erg  $\text{sec}^{-1}$ .

X-ray luminosity functions for the G and K stars in the cluster were derived and show that for the G stars, the Pleiades X-ray luminosity function is significantly brighter than the corresponding function for Hyades G dwarf stars. Also, the significantly larger fraction of X-ray bright G stars than K stars (even though the Pleiades K stars appear to be relatively rapid rotators), and the lack of detection of M stars, suggests that the connection between stellar rotation and coronal activity is not as straightforward as has heretofore been thought.

A map of the region surveyed, giving the locations of the Pleiades stars in the two IPC fields and of the detected sources is shown in Figure 8. A total of 21 sources associated with cluster members was detected and three additional sources were seen which did not correspond to any cataloged Pleiades stars. The results are illustrated graphically in Figure 9, which shows that 50% of the G stars were detected and smaller fractions of the remaining spectral types.

The median luminosity of the Pleiades G stars is thus  $10^{29.5}$  erg  $\text{s}^{-1}$ . This may be compared to the result for the ten times older Hyades cluster,  $10^{29.1}$  erg  $\text{s}^{-1}$ . (Stern *et al.* 1981); only one-fourth of the Hyades G-stars are stronger than  $\log L_x = 29.5$ . Thus, a clear decrease in activity level with age is evident.

However, the Pleiades data suggest that a simple picture in which the stellar activity level of late-type stars is determined primarily by the stellar rotation rate is not the entire story. In particular, the absence of M-dwarf detections is puzzling. For example, if we assume that the X-ray luminosity function for dM stars in the Pleiades is shifted upward by the same amount as that of dG field stars (a factor of 50), then  $\sim 10$  dM stars should have been detected above the survey threshold. Instead, there is only one source seen which is coincident with a faint red object and so could even possibly be a Pleiades M-dwarf. The clue to explaining the non-observation of M-dwarfs may

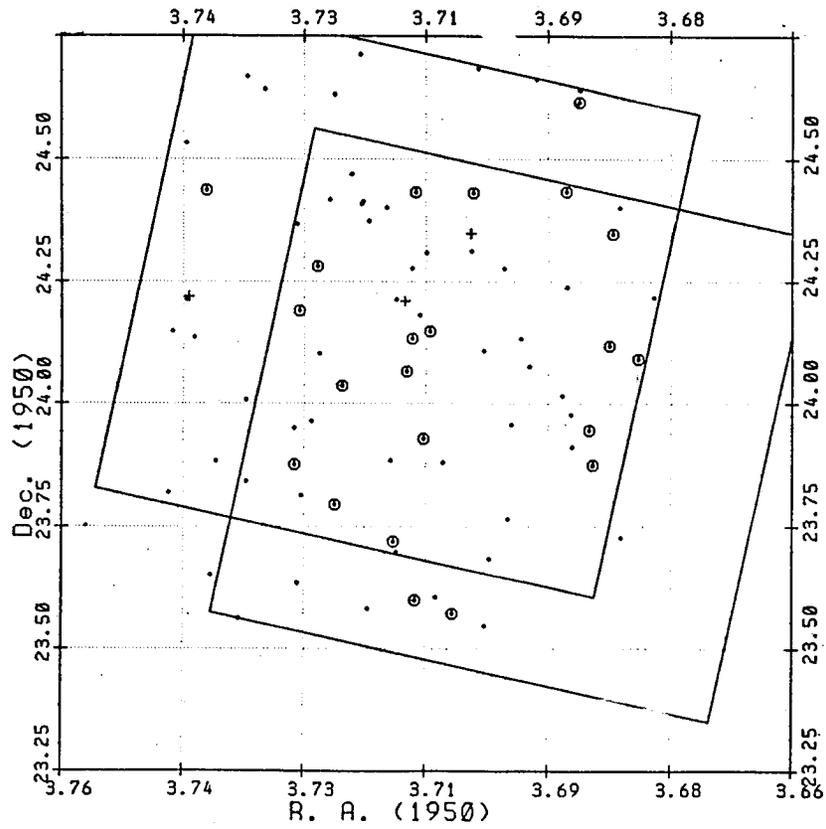
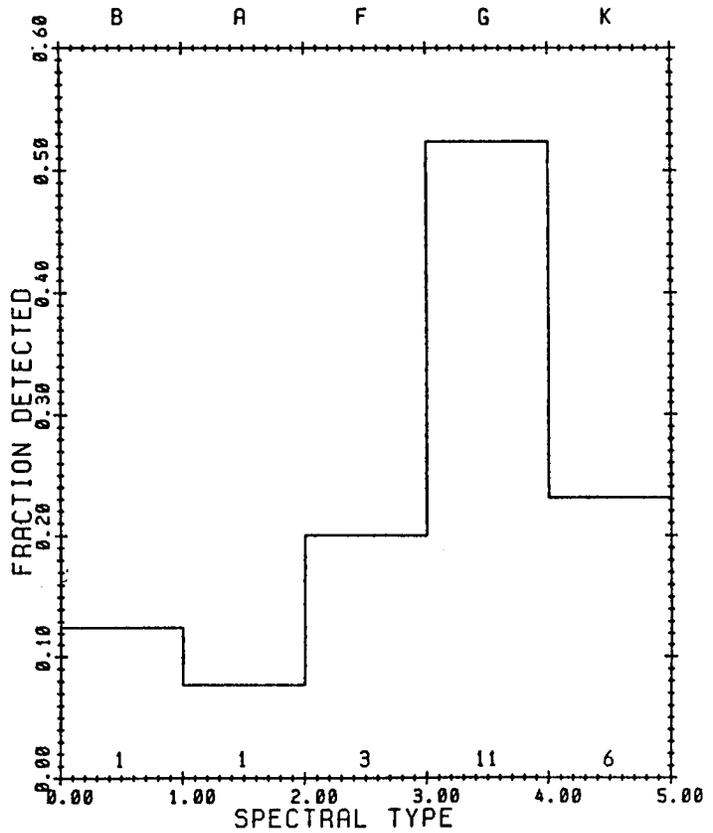


Figure 8. (top) Pleiades x-ray survey. Dots represent cluster members in the IPC fields, dots with circles are detected stars.

Figure 9. (right) Fraction of Pleiades stars detected as a function of spectral type.



lie in the K-dwarf observations.

Only 8 of the stars later than F7 (specifically: 4 K, 1 G, 3 F) in the sample have known values of projected equatorial velocities  $v \sin i$ ; for 11 K stars, Micela *et al.* have upper limits to  $v \sin i$  and for 2 stars (1 K, 1 G) they have lower limits to  $v \sin i$ . In particular, 2 K, 2 G and 1 F stars detected as X-ray sources have projected equatorial velocity  $v \sin i$  in excess of  $45 \text{ km s}^{-1}$ , while 2 K stars with  $v \sin i > 50 \text{ km s}^{-1}$  were not detected. Given the currently popular notion that stellar activity levels ought to correlate well with stellar rotation rates, it seems surprising that the Pleiades K dwarfs have systematically lower activity levels than the corresponding G dwarfs because the dK stars in this cluster include a number of rapid rotators.

Micela *et al.* believe that one can however account for this behavior. As suggested by the solar rotation evolution models of Endal and Sofia (1981), rapid evolution on the radiative track leads to spin-up of the entire star, which is followed by rapid spin-down (by magnetic braking) of the outer convective envelope. If, on average, the K stars correspond to the former evolutionary stage, while the G stars (again on average) correspond to the latter stage, then one would expect the rapidly rotating K dwarfs to have relatively modest rates of internal differential rotation at the convection zone-radiative core interface, whereas more slowly rotating G dwarfs would still have (at least just after the rapid envelope spin-down period) a rapidly spinning core, and hence substantial differential rotation at this interface.

This scenario is supported by the fact that, at the nominal Pleiades age of  $\sim 10^{7.7}$  years, a solar-like star would have just reached the ZAMS, as shown by Figure 5 of Endal and Sofia (1981). Such a star would already show a greater than three-fold difference between its surface rotation rate and the (larger) radiative core rotation rate. In contrast, a lower mass K dwarf at the Pleiades age would not have reached this stage as yet and the consequent maximum difference in rotation rate between the core and the surface would be less than two-fold.

As has been recently suggested, the presence of a shear layer near the base of an outer convective zone is highly favorable to a "shell dynamo" driven by the steep gradient in  $\Omega$  at the convective envelope-radiative core boundary. Hence, one would expect on this model, at least qualitatively, that magnetic activity is most vigorous just at the point at which this differential rotation is maximized, thereby accounting for the observed difference in activity levels in the Pleiades G and K dwarfs. This scenario would also account for the paucity of X-ray sources associated with dM stars in the Pleiades fields.

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#### DISCUSSION

Wentzel: This method of deducing fields and coverage fractions selects fields on the scale of solar active regions, as shown by the solar  $B = 30 - 80$  G in the table. For radio observations, smaller sites with higher  $B$  are important; for winds, regions of lower  $B$  dominate. Is there any evidence for some  $B$  larger or smaller than in your table by an order of magnitude?

Golub: The  $B$  strengths shown are those calculated in the corona and the emitting regions; the filling factor gives an idea of the extent of the regions. Larger  $B$  values should cause higher temperature emission, which is often observed on active stars.

Sreenivasan: It was not obvious to me why T Tauri stars do not have dynamos operating in them. They are convective as they contract to the ZAMS line. They should spin up owing to contraction. They are known to lose mass and that should cause loss of angular momentum. Since not all T Tauri stars end up on the main sequence with zero rotation, why does a dynamo not operate along the way?

Golub: There are other types of dynamos, such as the " $\alpha^2$ " type which could be operating in fully convective stars. They are less efficient without an  $\omega$ -effect, and they may not show cyclic behavior so that there may be observational consequences. The point I made is that if stars which are just approaching the main sequence go through a relative minimum in their coronal emission, then we should consider that there is a change of mechanisms occurring.

Mullan: You derive the magnetic fields in the X-ray emitting regions; the surface fields will be stronger. An alternative interpretation of large X-ray fluxes ( $\sim 1\% L_{\text{Bol}}$ ) in early M dwarfs involves electrodynamic coupling efficiencies  $\epsilon$  (Ionson 1984) which may pass through a resonance ( $\epsilon = 1$ ) in M0 - M1 stars. This would predict  $F_{\text{corona}} = F_{\text{mech}} = 1\%$  of  $F_{\text{Bol}}$  in M dwarfs (Mullan 1984, Ap.J. July 1). Rapid decrease in  $L_X/L_{\text{Bol}}$  at later M types is due to departures from impedance matching.

Golub: I agree. These calculations give B values near the bottom of the corona, which should be a lower limit to photospheric values. Regarding your calculation of the heating efficiency, which I have chosen to leave as a constant in these calculations, your numbers may turn out to be right. Fortunately, it is now becoming possible to obtain direct measurements of the B and the filling factor values on dK and possibly dM stars, so we may soon know for certain.

Pismis: You showed that from late A type stars on to later types  $L_X$  increases abruptly. Now in the F and G type stars it has been known for quite some time that there are metal rich as well as metal poor stars. Have you made any distinctions between metal abundances in your statistics?

Golub: Unfortunately, the number of A stars detected was too small for any further subdivision to be meaningful. However, this question should be looked into in the future, by ROSAT or AXAF.

Linsky: Previous X-ray surveys have found a monotonic increase in  $L_X$  with decreasing cluster age (e.g. reviews by Stern at COSPAR and the Third Cambridge Workshop on Cool Stars). Therefore, I am confused by your interpretation of why so few Pleiades K and M stars are detected as X-ray sources. Should these stars not be pre-main-sequence or T Tauri stars that are strong X-ray sources unless the X-rays are smothered (i.e. absorbed by the overlying wind)?

Golub: I believe the Pleiades results force us to re-examine this view. We have long known that pre-MS and T Tauri stars show little, if any, relation between coronal emission and rotation - except that as a group they are in the right place on an  $L_X$  vs.  $v_{\text{rot}}$  diagram. At the same time the argument has been that coronal emission is linked to age only because rotation rates are linked to age. It is still possible to view the Orion pre-MS, Pleiades, and Hyades X-ray levels as being correlated with age, but I feel that it now makes more sense to think of a division between primordial and dynamo-generated fields and to explore the consequences of that viewpoint.

Uchida: I think you covered the problems of the solar-type stars, leaving out the problems of non-thermal energy/momentum problems for early-type stars. I think there are processes working for early-type stars which are related to magnetic fields. Do you disagree on this point, or were there no theories proposed which can be tested in such stars?

Golub: At the moment I know of no theoretical work which gives quantitative, testable predictions. There is some work underway and in a few months there may be results along these lines.

Underhill: Can you make any statement on the type of dynamo theory ( $\alpha$ - $\omega$ ,  $\alpha^2$ , or other) which would be appropriate for early-type stars with shallow convection zones? Alternatively, may I ask is it theoretically forbidden to postulate that weak dynamos may be present in the outer layers of hot stars?

Golub: It would be premature to speculate. However, I can say with confidence that the possible existence of such dynamos cannot be ruled out and I believe that it is a fruitful area for present study.

Praderie: Concerning the  $L_X$  vs  $R_O$  number you obtained for A and F stars, what is the exponent you get? Margeney and Praderie (1984) find  $L_X \sim R_O^{-1.2}$ , with an effective  $R_O$  number which is, to within a factor of about 2, proportional to your local  $R_O$  at the bottom of the convection zone. By how much could you extend your relation toward the B stars? When we considered the available observed O stars to place them on our relation, in order to compute  $R_O$  in the same way as for other stars along the main sequence, we used Maeder's convection-zone models, which have such zones up to  $20M_\odot$  (i.e.  $\sim 32000$  K for  $T_{\text{eff}}$ ). We simply extrapolated up to  $T_{\text{eff}} = 35000$  K, not more. It seems that is not too bold a treatment.

Golub: The relation we obtain for late A and early F stars only is  $L_X \sim R_O^{-2}$ . For late F, G, etc., the relation is flatter. The early A stars are not detected in X-rays, so I do not see a way to continue directly from F to A to B stars: there does seem to be a gap. Stated explicitly, this means that Altair is the first late-type star observed to date.

Bookbinder: There are two major problems in the study of late B and early A stars. First, there are relatively few such stars observed in X-rays by Einstein. Second, there is an interesting problem associated with duplicity among these stars. If these late B stars are binaries with late-type dwarf companions, and if the X-rays are from the dwarf star, while the bolometric luminosity is that of the early-type star, then  $L_X/L_{\text{Bol}} \sim 10^{-7}$ , in accordance with the standard relation for O and early B stars. I point out this coincidence to emphasize that there is a region of the HR Diagram for which it will be difficult to obtain meaningful X-ray data.

Cassinelli: You have pointed out the importance of having an interface between the core radiative zone and the outer convection zone. What about the inverse situation of a large interior convection zone and a thin outer radiative zone. Would that also lead to an  $\alpha$ - $\omega$  mechanism for generating strong fields?

Golub: In principle, such an interface should give you field amplification via the  $\omega$ -effect, but a shear region is required at the interface. It would seem that polarity reversal requires an outer convection zone which reaches down to the field generation-regions, so that cyclic behavior might occur under the conditions you have presented.

Owociki: You concentrated only on the interpretation of X-ray observations. It seems that a large data set is currently being accumulated on stellar activity cycles through observations of Ca K-line cores. This material should also provide observational tests for theories.

Golub: I agree that there is available a very impressive body of observational data, both old and new, and recent results are exciting; examples could have been drawn from those studies. The main problem I see with some of the Ca K work is that the interpretation of those data in terms of dynamo behavior is quite problematical and some of the recent order of magnitude estimates which have been attempted have a very low probability of being accurate, owing to the non-linear nature of the problem.

Praderie: If we get into trouble with correlations  $L_X/L_{\text{Bol}}$  vs  $R_O$ , is it not that  $L_{\text{Bol}}$  is not the right quantity with which to normalize  $L_X$ ? We would rather normalize it with a quantity relevant to the region of the star where the magnetic field is generated (bottom of convection zone). This has the disadvantage of not being an observed quantity. In as much as we use models to compute  $R_O$ , we could use them to compute a convective (or an acoustic) flux which would be the proper normalization for  $L_X$ .

Golub: I agree. One never knows what the relevant parameters are until there is an accepted theory.

Mullan: In cool dwarfs,  $F_{\text{mech}}/F_{\text{Bol}} \approx \text{constant}$ . Therefore,  $F_X/F_{\text{Bol}}$  is essentially  $F_X/F_{\text{mech}}$ , which is the electrodynamic coupling efficiency, a useful parameter to test Ionson's theory.

Underhill: It appears from what Owocki and others have said that the correlation of observables in the optical range (referring to temperatures between  $10^4$  and  $3 \times 10^5 \text{K}$ ) with magnetic field may lead to the empirical possibility of estimating the efficiency factors in different parts of the mantle for the processes reviewed by Chiuderi.

Golub: It is appealing to think of doing this sort of work with early-type stars. I know of a few attempts, but so far the data do not seem to be adequate for drawing any convincing conclusions.

# THE SCALING OF CORONAL MODELS FROM ONE STAR TO ANOTHER

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## INTRODUCTION

The purpose of this paper is the discussion of the requirements that must be met in order that stationary numerical corona models can be scaled from one star to another. A corona model is a solution of the conservation equations for mass, momentum, and energy, subject to appropriate boundary conditions, and of the equation of state. In general, the mass  $M$  and radius  $R$  of the star enter these equations and boundary conditions as free parameters. Obviously, a given solution can be scaled to other stars only if all equations can be rewritten in such a form that  $M$  and  $R$  do no longer appear explicitly as free parameters, but only implicitly as scaling factors of the variables. An adequate means to find these scaling factors is a homologous transformation: One multiplies all variables and parameters by separate constants (i.e., scaling factors) and requires that the equations and boundary conditions remain valid. This leads to a set of nonlinear relations between the transformation constants. Only if in this set the two constants associated with  $M$  and  $R$  can be chosen independently, a given numerical corona model can be scaled to arbitrary stars.

## OPEN CORONAL REGIONS

I first consider spherically symmetric, optically thin open coronal regions. When the effects of magnetic fields are neglected, these regions depend on  $M$ ,  $R$ , and on the heating law. The latter is usually written as an exponential law,

$$F_M = F_{Mo} \left(\frac{R}{r}\right)^2 \exp\left(-\frac{r-R}{L}\right) \quad (1)$$

or as a shock heating law,

$$\nabla \cdot F_M = -\alpha \rho^{-1/2} T^{-5/4} F_M^{3/2} \quad \text{with} \quad F_M(r=R) = F_{Mo} \quad (2)$$

$F_{Mo}$  is the total mechanical energy flux at the base of the transition region, and  $L$  is the characteristic damping length over which the energy is dissipated in the corona. In the shock heating law (2), the role of  $L$  is played by the parameter  $\alpha$ , which depends on the shape of the waves, and which is inversely proportional to the period.

Fortunately, the boundaries can be specified in such a way that the solution is virtually independent of the boundary values. This is the case, for example, when one chooses as the inner boundary the base of the transition region, where the values of the temperature and conductive flux are unimportant (Souffrin 1981; Hammer 1982a). Similarly, the classical outer boundary conditions; i.e., that the solution goes through the critical point and that the temperature is restricted at large distances, do also not introduce additional free parameters.

With the method outlined above it can be shown (Hammer 1984) that corona models of this kind can be scaled to stars of arbitrary mass and radius if the following requirements are met:

1. The thermal conductivity  $\kappa$  must be approximated by a single power law in the temperature  $T$ . This is an excellent approximation because for collision dominated conduction in a fully ionized gas ( $T > 2 \cdot 10^4 \text{K}$ )  $\kappa$  varies as  $T^{5/2}$ .
2. The coefficient  $P_R$  of the optically thin radiative losses must also be approximated by a power law. If flows are involved, the two power law fits cannot be chosen independently, but must be coupled together,  $\kappa P_R \sim T^2$ . Since  $\kappa$  varies as  $T^{5/2}$ , we are forced to approximate  $P_R$  by  $T^{-1/2}$ . It is a fortunate coincidence that this fit is in fact reasonably accurate up to  $T \approx 2 \cdot 10^7 \text{K}$ . It represents the best power law fit to  $P_R$  over a large temperature range, and it has often been used in the literature.

Only this fortunate coincidence allows us to scale corona models from a given star of mass  $M_O$  and radius  $R_O$  to any other star of mass  $M$  and radius  $R$ . The scaling factors by which the numerical values of various quantities must be multiplied are given in Table 1. The scaling is particularly accurate when both stars have about the same  $M/R$  ratio, because in this special case the temperature dependences of  $\kappa$  and  $P_R$  may be arbitrary and need not be approximated by power laws.

Examples for the application of this scaling transformation have been given in Hammer (1984). In particular the grid of solar corona models of Hammer (1982b) has been used to derive an equation that gives the maximum coronal temperature  $T_m$  of open coronal regions as a function of all four parameters on which it depends; namely,  $M, R, F_{M_O}$ , and  $L$ .

Table 1 is, however, also applicable to the corona models that have been computed by Hearn (1982) for an OB supergiant of a radius  $R = 27.8 R_\odot$  and an effective mass (corrected for electron scattering)  $M = 25.1 M_\odot$ . Although the lower boundary of the complete models lies deep in the photosphere of the star, the transition region and corona part fulfills the same boundary conditions and equations as the models mentioned above. The heating law is the shock heating law (2). Consequently, the models of Hearn (1982) can be scaled to other stars with the same scaling factors (Table 1). The scaling to the Sun is particularly accurate since the  $M/R$  ratio of the underlying OB star has almost the solar value. Table 2 shows the main properties of a selection of models after scaling to the Sun. The table gives the wave period, the heating flux at the base of the transition region, the base pressure  $p_{TR}$ , the maximum coronal temperature  $T_m$ , the radius of the temperature maximum, the mass loss rate in solar masses per year, and the wind speed at  $400 R_\odot$ . The model with zero mass loss belongs to a new class of hydrostatic compact coronal shells (c f. Hearn and Vardavas 1982), which are discussed in my second paper in this volume.

quantity	factor
length	$R/R_\odot$
velocity	$(M/M_\odot)^{1/2} (R/R_\odot)^{-1/2}$
temperature	$(M/M_\odot) (R/R_\odot)^{-1}$
pressure	$(M/M_\odot)^3 (R/R_\odot)^{-4}$
energy flux	$(M/M_\odot)^{7/2} (R/R_\odot)^{-9/2}$
mass loss	$(M/M_\odot)^{5/2} (R/R_\odot)^{-3/2}$
$\alpha$	$(M/M_\odot)^{1/2} (R/R_\odot)^{-3/2}$

Table 1.

Scaling factors.

Period	$F_{MO}$	$P_{TR}$	$T_m$	$r_m/R_\odot$	$\dot{M}$	$V_\infty$
5.81(2)	3.46(4)	3.04(-2)	7.07(5)	1.24	7.9(-18)	2.08(7)
5.81(2)	3.76(4)	3.15(-2)	7.27(5)	1.23	1.3(-17)	2.15(7)
5.81(2)	9.92(4)	7.13(-2)	9.84(5)	1.24	1.6(-15)	2.56(7)
5.81(2)	3.18(5)	1.72(-1)	1.30(6)	1.25	2.0(-14)	1.61(7)
5.81(2)	3.70(5)	1.92(-1)	1.34(6)	1.22	2.5(-14)	1.38(7)
5.81(2)	5.76(5)	2.66(-1)	1.47(6)	1.21	4.4(-14)	6.47(6)
5.81(2)	1.09(6)	2.76(-1)	8.16(5)	1.05	0	0
5.81(3)	3.18(5)	8.07(-2)	1.59(6)	1.41	1.1(-13)	2.15(7)
5.81(4)	3.70(5)	4.30(-2)	1.93(6)	2.26	8.4(-14)	5.42(7)
5.81(5)	3.78(5)	3.14(-2)	2.00(6)	3.44	3.7(-14)	6.59(7)
5.81(3)	2.50(6)	1.38(-1)	2.29(6)	1.38	1.1(-12)	2.30(7)
5.81(4)	3.58(6)	8.56(-2)	3.30(6)	2.25	7.0(-13)	7.83(7)
5.81(5)	3.75(6)	5.62(-2)	3.50(6)	3.84	3.1(-13)	9.54(7)
5.81(6)	3.76(6)	4.04(-2)	3.03(6)	5.63	1.3(-13)	9.40(7)

Table 2. Main parameters (cgs units) of several corona models computed by Hearn (1982) for an OB supergiant, after scaling to the Sun. The first 7 models are from Table 3, the remaining models from Table 1 (models 8-10 and 13-16) of Hearn (1982).

#### CORONAL LOOPS

The scaling properties of coronal loop models depend on the relative sizes of the semilength  $S$  of the loop, the average coronal pressure scale height  $H$ , and the stellar radius  $R$ . In the most general case  $S$  need not be smaller than either  $H$  or  $R$ . Such large loops depend, like open regions, on  $R$  and  $M$  separately. There is evidence that such large loops really exist on some stars (Walter et al. 1983).

Flows within coronal loops are usually neglected. For static loops one finds that the power law fits to  $\kappa$  and  $P_R$  need not be coupled together, so that in principle arbitrary power law fits would be possible. However, as discussed above, the fits  $\kappa \sim T^{5/2}$  and  $P_R \sim T^{-1/2}$  represent the best available fits for temperatures cooler than about  $2 \cdot 10^7 K$ . Therefore, one obtains the same scaling factors as before; and Table 1 can also be used to scale numerical models of large loops with or without flows, such as the static models of Serio et al. (1981). Only for extremely hot loops the scaling factors must be modified due to the changed temperature dependence of  $P_R$ . Such a modification is, however, only possible when  $\kappa$  and  $P_R$  are not coupled together; i.e., when flows can be neglected.

Coronal loops that are larger than the coronal pressure scale height, but smaller than the stellar radius, do not depend on  $M$  and  $R$  separately, but only on  $g \approx \text{const}$ . Hence, such loops depend on only one stellar parameter; and the two degrees of freedom which we have previously used to choose  $M$  and  $R$  can now be used to specify the star and one other quantity, such as the heating flux. The scaling properties of a special type of such loops have been discussed by Landini and Monsignori Fossi (1981).

Loops smaller than the coronal pressure scale height, finally, are independent of  $g$ . For static loops of constant cross section, Rosner et al.

(1978) derived two so-called scaling laws,

$$T_m \sim P_{TR}^{1/3} S^{1/3} \quad \text{and} \quad F_{MO} \sim P_{TR}^{7/6} S^{1/6} \quad (3)$$

which were later generalized to large loops (Serio et al. 1981). Curiously, the "scaling laws" are invariant with respect to the scaling transformation; therefore, they can be applied to other stars without scaling.

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#### DISCUSSION

Mullan: Have you applied your scaling laws to cool giants? Can you explain the dividing line between solar-like coronae and non-solar-like atmospheres (Linsky and Haisch)?

Hammer: I have tried to apply my numerical models of open coronal regions to stars other than the Sun by means of this scaling transformation. However, I do not think that they can be applied to the giants and supergiants near the dividing line because pressure, energy flux, and mass-loss rate scale so rapidly with the stellar radius that one obtains totally unreasonable values of these quantities when one scales my models to stars with small  $g$ . This probably confirms the general view that the winds of red giants are not thermally driven. I believe that this is not only true for the red giants beyond the dividing line, but also for the "solar-like" stars close to the dividing line.

## OVERHEATED OPEN CORONAL REGIONS

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### INTRODUCTION

The open corona of the Sun and of similar stars is usually thought of as a hot, virtually infinitely extended plasma which can be described as time-independent, at least on a large scale. Recently, however, model calculations (Hammer 1982; Hearn and Vardavas 1981; Souffrin 1982) have shown that this classical picture must break down when the coronal heating flux  $F_{M0}$  exceeds a certain limit, which depends on the characteristic damping length  $L$  over which the energy is dissipated in the corona.

As one approaches this limit, both the maximum coronal temperature  $T_m$  and the base pressure  $p_{TR}$  of the transition region are found to increase. For intermediate damping lengths ( $L \approx 10^{-1}R$ ), this leads to a rapid increase of the wind energy losses, which occur on a characteristic scale height of the order of the stellar radius  $R$ . For very small damping lengths ( $L < 10^{-2}R$ ), on the other hand, wind losses are unimportant (Hammer 1982), but the increase of the base pressure leads to increasing radiative losses of the corona. In both cases,  $L$  is so small that the energy losses of the outer regions cannot be supplied by direct mechanical heating, but only by outward thermal conduction. This necessitates a steep temperature gradient; the temperature of the outer regions must decrease and finally reach chromospheric values when the heating flux exceeds the critical value. The decreasing temperature of the outer layers implies an increasing radius of the critical point. Ultimately, the wind is switched off. Therefore, "overheated" coronae tend to collapse into compact, hydrostatic coronal shells.

A numerical model of such a shell was presented by Hearn and Vardavas (1981), who solved the conservation equations by an iterative finite difference technique. Later, Hearn et al. (1983) found that this model was not yet converged, but that the iteration exhibits an oscillatory behavior. From this they speculated that a real overheated corona might be subject to a relaxation oscillation, in which periodically an extended corona forms at greater heights and moves inward because excess thermal conduction evaporates chromospheric material. Then the extended corona swallows the coronal shell to form a single extended corona, the outer parts of which collapse to form a new coronal shell; etc.

In any case, before we can understand the physics of overheated coronae, we must understand the physics of compact coronal shells, which appear to be a building block of overheated coronae, at least temporarily. Therefore, I computed a large number ( $\approx 150$ ) of hydrostatic shells for the usual exponential heating law with constant damping length. The boundary conditions were that on both sides of a shell the conductive flux at chromospheric temperatures is small. The boundary value problem was solved with a shooting technique. The main goal of the calculations was to determine the dependence of the shells on  $F_{M0}$  and  $L$ ; in particular, I wanted to localize the boundary line in the parameter space  $(F_{M0}, L)$  that separates normal extended coronae from coronal shells.

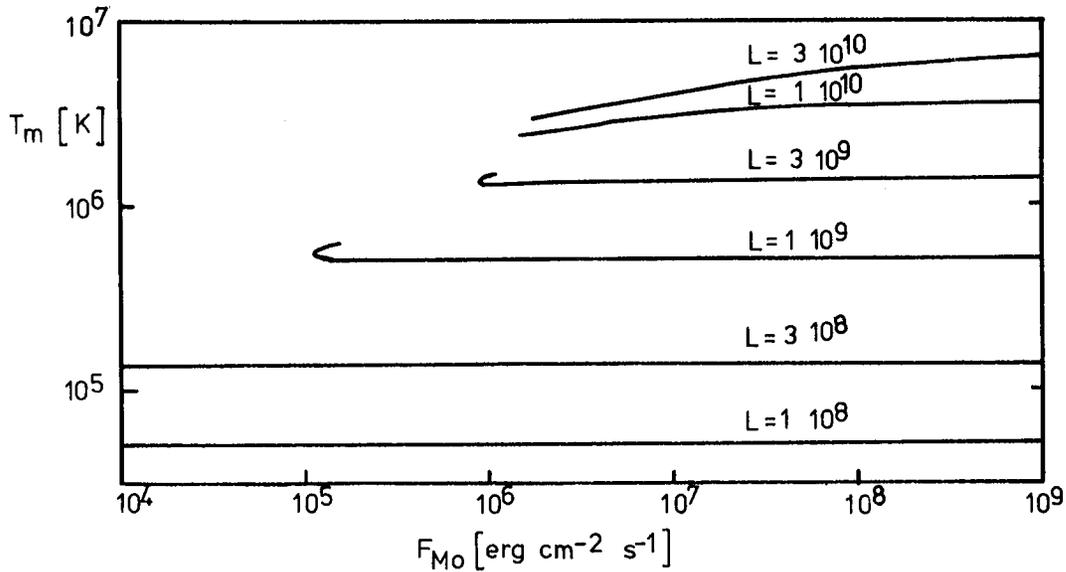


Figure 1. Maximum temperature

## RESULTS

The results can be summarized as follows. With increasing heating flux the shells have larger base pressures, they become thinner and use up a smaller fraction of the available energy, but the maximum temperature remains essentially unchanged (cf. Fig. 1). With increasing damping length the base pressure increases, too; but now the shells become thicker and hotter (Fig. 1), and their energy consumption increases. Particularly small shells (i.e., for small  $L$  and large  $F_{Mo}$ ) show the following asymptotic behavior, which can be verified analytically: The maximum temperature is proportional to  $L$ ,  $T_m = 5.2 \cdot 10^{-4} L$ . The base pressure increases with the heating flux ( $\sim F_{Mo}^{1/2}$ ), whereas the relative changes of the pressure and energy flux within the shell decrease ( $\sim F_{Mo}^{-1/2}$ ).

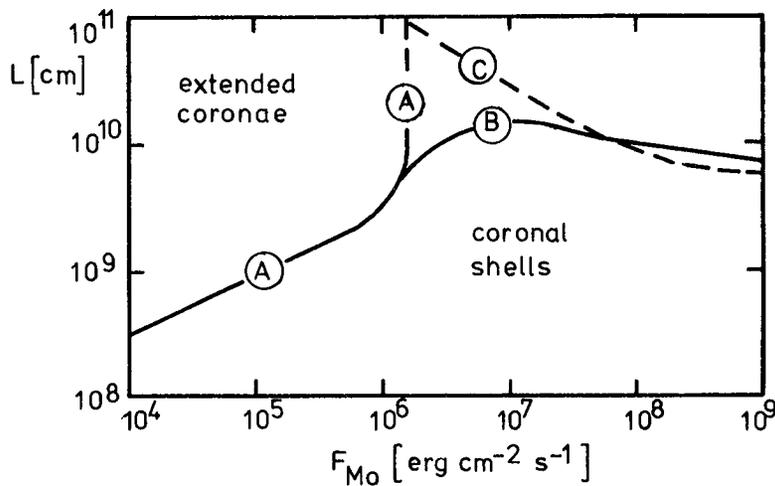


Figure 2. Parameter space

Figure 2 gives an overview of the parameter space covered by the present calculations (for solar mass and radius). Hydrostatic coronal shells exist below and to the right of line A; whereas the models of extended coronae that I had computed earlier (Hammer 1982) lie above this line. The shells are uniquely determined by the specification of  $F_{M0}$  and  $L$ ; except very close to the dividing line, where sometimes two or three shell solutions exist (see also Fig. 1). The shells above line B are so extended and/or hot that the inclusion of a wind in the calculation would very likely lead to additional extended solutions.

The location of a coronal shell is determined by the energy balance of the atmosphere. In the chromosphere, the emission is balanced locally by the dissipation of some kind of "mechanical" energy flux; therefore, the total mechanical flux  $F_M$  decreases with increasing height and thus decreasing pressure. This is schematically shown in Fig. 3. As was discussed by Hammer and Linsky (1984), the transition region must lie at the intersection point (point 1 in Fig. 3) of the curve  $\log F_M$  ( $\log p$ ) with a second curve,  $\log F_{M0}$  ( $\log p_{TR}$ ), which describes the relationship between the pressure and the total mechanical energy flux at the base of the transition region. As mentioned above, the latter curve has an asymptotic slope of about 2 for coronal shells. The slope of the former curve, on the other hand, is much smaller: Theoretically reasonable values lie between 0, for no dissipation in the upper chromosphere, and 1, for the particularly rapid dissipation of acoustic waves. From empirical chromosphere models one finds an average slope of about 1/3 (cf. Hammer and Linsky 1984).

Within the coronal shell, both the mechanical energy flux and the pressure must decrease by certain amounts. If the ratio of these changes is larger than the slope of the coronal curve, then the top of the shell is located below the coronal curve in Fig. 3, for example at point 2. This means that above the coronal shell there exists cool chromospheric material, which is characterized by the curve with the flat slope. Consequently, both curves intersect again (at point 3); therefore, we obtain a second coronal shell.

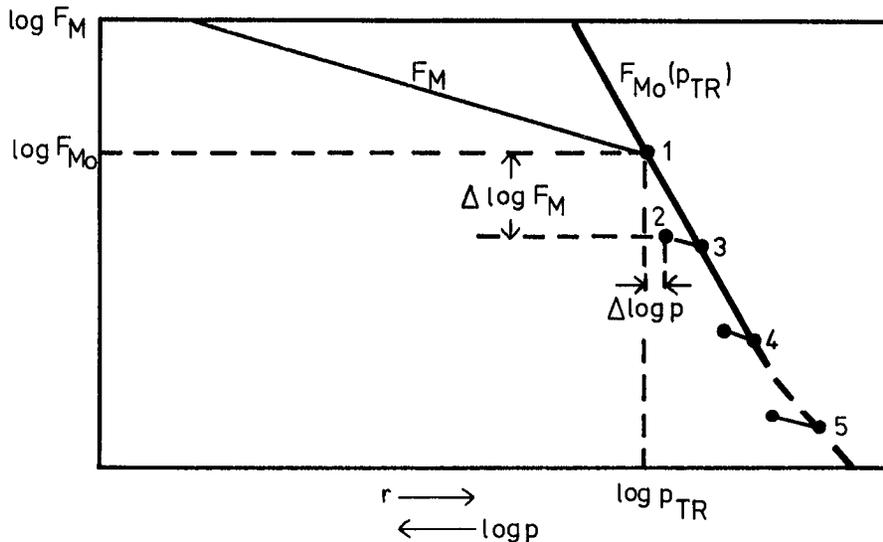


Figure 3. Location of coronal shells

This procedure is repeated until, finally, the remaining energy flux is so small that we leave the domain of overheated coronae (cf. Fig. 2) and obtain a normal, infinitely extended corona (point 5).

Therefore, as long as the ratio  $\Delta \log F_M / \Delta \log p$  of the logarithmic energy flux and pressure changes within the shell is larger than the slope  $d \log F_{M0} / d \log p_{TR} \approx 2$  of the coronal curve, the overheated corona problem has a stationary solution that consists of one or several compact shells, topped by an extended corona. In Fig. 2, only the shells above line C and some of the non-unique shells near line A do not fulfill this condition. (However, these shells are so extended that the dependence of the coronal curve on the radius of the base of the transition region begins to become important. Therefore, the condition for multiple shells must be modified for these extended shells). In the remaining part of the parameter space there exist stationary equilibrium solutions which consist of multiple coronal shells and an extended corona. This does not mean that relaxation oscillations are not possible, but they are not necessary in this part of the diagram.

Unfortunately, in this contributed paper it is not possible to discuss the very interesting aspects of the stability of coronal shells and to speculate about the astronomical objects that may possess overheated coronae. This will be done elsewhere (in preparation). I acknowledge support by the Deutsche Forschungsgemeinschaft.

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#### DISCUSSION

Hearn: Have you obtained a scaling law for the maximum mechanical flux for which an extended corona is possible?

Hammer: The maximum flux depends on the damping length  $L$ . For large  $L$ , it is somewhat larger than  $10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$  in the case of the Sun. According to the other paper I presented at this meeting, the maximum energy flux must be multiplied by  $(M/M_\odot)^{7/2} (R/R_\odot)^{-9/2}$ , and the damping length must be multiplied by  $(R/R_\odot)$  when we go to stars other than the Sun.

Rybicki: The energy deposition law you have chosen falls off exponentially with height with a fixed scale height. However, it seems to me that the energy deposition might react strongly to the multiple coronal structures you are forming. Might a different law, for example depending on mass column density, give essentially different results?

Hammer: Generally, I think that not enough is known yet about the heating mechanism(s) of open stellar coronal regions to say that any other heating law is more realistic than the one I used. For the multiple shell coronae, I assumed constant damping length only for the hot parts ( $T > 20,000$  K); for the cool chromospheric parts I used the heating law  $F_M \sim p^{1/3}$  derived from empirical chromosphere models. As for the hot parts, I do not think that a change of the heating law would change my results significantly, for the following reasons: First, in the case of extended coronae I have shown that one obtains essentially the same solutions for an exponential and for other heating laws. Second, as I mentioned, Hearn and Vardavas found similar compact coronal shells for a shock heating law, in which the heating depends not only on height, but also on temperature and density. Finally, Souffrin confirmed the existence of an upper limit of the heating flux even for an analytical two-component corona model.

Uchida: I was thinking of asking a question similar to that by Dr. Rybicki. The formation of the cool part is related to the thermal instability modified by heat conduction, but in order to radiate away the heat conducted into that region, you have to have a condensation of density by a large factor in a short time, introducing a highly dynamic situation. Is it covered by your treatment, and also is your damping law with a constant damping length applicable to these situations?

Hammer: I have only treated the time-independent problem. My heating law and my results refer only to that case. I agree with you that time-dependent phenomena are extremely interesting. This applies not only to the formation of such shells, perhaps by a thermal instability as you mentioned, but also to their eventual destruction by other kinds of instabilities. I am working on such problems.

CO-ROTATING INTERACTION REGIONS IN STELLAR WINDS: PARTICLE ACCELERATION  
AND NON-THERMAL RADIO EMISSION IN HOT STARS

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ABSTRACT

A co-rotating interaction region (CIR) forms in a stellar wind when a fast stream from a rotating star overtakes a slow stream. CIR's have been studied in detail in the solar wind over the past decade primarily because they are efficient sources of particle acceleration. Here, we point out the usefulness of CIR's in OB Star winds to explain two properties of such winds: deposition of non-radiative energy in the wind far from the stellar surfaces and acceleration of non-thermal particles.

INTRODUCTION

Stars emit wind with a velocity which is not in general spherically symmetric. The origins of departure from spherical symmetry are not known, but magnetic fields probably play some role. Since all stars rotate, it is possible for faster wind to catch up with slower wind and form an interaction region which co-rotates with the star. CIR's have been the subject of extensive study for the past decade in the solar wind, mainly because they act as sources of energetic charged particles. When a CIR is fully developed, it consists of a forward shock, a stream-stream interface, and a reverse shock. The shock pair separates in time: at radial distance  $r$ , the separation of the shock pair is typically  $0.1r$  in the solar wind.

A detector passing through a CIR in the solar wind records variations in density, temperature, and velocity as shown schematically in Figure 1. The non-linear development of the interaction creates a velocity plateau between the forward and reverse shocks (Hundhausen, 1973). The velocity plateau remains well-defined as the CIR propagates out through the wind (Holzer, 1979). The density has a marked peak while the velocity is passing through its plateau.

The temperature profile in a solar wind CIR is observed to be complicated. Particle acceleration at the shocks suggests (Smith and Wolfe, 1977) that MHD turbulence is enhanced there. The detailed temperature structure in the CIR depends on how this turbulence is dissipated. Model calculations of non-turbulent CIR evolution (Hundhausen, 1973) suggest that strong cooling is expected to occur in the CIR as it evolves. The dashed lines in Fig. 1 are meant to indicate that this prediction may be modified in particular cases. However, the

temperature jumps in the immediate vicinity of the shocks can be predicted reliably.

For the case of stellar observations, the most readily detectable features of CIR's are the velocity plateau and the shock heating. We have proposed (Mullan, 1984) that narrow absorption features observed in the spectra of various types of stars, with associated enhanced levels of ionization, are formed when light from the central star passes through the CIR on the line of sight. Here we discuss the role of CIR's in heating distant regions of OB star winds and accelerating particles.

### Velocities in CIR's

Narrow absorption features are observed in OB stars at velocities which are typically 0.7 times terminal speed  $v_t$  (Lamers et al, 1981). If these features are due to CIR's then the velocity jump at a CIR shock in such stars ( $v_{t3} \approx (1-3) \times 10^3$  km/sec) is  $\approx 300-1000$  km/sec. Finite lifetimes of the narrow absorption features can be ascribed to propagation time-scales of the CIR's through the wind: in the outlying regions of the wind, the CIR velocity remains essentially unchanged, but the column density along the line of sight ( $\propto r^{-3}$ ) eventually falls below detectability.

### Deposit of Non-radiative Energy in the Wind

At a shock where the velocity jump is  $\Delta v$ , the Rankine-Hugoniot relations predict the temperature jump. In the limit of a strong shock, with  $\gamma = 5/3$ , we find  $\Delta T \approx (\mu/3R_g) (\Delta v)^2$ , where  $\mu$  is the mean molecular weight, and  $R_g$  is the gas constant.

In OB stars, this yields  $\Delta T \approx (2-20) \times 10^6$  K, in the immediate vicinity of the CIR shocks. These temperatures are sufficient to make the CIR's acts as sources of X-rays. This is an alternative to the Lucy-White mechanism of X-ray emission from "blobs" in the winds. Moreover, enhanced temperatures in CIR's explain why the ionization level is higher in the narrow absorption components (Lamers et al, 1982). However, appreciable cooling in the CIR is required if lines of OVI, NV, CIV and SiIV are to be observed.

### Distance of CIR Formation

Kinematic arguments can be used to show that CIR's form at a radial distance  $r_i$  which is related to the stellar radius  $R_*$  by  $r_i/R_* \approx v_0/v_r =$  wind speed/rotational speed (Mullan, 1984).

Stars have  $(v_0/v_r)$  ratios which may be much smaller than the solar value (200). Hence, CIR's are predicted to form much closer to the surfaces of other stars than in the solar wind. In OB stars, with  $v_0 \approx (1-3) \times 10^3$  km/sec and  $v_r \approx (1-3) \times 10^2$  km/sec,  $v_0/v_r$  is typically smaller than solar by an order of magnitude. In such stars,

CIR's should form at a few tens of stellar radii. At such radii, CIR's have sufficient emission measure to account for much of the Einstein X-ray emission in, say,  $\zeta$  Puppis (cf. Mullan, 1984). We note that White and Becker (1983) have observed radio emission from a hot star which seems to require excess heating of the wind at many tens of stellar radii from the star. We propose CIR's as the origin of such excess heating in an otherwise (comparatively) cool wind.

### Particle Acceleration in CIR's

Fisk and Lee (1980, hereafter FL) have discussed particle acceleration in CIR shocks in terms of a diffusion coefficient  $K$  and a shock jump parameter  $\beta = (V_d^2 + \Omega^2 r_s^2)^{1/2} B_u / (V_u^2 + \Omega^2 r_s^2)^{1/2} B_d$ . Subscripts  $u$  and  $d$  refer to upstream and downstream,  $B$  is magnetic field strength,  $V$  is wind speed,  $r_s$  is the distance of the shock from the star, and  $\Omega$  is the angular velocity of the star. In OB star winds,  $r_s \approx$  several tens of stellar radii ( $R_*$ ). Since  $R_* \approx 0.1 v_t$  in these stars,  $\Omega r_s > v_t$  i.e.  $\Omega r_s$  exceeds  $V_d$  or  $V_u$ . Hence  $\beta \approx B_u/B_d$ . If the shock is strong,  $\beta \approx 1/4$  (assuming  $\gamma = 5/3$ ).

FL consider two forms for  $K$ . First  $K = K_0 v r$ , where  $v$  is particle speed,  $r$  is radial distance in the wind and  $K_0$  depends on the spectrum of magnetic turbulence in the wind. With  $\beta = 1/4$ , the velocity distribution  $f(v)$  of the particles accelerated in the shock turns out to be

$$f \sim v^{-4} \exp(-v/v_0)$$

where  $v_0 = 3V/8K_0$ . A distribution function of exponential form fits solar wind data from CIR's quite well, with characteristic cut-off velocities  $v_0 \approx (1-2) \times 10^9$  cm/sec (corresponding to proton energies of order 1 MeV). We have no way of knowing how  $K_0$  behaves in the winds of other stars. (Its value can be evaluated in the solar wind to a fair approximation by in situ measurements of the magnetic power spectrum.) Suppose, however, that  $K_0$  is the same in the stellar wind as in the solar wind. Then in OB star winds, where wind speed  $V$  can be up to 3000 km/sec, i.e. up to ten times the normal solar wind speed, we expect  $v_0$  to be  $\approx 10$  times larger than in the solar wind. Hence in OB star winds, the exponential cut-off of the proton spectrum would occur at velocities close to the speed of light, i.e. at energies of 100-200 MeV.

The second form of  $K$  suggested by FL is  $K = Vr/2$ , with particle injection at velocity  $v = v_0$ . Then at high energies, FL find

$$f(v) \sim v^{-16/3}$$

The differential energy spectrum  $j \propto v^2 f(v)$  has the form  $v^{-10/3}$  in this case, i.e.,  $E^{-5/3}$  (for non-relativistic particles; FL discuss only such particles). This spectrum is quite hard, and again suggests that appreciable fluxes of highly energetic particles will be accelerated in the winds of OB stars.

Abbott (1984) has reported the detection of radio emission from several OB and Wolf-Rayet stars which is definitely non-thermal. We propose that the source of the non-thermal radio emission is particles accelerated in CIR shocks in the winds.

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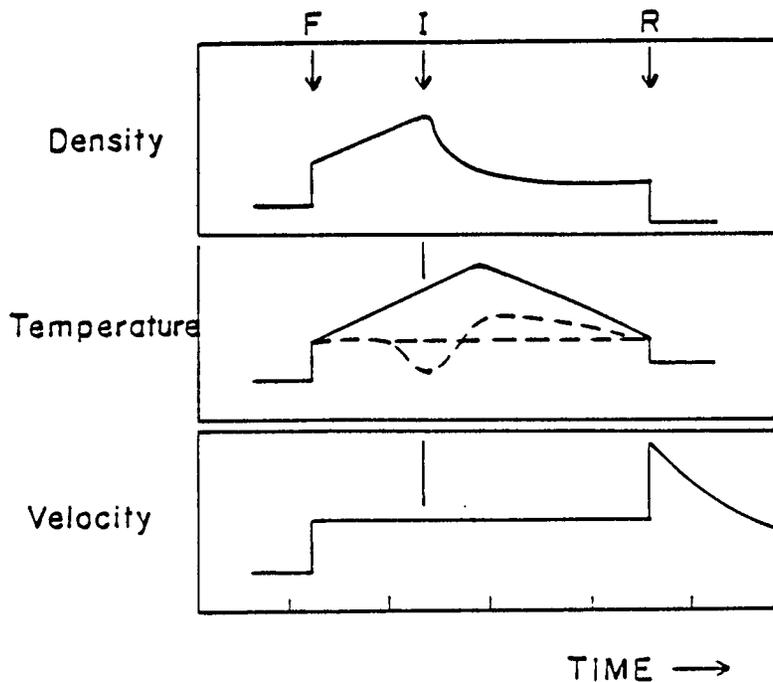


Fig. 1 Variations of solar wind parameters as CIR sweeps past a spacecraft (courtesy of E.J. Smith). The spacecraft, initially in slow wind, is overtaken by F, a forward shock. I is the interface between fast and slow wind, where density has a maximum. R is a reverse shock where the spacecraft emerges into the fast wind. Particle acceleration is observed to be most efficient at F and R.

## DISCUSSION

Underhill: You postulate that there are two different kinds of winds, namely fast streams and slow streams. This means that there are at least two different kinds of starting areas on or near the surface of the star. To define different areas (spots) on the disk of the star you have to consider magnetic fields. Magnetic fields are the only available agent which has a local definition.

Mullan: I agree that magnetic topology may be a reasonable explanation for the existence of flows of different velocities from different points of a star.

Friend: Why should the velocity in the corotating interaction region be a constant? Why couldn't it vary smoothly between shocks?

Mullan: The plateau occurs as the interaction evolves into its nonlinear phase. At first, when interaction begins, the velocity changes by a sharp jump but a pair of shocks emerges from the interaction to help the slow and fast streams adjust to one another. Eventually, the non-linearities dominate the development.

Underhill: In your theory you emphasize the creation of high temperature plasma,  $10^7 < T < 10^8$  K, in interaction regions between fast and slow streams. Such regions will generate X-rays but not the ions which give the usually observed optical lines. For them you need  $10^4 < T < 10^7$  K. The theory of Underhill and Fahey (1984) concentrates on accounting for the fast and slow streams containing plasma with  $10^4 < T < 10^5$  K. Our two concepts are complementary.

Mullan: In CIR's, shock heating does lead to temperatures of up to  $10^7$  K in the immediate vicinity of the shocks. But in CIR's the temperature may cool significantly between forward and reverse shocks due to expansion, radiation, etc. Calculations by Hundhausen (J.G.R. 1973) show strong cooling inside the CIR's. Therefore, temperatures  $\sim 10^5$  may be present in the CIR's of hot stars.

Uchida: If you hold the picture of the interaction of two streams, one catching up with the other, I am afraid that Dr. Underhill's objection may apply. Namely, in the off-equatorial zones the two helices with different velocity may not cross. The mechanism you are proposing may then reduce to that in which the fast stream thrusts into the amorphous shell.

Castor: This paper is persuasive about the virtues of a shock model for OB stars, for getting X-rays and non-thermal particles (producing non-thermal radio emission). There are lots of ways of getting shocks. The colliding streams are good for giving stronger shocks than the Lucy-White model can. The only problem is explaining the 2:1 range of stream speed needed. The observed P-Cygni profiles support only a 10-15 % range of speeds.

Mullan: A ratio 2:1 for  $v_{\text{fast}}/v_{\text{slow}}$  has been assumed for our kinematic estimates. But this is not necessary. Even if the velocity contrast is 10-15 %, i.e. several hundred  $\text{km s}^{-1}$ , this is still sufficient to create shocks in the CIR's. The radius of the onset of interaction will change somewhat if the velocity contrast is only 10-15 %.

Praderie: In at least one star I showed yesterday (AB Aur, Herbig Ae star) we have found that the terminal velocity varies with time by a factor 2 (from  $260 \text{ km s}^{-1}$  to  $520 \text{ km s}^{-1}$ , see Praderie *et al.* 1984; in Space Research Prospects in Stellar Activity and Variability, Meudon, eds. A.Margeney and F. Praderie, in press).

Underhill: The theory of Underhill and Fahey accounts for  $v$  (discrete component) being less than  $v_{\infty}$ . It postulates that the material forming the discrete components is released higher in the mantle than is most of the wind material. Therefore, the material suffers less acceleration because with the usual velocity laws most of the acceleration occurs very near the photosphere. The photosphere seems to be the place of origin of most of the wind.

Mullan: My model indeed places discrete components far out in the wind. In the very farthest reaches of the wind, CIR's run together and so cannot be distinguished as separate components as  $v \rightarrow v_{\infty}$ .

Cassinelli: Lucy has pointed out that the shortward edge of P-Cygni line profiles is not sharp. This indicates that there is not a sharp unique terminal velocity but a spread of at least several hundred  $\text{km s}^{-1}$ .

# SYNCHROTRON EMISSION FROM CHAOTIC STELLAR WINDS

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## ABSTRACT

A new model is presented for the radio emission from hot stars. Electrons are accelerated to relativistic energies by shocks in the wind near the star and emit radio radiation through the synchrotron mechanism. The particle energy spectrum and radio spectrum for this model are derived; the model can account for many of the observed characteristics of some recently discovered stars which have peculiar radio emission.

## I. INTRODUCTION

Radio emission from hot stars has been studied for more than ten years and usually has been interpreted as free-free emission from the massive ionized winds surrounding these stars (Wright and Barlow 1975; Panagia and Felli 1975). Recent observations have cast doubt on this interpretation for some stars (Castor and Simon 1983; Abbott, Telesco, and Wolff 1984; White and Becker 1983; Abbott, Biegging, and Churchwell 1984, hereafter ABC). These observations suggest a nonthermal origin for the radio emission from some early-type stars (Abbott, Biegging, Churchwell, and Bignell 1982; ABC). ABC propose that the radio emission from such stars comes from accretion onto an unseen, compact companion; however, they point out some difficulties with that hypothesis.

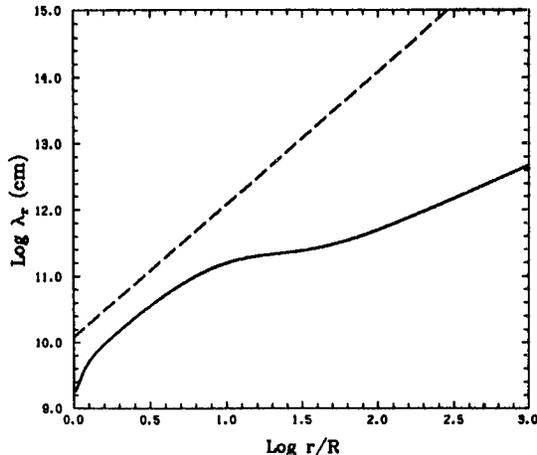
This paper presents a new model in which nonthermal radio emission is produced by the stellar wind. Since no companion is required, it is not subject to the same objections as the binary hypothesis. The model is described in §II, §III compares the theory to observations, and §IV summarizes the results. A more detailed discussion of the model and the results can be found in a forthcoming paper (White 1984).

## II. THEORY

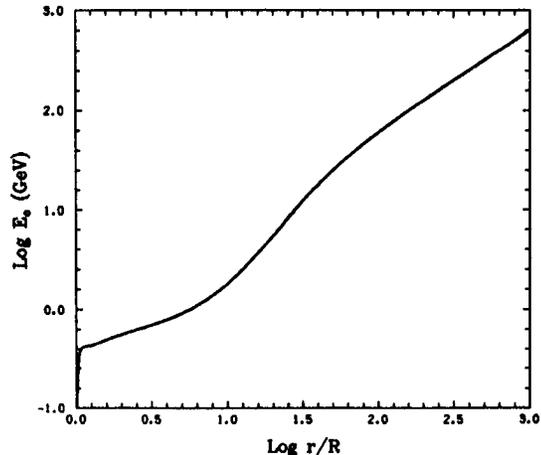
The winds of O and B stars are radiatively driven (Lucy and Solomon 1970) and are subject to instabilities (Lucy and Solomon 1970, Hearn 1975, Carlberg 1980, Owocki and Rybicki 1984). Lucy and White (1980) and Lucy (1982b) suggested that the instabilities lead to chaotic stellar winds with embedded shocks, large density variations, and velocities which do not monotonically increase with radius. They developed models for chaotic winds and argued that the observed X-rays from hot stars are generated by shocks in the winds. This model for the production of X-rays in hot stars has received observational support from several directions (Long and White 1980, Cassinelli and Swank 1983, Lucy 1982a, Lucy 1983).

Thus, there is now considerable observational and theoretical evidence that stellar winds have embedded shocks. Shocks can accelerate particles to relativistic energies (Bell 1978; Blandford and Ostriker 1978). However, stellar winds contain a network of embedded shocks; consequently, to calculate the particle spectrum we must consider not only particles which are accelerated by a single shock but also particles which undergo many shock encounters, each of which further accelerates the particles. There are two length scales which are important for particle acceleration by multiple shocks: the mean free path for high energy particles and the distance between shocks in the wind.

The diffusion of high energy particles in a stellar wind is limited mainly by irregularities in the magnetic field embedded in the wind (Völk and Forman 1982) and consequently is very complicated in a chaotic wind. Fortunately, there are reasonable approximations which greatly simplify the calculation of the mean free path. White (1984) derives the mean free path which is used in this paper; the particular expression used affects the qualitative results only weakly, but probably does affect the quantitative results.



**Fig. 1** — *Solid line*: the mean free path for scattering in the radial direction for 100 GeV particles in a stellar wind with  $B_* = 1$  G,  $V_\infty = 2500$  km/s, and  $V_{rot} = 250$  km/s. *Dashed line*: the separation between shocks as a function of radius for the same wind if  $R = 35 R_\odot$ ,  $a = 25$  km/s, and  $\eta = 0.5$ .



**Fig. 2** — Energy where diffusion between shocks cuts off acceleration for particles. Model parameters are the same as for Figure 1.

Throughout the stellar wind the mean free path for diffusion in the radial direction,  $\lambda_r$ , is a very small fraction of the radius. Figure 1 shows that  $\lambda_r(r)/r$  is less than 0.01 even for particles with energies of 100 GeV. As a consequence, high energy particles are effectively frozen into the wind.

The mean free path is also short compared to the distance between shocks derived by Lucy (1982b) (Fig. 1). However, because the mean free path increases with energy, particles with high enough energy can diffuse from shock to shock, which renders the shocks ineffective for further acceleration. Figure 2 shows as a function of radius the critical energy beyond which particles cannot be accelerated.

Even particles which are frozen in the wind pass through many shocks as they are carried away from the star. Using Lucy's (1982b) model, we find that each piece of wind material encounters about 20 shocks as it flows from the star.

The particle momentum spectrum after a single shock is a power law  $N(p) \propto p^{-\mu}$ , where  $\mu$  depends on the compression ratio  $\chi$  for the shock:  $\mu = (\chi + 2)/(\chi - 1)$  (Bell 1978; Blandford and Ostriker 1978). For a strong shock,  $\chi = 4$  and  $\mu = 2$ . Each subsequent shock encounter flattens the spectrum; in the limit of many shocks we find that

$$N(p) \propto p^{-1}. \quad (1)$$

The shape of the spectrum in equation (1),  $p^{-1}$ , is independent both of the momentum of the injected particles and of the compression ratio for the shocks. Consequently, it is a "universal" spectrum toward which all multiply shocked particle spectra will tend. The particle spectrum in the wind will be  $\propto p^{-1}$  up to a cutoff determined by the diffusion length. Far out in the wind, the spectrum drops as  $p^{-2.6}$  beyond the cutoff.

The total number of particles present can be set from the requirement that the particle pressure not exceed the postshock gas pressure; otherwise the shock is not able to accelerate any particles (Eichler 1979). Requiring the particle pressure to be equal to the

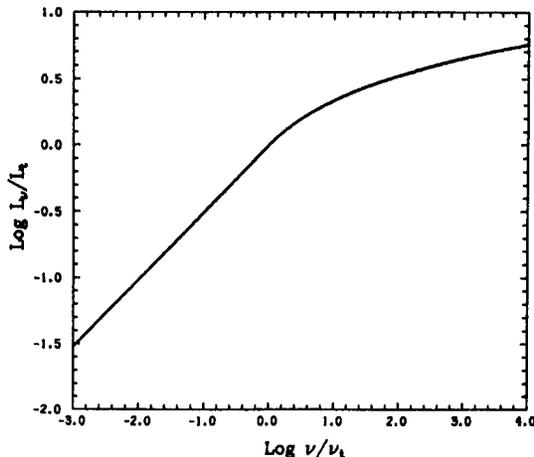


Fig. 3 — Synchrotron spectrum for shock-accelerated particles in a stellar wind.

postshock pressure is reasonable because there are so many shocks to pump energy into the particle distribution. From these considerations one can completely determine the particle spectrum as a function of radius (White 1984).

Given the particle spectrum, we can calculate the synchrotron spectrum produced by a stellar wind. The synchrotron optical depth of the wind is small; however, the free-free optical depth of the wind is large and varies strongly with frequency. As a result, the wind synchrotron spectrum is very different from that observed for optically thin synchrotron sources ( $L_\nu \propto \nu^{-1}$ ). For the cut off  $p^{-1}$  spectrum described above, the radio spectrum can be shown to be

$$L_\nu = \begin{cases} L_t \left( \frac{\nu}{\nu_t} \right)^{0.51}, & \nu < \nu_t \\ L_t \left( 1 + 0.51 \ln \frac{\nu}{\nu_t} \right), & \nu > \nu_t, \end{cases} \quad (2)$$

where  $L_t \simeq 6 \times 10^{19}$  ergs/s ( $\dot{M}/2 \times 10^{-5} M_\odot/\text{yr}$ ) and  $\nu_t$  is a complicated and strong function of many of the model parameters. This spectrum is displayed in Figure 3.

Several features of the wind synchrotron spectrum are notable. The low frequency spectrum is very similar to the thermal free-free spectrum for a stellar wind:  $L_\nu \propto \nu^{0.60}$  (Wright and Barlow 1975, Panagia and Felli 1975). It may not always be easy to determine from the radio spectrum which mechanism is producing the radio emission for a particular star. Another interesting feature of the spectrum is that the luminosity at the turnover frequency is almost entirely determined by the mass loss rate  $\dot{M}$ . On the other hand,  $\nu_t$  depends strongly on all the model parameters including the stellar magnetic field, which is very difficult to determine observationally.

### III. COMPARISON WITH OBSERVATIONS

In general, the model is quite successful at accounting for the observed properties of Cyg OB2 No. 9 (ABC). First, the fluxes predicted by the model are quite similar to those which have been observed. Second, the model spectrum is flat at high frequencies and steepens to  $\nu^{0.5}$  at low frequencies. Third, the flat high frequency synchrotron spectrum contributes very little infrared emission, so the infrared spectrum is dominated by thermal emission from the wind. Fourth, the emission is compact and cannot be resolved by the

VLA at 6 cm. Fifth, small changes in the model parameters can cause large changes in  $\nu_t$ , which can lead to large variations in the radio flux. The stellar magnetic field required to produce the observed  $\nu_t$  is about 5 Gauss, which seems a plausible value for a hot star such as Cyg OB2 No. 9.

The fluxes predicted by the model are larger than those observed for Cyg OB2 No. 9 by a factor of a few. However, there are effects which might reduce the fluxes by a factor of 2 or 3 without changing the shape of the spectrum very much.

The wind synchrotron model has more difficulty accounting for ABC's observations of 9 Sgr, which has a spectrum which is falling with frequency ( $F_\nu \propto \nu^{-0.3}$ ). The spectrum in equation (2) cannot fit a falling spectrum, so this must indicate some deficiency in the model. On the other hand, the model spectrum is asymptotically flat for  $\nu \gg \nu_t$ , so it appears likely that a similar model can produce a slowly falling spectrum.

#### IV. CONCLUSIONS

This paper describes how the acceleration of relativistic electrons by shocks in the winds of hot stars can lead to observable synchrotron radio emission. Even though the synchrotron emission is optically thin, the radio spectrum is flat (for  $\nu$  large) or rising with frequency (for  $\nu$  small) because the free-free optical depth of the wind is large and depends strongly on frequency. The model spectra agree fairly well with observations of two stars whose radio spectra are inconsistent with the usual thermal free-free spectrum for a stellar wind; the synchrotron spectrum can also look disquietingly similar to a thermal wind spectrum, so that it may not always be easy to distinguish them.

The model presented in this paper does have some failings when compared to the observations. In particular, it is difficult to generate a spectrum which falls slowly with frequency, as has been observed for one star. This could probably be remedied by a more sophisticated model; the results presented here are encouraging enough to warrant further elaboration of these ideas.

The model makes several predictions which can be tested against future observations:

- (1) Nonthermal wind sources should not vary faster than the wind flow timescale and should vary more slowly at low frequencies than at high frequencies.
- (2) Most stars with rising non-thermal spectra will not be resolved by the VLA, but some flat spectrum sources might be resolvable.

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## DISCUSSION

Mullan: How do you estimate scattering lengths of particles in the winds?

R.L. White: I used a mean free path similar to that suggested by Volk and Forman (1982, Ap.J. 253, 188). The magnetic field fluctuations  $\delta B/B$  are assumed to be near unity so that the mean free paths are a few gyral radii.

Cassinelli: I have two questions: (1) The radio emission comes primarily from regions within  $10 R_*$  of the base. Would there not be the same problem in getting the radiation out that we discussed yesterday? At that time, you may recall that I appealed to a cactus picture. (2) The particle pressure is large. Could this provide lateral pressure to support streams? The other strong pressures in the wind are primarily radial. The particle pressure has a component tangential to the streams.

R.L. White: (1) The radio emission from the star comes from far out in the wind (outside the point where the free-free optical depth is equal to 1) so there is no need to see down to the surface of the star. (2) I had not previously thought about this, but it is conceivably important.

Abbott: I have two questions: (1) Do you expect the emission to exhibit polarization? (2) Is it correct that your mechanism gives variability by having the  $B$  field turn on and off?

R.L. White: (1) If the magnetic field fluctuations are large (see the answer to Mullan's question) then the random variations in the field direction would tend to average out any polarization. Also the wind rotation measure is very large, which depolarizes the emission. (2) Yes, although only small variations in the  $B$  field (or other parameters) are required. The dependence on all the parameters (including the mass loss rate, the terminal velocity, etc.) is strong, so any of them could cause the emission to vary.

Underhill: An upper limit is set to the spherically symmetric  $\dot{M}$  which may be assigned to a star by the fact that if one sees a normal absorption-line spectrum one must be able to see through to the photosphere. This means that  $\tau_{el. scat.} < \sim 0.25$ . (In a spherical atmosphere, the characteristic optical depth at which the source function equals the emergent flux is about 0.25 to 0.30.) Typically,  $\dot{M}$  should not exceed about  $2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$  or  $\tau_{el. scat.}$  becomes too large.

R.L. White: For Cyg OB2 No. 9,  $\dot{M} = 2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$  leads to  $\tau_{el. scat.} \sim 0.1$  (for  $R = 35R_{\odot}$ ,  $v_{\infty} = 2650 \text{ km s}^{-1}$ ). Your comment may be correct, but it does not seem to be relevant for any O star. Some Wolf-Rayet stars have larger mass loss rates, so that  $\tau_{el. scat.} > 1$ . However, they certainly do not show normal absorption-line spectra. That would seem to support the idea of large mass loss rates for WR stars.

Underhill: Have you ever considered the fact that in Wolf-Rayet spectra the regions where the absorption lines characteristic of O and B type spectra occur are masked by wide, strong emission lines from the mantle of the star. This is sufficient reason for one not to see a "normal" absorption-line spectrum for most Wolf-Rayet stars. Some Wolf-Rayet stars do show OB absorption lines shortward of 4000 Å where the emission lines are weak on the whole.

Sreenivasan: The cosmic ray people use the power spectrum of interplanetary magnetic fields to obtain the length scales of the inhomogeneity in the field in their scattering of particles. How do you estimate or get yours? Is there not also a Fermi-type of acceleration with the blobs that are generated by the instabilities in the radiatively driven winds? Is it efficient to accelerate particles in your case? Why are your particles relativistic?

R.L. White: (1) See the remark above which refers to the mean free path. The magnetic field spectrum is similar to that observed for the solar wind. (2) Particle acceleration occurs within single shocks. Fermi acceleration from particles bouncing from blob to blob will not be important because the system of blobs is generally expanding rather than contracting. (3) The particles are accelerated to relativistic energies because the mean free path is short enough that particles do not escape from the shock until they are accelerated to about a GeV.

Lafon: An important assumption of your model is seemingly the limitation of the mean free path of the accelerated particles by the magnetic field (is it radial?). However, this limitation is never isotropic (no limitation along B) and this should not be without consequences.

R.L. White: The B field changes direction randomly on small scales; on large scales it is generally azimuthal. The mean free path along B is about 10 times that perpendicular to B, but it is not infinite. I have taken full account of the magnetic field geometry and scattering parallel and perpendicular to it in my calculations.

# WINDS FROM ROTATING, MAGNETIC, HOT STARS

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In this paper I will attempt to answer the following question: Can a magnetic field, coupled with stellar rotation, enhance the wind from a hot star, which is driven primarily by line radiation pressure? There are a number of reasons why such a question is interesting. Measured values of the mass loss rate ( $\dot{M}$ ) and the terminal velocity ( $v_\infty$ ) in hot star winds exhibit a large amount of scatter which may be larger than the observational uncertainties (see Abbott 1982). This fact is often cited as evidence of an additional force, besides line radiation pressure, helping to drive the winds. One possibility for such an additional force is a stellar magnetic field coupled to the star's rotation. (The rotational motion causes the curvature in the magnetic field lines, which is necessary to get a  $\underline{J} \times \underline{B}$  force, and also produces a centrifugal force.) All hot stars are fairly rapid rotators (Fukuda 1982), and the emission line hot stars (Oe, Oef, and Be) have the highest rotational velocities of any stellar types. The existence of magnetic fields in hot star atmospheres is, however, much less certain. As we heard from Cassinelli (1984, this volume), there is now extensive "circumstantial" evidence for magnetic fields in the atmospheres of hot stars, such as the presence of very hot gas, X-ray emission, narrow absorption components in the spectral lines, and non-thermal radio emission. If there are magnetic fields on hot stars (and this is still far from certain), it is important to know how they would affect the properties of the winds.

To construct a model of a wind from a rotating, magnetic, hot star, I have combined the Weber and Davis (1967) description of a rotating magnetic solar wind with the Castor, Abbott, and Klein (1975; hereafter CAK) theory for a line-radiation-driven wind. The following simplifications were made to keep the problem tractable. The model treats the equatorial plane only, so that meridional flow (and gradients) are ignored. Meridional flow could be important (see Suess and Nerney 1973), but is probably less important here than in a solar wind model, because of the stronger radial forces present. Axial symmetry is also assumed, so that the velocity and magnetic field have radial and azimuthal components only, and these components are all functions of just the radius  $r$ . The magnetic field lines are open in this model, so that closed magnetic loops, which could have important dynamical consequences, are not being considered.

The radial equation of motion now has magnetic and centrifugal forces, as well as the line radiation pressure force of CAK. These forces contain the azimuthal quantities  $v_\phi$  and  $B_\phi$ . We now also have an azimuthal

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equation of motion, which, together with the induction equation, allows us to solve for  $v_\phi$  and  $B_\phi$  as functions of the radius  $r$  and the radial velocity  $v_r$ . These expressions can then be substituted in the radial equation of motion to give us a single differential equation for  $v_r$  as a function of  $r$ . This equation is nonlinear in  $dv_r/dr$ , so it must be solved numerically by specifying  $v_r$  and  $v_\phi$  at the photosphere. A unique solution for  $v_r$ , which is subsonic at the photosphere and which rises monotonically to a constant value  $v_\infty$  as  $r \rightarrow \infty$  must pass through two CAK-type critical points, as well as the Alfvén point (where the flow velocity is equal to the Alfvén speed).

The inputs to the model are the stellar mass, radius, and luminosity, as well as the equatorial rotational velocity (denoted  $v_{rot}$ ) and the radial component of the surface magnetic field strength ( $B_0$ ). To obtain concrete results I chose the stellar parameters of the O6ef star  $\lambda$  Cep, which has a mass of 50 solar masses, a radius of 19.7 solar radii, and a luminosity of  $6.76 \times 10^6$  solar luminosities (Garmany et al. 1981). I used a grid of values for  $B_0$  and  $v_{rot}$ :  $B_0$  took on the values 200, 400, 800, and 1600 gauss, while  $v_{rot}$  had the values 125, 247, 350, and 400 km/s (note that the break-up speed for this star is roughly 570 km/s). The mass loss rates and terminal velocities for all 16 models are shown in figures 1 and 2. We see that increasing the magnetic field strength has a large effect on the terminal velocity, and a lesser effect on the mass loss rate. Increasing the rotational velocity, on the other hand, has a large effect on the mass loss rate, and a lesser effect on the terminal velocity. When the rotation rate and the magnetic field are both large, there is a coupling between the magnetic and centrifugal forces, which makes an increase in  $B_0$  or  $v_{rot}$  effective in increasing  $v_\infty$  and  $\dot{M}$ . For a physical description of how the different forces cause these effects, see Friend and MacGregor (1984).

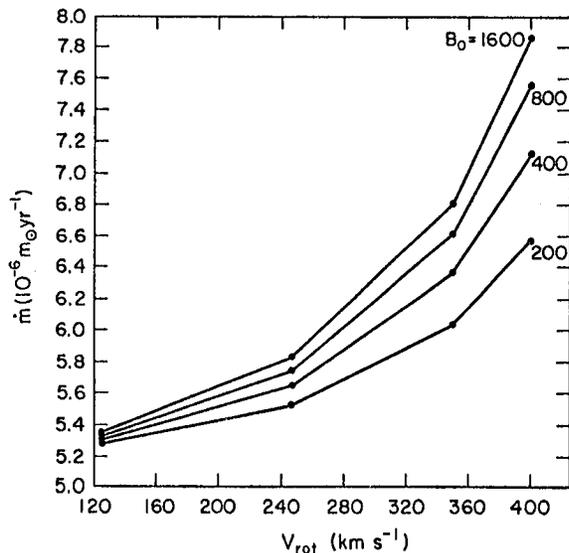


Figure 1

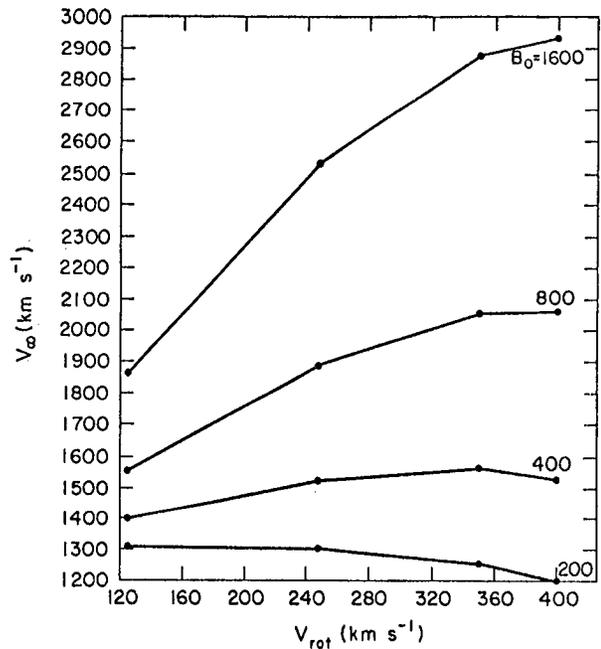


Figure 2

We see from figures 1 and 2 that rotation and a magnetic field can explain a scatter in measured mass loss rates and terminal velocities for stars that are otherwise identical. The mass loss rate varies by a factor of about 1.5 while the terminal velocity varies by a factor of about 2.5 for the 16 models. However, this spread in  $\dot{M}$  and  $v_\infty$  requires the full range of magnetic field strengths used. If the size of the magnetic field is constrained to be much smaller than 1600 gauss, then the magnetic field will not be able to explain the scatter in the wind properties. The spin-down of the star due to angular momentum loss in the wind and the magnetic field will set such a limit on the magnetic field strength.

A rotating wind with a magnetic field loses angular momentum at a rate

$$dJ/dt = 2/3 \dot{M} \Omega r_A^2 ,$$

where  $\Omega$  is the angular velocity of the star, and  $r_A$  is the radius of the Alfvén point (Weber and Davis 1967). The strength of the magnetic field plays a major role in spinning down the star, since  $dJ/dt$  goes as the square of the Alfvén radius, which is larger for larger magnetic fields. To see how large a magnetic field can exist without spinning down stars faster than they are observed to, I followed the evolution of the rotational velocity for evolving 15  $M_\odot$  and 30  $M_\odot$  stars. These calculations assume that magnetic flux is conserved as the star evolves in radius, so that as the radius grows, the magnetic field falls off as  $1/R^2$ . It was also assumed that the star rotates like a rigid body, which is probably not the case, but is the only assumption that can be easily modeled. The moment of inertia of the star is calculated by the evolutionary code, and the wind parameters, namely  $\dot{M}$  and  $r_A$ , are computed with the wind model described above. In order to compare these computed rotational velocities to observations, I used the tabulations of Fukuda (1982) of rotational velocities for a large number of stars, organized by spectral types and luminosity classes. Thus, as the model star is evolved in time, I can compare its rotational velocity at a certain stage with the (average) measured value from Fukuda for stars of the appropriate type.

The results of this comparison are shown in figure 3 for the 30  $M_\odot$  star, and figure 4 shows the results for the 15  $M_\odot$  star. The solid curves are the theoretical calculations, and the individual points (with error bars) are the observed values from Fukuda (1982). The numbers in parentheses next to each point are the numbers of stars in each category. For each star, an evolutionary track was computed with no magnetic field and with a field of 100 gauss. For the 30  $M_\odot$  star, I also computed an evolutionary track with a lower mass loss rate (taken from the empirical formula of Garmany and Conti 1984), since the value computed from the model is higher than observations indicate for a star of this mass. In both cases, the observed values of the rotational velocity are most consistent with the zero magnetic field case, and even a field of 100 gauss seems to spin the star down too rapidly (especially for the 15  $M_\odot$  star). We are therefore led to the conclusion that the average open magnetic field on the equator of OB stars is less than 100 gauss, and possibly zero. Note that this analysis says nothing about

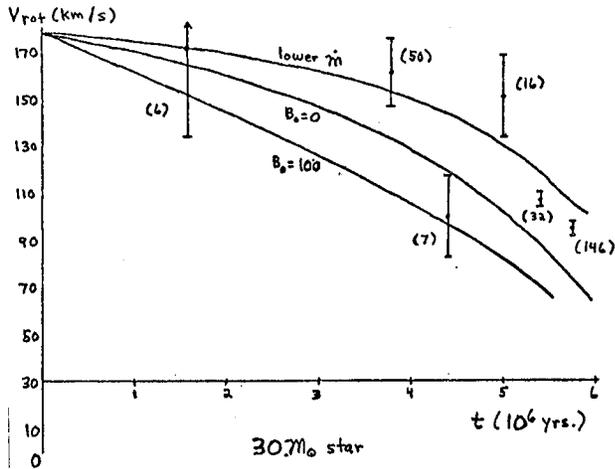


Figure 3

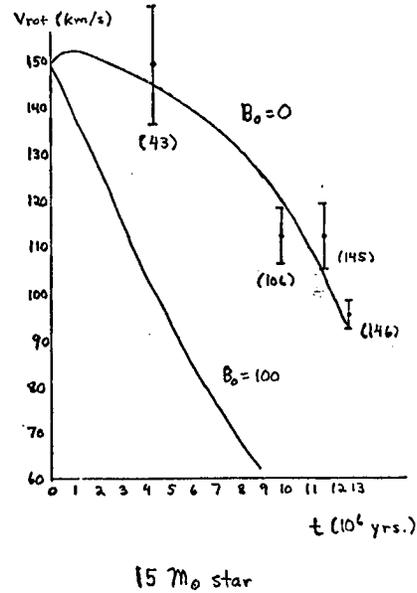


Figure 4

closed fields, or open fields at the poles. The presence of closed field regions over a large portion of the stellar surface could reduce the spin-down rate. An opposing effect is that if the assumption of rigid body rotation were relaxed, the rotational velocity would be lowered even more, since the surface could then spin down more rapidly than the core. It should be pointed out that any statements made on the basis of this analysis refer only to an average of a large number of stars, and individual stars may still have large open magnetic fields. For the average OB star, however, we must conclude that a magnetic field could affect the dynamics of the wind, but in order to do so, it would have to be large enough that it would spin down the star much more rapidly than is observed.

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## DISCUSSION

Uchida: Is not the short damping time of rotation due to your use of monopole-type magnetic fields dropping off as  $r^{-2}$ ? Then the moment arm can be rather long and the angular momentum loss due to this can be large. If you, instead, use dipolar or quadrupolar fields, the spin-down rate may be smaller.

Friend: I agree.

Uchida: Also, your figure seems to me to show that even without the magnetic field (the curve for  $B = 0$ ) the damping is already too strong. This may indicate the presence of some problem already before the introduction of the field.

Friend: The main problem is probably that the mass loss rates assumed in the model calculations are too high.

M.A. Smith: A general comment, not just on your paper. The speaker has correctly remarked that there is extensive circumstantial evidence for magnetic fields in chemically normal OB stars. However, as an observer I would trade all that for one solid piece of observational evidence for these fields; simple broad-band polarization reports are not sufficient. I would remind the conference participants that some 15 years ago an observer created mischief by underestimating his detection limits for a Zeeman observation for one Am star. Yet a small literature blossomed quickly around this "detection" and purported to explain the spectral peculiarities of Am stars in terms of magnetic atmospheric distension effects.

At this conference I would like to see some attention given to observational evidence or model signatures in the future. From the theoretician we need observational predictions from magnetic models that we can verify at the telescope. There are several bright, extremely sharp-lined B stars around that could provide quite low detection limits. Also, I would like to point out that in certain areas, technical instrumental advances (e.g. in optical spectroscopy, solid state array detectors coupled with Pochel cells that chop between polarization states) promise improvements in detection of polarizations by a factor 10 or so over old techniques. Such techniques open new vistas and allow for the attack of qualitatively new problems such as this one. In this case, I do not know whether the theoreticians are away ahead or away behind the observers, but I am convinced the two groups are not working together.

Cassinelli: I would have been very pleased to present yesterday direct Zeeman-polarimetry measurements. However, only those stars with the very strongest, most spatially ordered, B fields show clear direct evidence. The fact that we do see some hot stars with Zeeman effect or with radio circular polarization suggests that many other stars will be found to show these effects, but, perhaps, to a lesser extent.

Underhill: Myron's comments indicate a way of searching for spectroscopic signatures of the presence of weak generally distributed magnetic fields. I find that geometric models requiring ejection from a point (discrete components) and photometric results suggesting the rotation of a spotted disk are suggestive of the presence of locally created magnetic regions. If the period of change of the diagnostic is of the order of greater than 6 days, one favors rotation of a spotted disk over non-radial pulsation. Observations often are ambiguous. Insight and skill are needed to distinguish the correct answer from the less subtle one.

Sreenivasan: I am going to report later on some work done with Dr. Wilson. We do not consider magnetic fields but do consider differential rotation and take into account the transfer of angular momentum from the core to the mantle of the star and the loss of angular momentum from the star to space. Although the approaches are complementary, the conclusions are similar. The magnetic fields if they exist in these stars will only spin the star down even more drastically. The only way to understand the residual spin of these stars is to assume that the spin on the ZAMS should be a lot faster than what you and we take to be the case. Otherwise a final  $v_{\text{rot}}$  of about  $50 \text{ km s}^{-1}$  will not remain for the supergiants.

Friend: Possibly we do not understand the angular momentum transfer in the star's interior.

Lafon: Rotational motion seems to be important up to large radial distances. How can you reconcile the derivation of the radiation driving force from the CAK model (spherical symmetry), i.e. taking into account only the Doppler effect due to radial motions and neglecting rotational motion, with the results of dynamical calculation showing that the differential velocity is not a small fraction of the radial velocity?

Friend: This is a "zero-order" model which seeks to find the effect of magnetic fields on hot star winds. Using the CAK theory is certainly a rough approximation, but it shows how the magnetic field changes the situation. I am currently working on a more accurate treatment of the line radiation force which includes the transverse motion.

Chan: The wind data may set a limit for the magnetic field associated with the wind, but there is a lot of room for large local magnetic fields in bounded regions. Is this possible? Also, if the winds are generated in highly localized regions and have higher densities originally, would they lower the value of the Alfvén radius and provide more room for possible values of  $B$ ?

Friend: Large local fields could exist and not affect the spin-down problem. If the wind is generated locally and then diverges to fill a large solid angle, the Alfvén radius will change. But since the magnetic field and the density both fall off rapidly in this situation, it is not clear exactly how the Alfvén radius changes.

DEPARTURES FROM LTE POPULATIONS VS. ANOMALOUS ABUNDANCES;  
THE EFFECTS OF HEATING

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ABSTRACT

The deposit of nonradiative heat and momentum in the mantle of a hot star affects the interpretation of the spectrum of the star in two ways. First, it necessitates that one consider superheated and moving plasma when doing the analysis, and second it means that one should consider a model atom which is appropriate for the physical state of the line-forming regions. Some examples will be presented for H and He showing how changes in the electron temperature affect the solution of the equations of statistical equilibrium. The observed spectra of the Wolf-Rayet stars HD 191765, HD 192103, and HD 192163 are compatible with a normal H/He abundance ratio.

INTRODUCTION

The papers presented so far at this conference have demonstrated that nonradiative energy and momentum are deposited in the atmospheres of hot stars. One should, therefore, take account of this when analysing the spectra of B, O, and Wolf-Rayet stars. Some results are presented in this paper showing how the analytic results are affected by the presence of superheating. The problem is simplified by assuming that the line-forming process may be represented by considering conditions at one representative point.

When one assumes that radiative equilibrium occurs in a stellar atmosphere, one obtains the result that the electron temperature decreases as the outer edge of the atmosphere is approached. This happens because it becomes easy for photons to escape. Traditional theory suggests that in the

line-forming regions the electron temperature will not exceed about  $0.8 T_{\text{eff}}$ . Since the electron temperatures in the atmospheres of hot stars appear to be well above this value, particularly in the case of Wolf-Rayet stars, superheating occurs in the mantles of hot stars.

Previous work by others has shown that when one analyses the spectra of B, O, and Wolf-Rayet stars one is not justified in assuming that local thermodynamic equilibrium (LTE) occurs. It is necessary to find the fractional populations of the levels in which one is interested by solving the equations of statistical equilibrium. To do so one must adopt model atoms containing all relevant transitions and one must allow for all collisional and radiative process which may occur.

The published studies of H and He in the spectra of Wolf-Rayet stars (Castor and van Blerkom 1970; Willis and Wilson 1978; Smith and Willis 1982, 1983) use very simple model atoms. In fact, the case of the fractional populations of H has not been worked out using the equations of statistical equilibrium. Rather, it has been assumed that H is fully ionized and that the populations of the levels in which one is interested ( $n = 5$  and  $n = 6$  for  $H\gamma$  and  $H\delta$ ) can be found by taking Saha-Boltzmann ratios with respect to the abundance of  $H^+$  ions.

The case for He has been worked out using the principle of statistical equilibrium and a model atom which is composed of 30 states of the  $He^+$  ion plus the  $He^{++}$  ion. In two cases, (Smith and Willis 1982, 1983) the authors have added the ground level of He I to the model atom. In no cases was a representative selection of He I levels considered even though He I emission lines are quite prominent in Wolf-Rayet spectra. Radiative transitions and electron-collision transitions are taken into account in all solutions of the equations of statistical equilibrium.

The results of the published studies of H and He in the atmospheres of Wolf-Rayet stars have been interpreted to mean that H is underabundant in the atmospheres of Wolf-Rayet stars, perhaps being present in a ratio of 1/5 or less, rather than at the normal ratio of 10/1. The results to be reported here show that when one takes account of the high electron temperatures in the

line-forming regions of the atmospheres of Wolf-Rayet stars and one uses a realistic model He atom, as well as doing a statistical equilibrium solution for H, one finds that the observations are compatible with a normal abundance ratio (10/1) of H to He. The departures from LTE are severe for H, He I, and He II.

Because the emission lines in Wolf-Rayet spectra are not displaced, one can ignore flow when calculating the relative energies in lines in a first approximation. The velocity field in the atmosphere chiefly determines the width of a line, not its strength. This is true certainly for an optically thin line, and it is a good approximation for a moderately opaque line.

#### METHOD FOR PREDICTING RELATIVE ENERGIES IN EMISSION LINES

The method used is to invert the equations of statistical equilibrium in order to find the fractional population in each level of each model atom. After which the relative energies in lines which are observed are estimated.

Bhatia and Underhill (1984) have done this using many-level model atoms for He and H. Because one must estimate the radiation density in the atmosphere for many transitions in order to evaluate the terms in the equations of statistical equilibrium which are driven by radiation, it is necessary to use a simple approximation for the radiation density in each frequency at each point in the model mantle.

Bhatia and Underhill describe the physical conditions in the model mantle by assigning an electron temperature  $T$  and an electron density  $N_e$ . For their first approximation, they put the radiation density in each feature, continuum or line, equal to  $WB_\nu(T_*)$ . Here  $T_*$  is a radiation temperature chosen so that the radiation field at  $\lambda < 900 \text{ \AA}$  entering the mantle from the photosphere is about equal to the flux emerging from a Mihalas (1972) NLTE model atmosphere with  $T_{\text{eff}}$  in the range from 25000 to 30000 K. The "dilution factor",  $W$ , is assigned such values that  $WB_\nu(T_*)$  represents the ambient radiation density in the frequencies of typical lines at the representative point in the model mantle.

The method developed by Castor and van Blerkom (1970) for estimating the radiation density in order to solve the equations of statistical equilibrium in a model atom in an expanding atmosphere is equivalent to putting

$$\langle J_{\text{feature}} \rangle = W_{\text{feature}} B_{\nu}(T_{*}),$$

where  $W_{\text{feature}}$  is different for each line and continuum. Their values of  $W_{\text{feature}}$  range from about 0.02 to 0.4. An approximate method for estimating the radiation density in each line and continuum was adopted by Bhatia and Underhill (1984).

Bhatia and Underhill explored the effect of letting  $W$  range from 0.001 to 0.4,  $T_{*}$  from  $1.4 \times 10^4$  to  $3.0 \times 10^4$  K,  $N_e$  from  $10^9$  to  $10^{11} \text{ cm}^{-3}$ , and  $T$  from  $10^4$  to  $10^5$  K. The predicted ratios of the energy in observable lines of H, He I, and He II turn out not to be very sensitive to the choice of  $W$ . The results reported here are for the first approximation; then  $W = \text{constant}$ .

According to the theory of Castor and van Blerkom (1970), the relative energies radiated in two lines of He I and He II can be estimated from the following expression:

$$\frac{E(i \rightarrow j)}{E(k \rightarrow m)} = \frac{N_i/N(\text{He})}{N_k/N(\text{He})} \cdot \frac{A_{ij}}{A_{km}} \cdot \frac{\lambda_{km}}{\lambda_{ij}}.$$

Here one line comes from the transition  $i \rightarrow j$ , the other from the transition  $k \rightarrow m$ , where  $i$ ,  $j$ ,  $k$ , and  $m$  represent levels in the model atom. It is assumed, as a first approximation, that the same fraction of photons escapes for each line and that both lines come from the same volume of plasma.

#### MODEL ATOMS USED

Bhatia and Underhill have used a model H atom consisting of 24 bound states and the ion  $\text{H}^+$ . Reliable information exists about the rates of the radiative bound-bound and bound-free transitions. Information about the

bound-bound and bound-free rates of H resulting from collisions with thermalized electrons is unsatisfactory. Bhatia and Underhill describe the approximate expressions used for these cross sections.

The model He atom consists of 28 singly excited states and 25 doubly excited states of He I, the lowest 14 states of He<sup>+</sup>, and the He<sup>++</sup> ion. A detailed description of the adopted states of He I and He II can be found in Bhatia and Underhill (1984). Bound-bound and bound-free radiative transitions as well as bound-bound and bound-free electron collision transitions are considered. Explicit account is taken of autoionization in the case of 4 low lying doubly excited states, and allowance is made for dielectronic recombination as well as for radiative recombination and three-body recombination.

Bhatia and Underhill solve for the statistical-equilibrium populations of helium starting with the assumption that hydrogen is fully ionized. The ratio  $N(H)/N(He)$  is a free parameter. The helium results are only slightly dependent on the choice made for the relative abundance of H to He. That parameter fixes the numbers of H and He atoms needed to provide the adopted value for  $N_e$ . Once the particle density has been established for the adopted set of parameters, a linked statistical equilibrium solution for H is done. The results of this confirmed the starting assumption that H is essentially completely ionized when the ultraviolet radiation field approximates that from a star with an effective temperature of  $2.5 \times 10^4$  to  $3.0 \times 10^4$  K, and the electron density is in the range from  $10^9$  to  $10^{11}$  cm<sup>-3</sup>. The electron temperature is chosen to be 1, 2, 3, 5, and 10 in units of  $10^4$  K.

## RESULTS

### a) Departures from LTE Fractional Populations

The fractional populations for the hydrogen levels having chief quantum numbers in the range from 5 to 9 are found to be about one-tenth what would be expected in LTE. For the highest levels ( $n > 15$ ), the fractional populations decrease to about 0.01 times the LTE values. The latter result may be fictitious because it may be generated by the approximate expressions which were

adopted in order to evaluate the collisional processes in hydrogen. Test calculations show that increasing the collisional ionization rates of hydrogen by a factor of 10 increases the fractional populations of the high levels by about a factor of 10. The calculations indicate that in plasmas having the densities, electron temperatures, and radiation fields studied by Bhatia and Underhill, the ground level of H is overpopulated by a factor between  $10^2$  and  $10^3$ , while the middle levels are underpopulated by a factor of the order of 10.

The fractional populations of the He I levels depart by large factors from LTE values, particularly when the electron temperature is high ( $5 \times 10^4$  K or  $10^5$  K). In general, the populations of the singlet levels are small in comparison to the populations of the triplet levels. When  $T = 5 \times 10^4$  K, the fractional population of the metastable  $2^3S$  level may be about  $10^{10}$  times its LTE value, while the population of the  $3^3D$  level is about  $3 \times 10^5$  times its LTE value. At  $T = 5 \times 10^4$  K, the LTE populations of the He I levels are very small.

In all the cases studied, the fractional populations of the He II levels from which the usually observed Pickering series lines arise are within a factor of 10 of their LTE values. The lower levels tend to be underpopulated while the higher levels tend to be overpopulated with respect to LTE by a small amount. More exact results cannot be obtained until accurate expressions are available for calculating the collisional excitation and collisional ionization rates from the levels of H, He I, and He II which have  $n > 1$ . In plasmas having electron densities in the range from  $10^{10}$  to  $10^{11}$   $\text{cm}^{-3}$ , it is the collisional rates which are the most important factor for determining the relative populations of the high levels of H, He I, and He II.

#### Predicted Relative Strengths of Observed Lines

Some predicted ratios of energies for H, He I, and He II lines observed in the spectra of Wolf-Rayet stars are given in Table 1 together with the observed ratios for three Wolf-Rayet stars. The observed ratios have an uncertainty of about  $\pm 25\%$ . The predictions for  $N_e = 10^{11}$   $\text{cm}^{-3}$  are displayed

because this electron density is typical of the values found in the outer line-forming layers of model atmospheres with  $T_{\text{eff}}$  in the ranges from  $2.5 \times 10^4$  to  $3.0 \times 10^4$  K, see Mihalas (1972). The results are not sensitive to the choice of  $N_e$  when  $\log N_e = 10 \pm 1$ .

The radiation temperature,  $T_*$ , is taken to be  $2 \times 10^4$  K in order to simulate the radiation density shortward of 900 Å from a model atmosphere with  $T_{\text{eff}}$  equal to  $2.5 \times 10^4$  K or so. Results are displayed for two choices of the parameter  $W$ , and for two choices of  $T$ , the electron temperature. Because C IV and N V emission lines are seen in the spectra of the three Wolf-Rayet stars which are analysed here, one expects the electron temperature to be of the order of  $10^5$  K.

The predicted energy in He I 5876 relative to that in He II 5411 is sensitive to the choice of electron temperature. The observations suggest that in HD 192103 and HD 192163 some plasma with  $T < \sim 5 \times 10^4$  K may be present. When  $T = 3 \times 10^4$  K, the predicted ratio is about 4.

The predicted ratio of He II 1640/He II 4686, when compared to the observed values, also suggests  $T \sim 5 \times 10^4$  K. The predictions for this line ratio are the least secure of all the results presented here because these two He II lines are intrinsically strong and the approximate theory with  $W = \text{constant}$  may not be accurate for these lines. The low observed value of the ratio He II 1640/He II 4686 in HD 192103 is caused by a strong central reversal of He II 1640 in the spectrum of HD 192103 suggestive of stationary hot plasma outside the line-forming region of HD 192103. The column density of this plasma cannot be large, however, because a central reversal appears only in He II 1640, not in He II 4686.

The predicted energy ratio He II 3203/He II 5411 is not sensitive to the electron temperature or electron density in the ranges studied here. The observed ratios are similar to the predicted ratios. Altogether, the predicted ratios for the dominant He I and He II lines suggest that the line-forming regions of HD 191765, HD 192103, and HD 192163 can be represented by the model mantles of Bhatia and Underhill.

The predicted ratios for He II 4338/H 4340 in the case that  $N(H)/N(He) = 10$  are given also in Table 1. This ratio is sensitive to the electron temperature, the H line becoming the dominant component when  $T$  is less than about  $5 \times 10^4$  K. The predicted results of Table 1 are compatible with the observed intensity variation along the Pickering series, see Underhill (1980).

Additional predicted values for the relative intensities of He II 4338 and H 4340 are given in Table 2. When the relative abundance of hydrogen to helium is normal (about 10/1), the hydrogen component dominates until  $T \sim 5 \times 10^4$  K. If  $T$  is as large as  $10^5$  K, then the hydrogen line will be so weak relative to the He II line that it will not be detected. If it is assumed that  $N(H)/N(He) = 0.1$ , then the He II line should dominate even when  $T = 3 \times 10^4$  K. The first-approximation results of Bhatia and Underhill (1984) suggest that the spectra of Wolf-Rayet stars are compatible with a normal H/He abundance ratio. In those stars where H is easy to detect, and in which He I 5876 is strong, some plasma with  $T \sim 3 \times 10^4$  K is probably present in addition to the hot plasma which produces the lines from high ions of C, N, and O.

#### CONCLUSIONS

1. When analysing Wolf-Rayet spectra, it is essential to do a statistical equilibrium solution for H, He I, and He II.
2. The spectra of Wolf-Rayet stars are compatible with a normal 10/1 abundance ratio for H to He.
3. Hot stars with spectra which show the Balmer lines of H and He I 5876 strongly in emission have much relatively cool plasma,  $T < 30000$  K, in their mantles.
4. It is doubtful that any true abundance anomalies have yet been demonstrated to exist in the atmospheres of Wolf-Rayet stars.

Table 1  
 Predicted and Observed Energy Ratios  
 Case:  $T_* = 2 \times 10^4$  K,  $N_e = 10^{11}$  cm $^{-3}$

Ratio	W = 0.01	W = 0.40	191765	192103	192163
Case T = $5 \times 10^4$ K					
5876/5411	0.23	0.286	0.3	3.1	1.1
1640/4686	6.20	12.0	7.45	1.53	8.24
3203/5411	3.50	3.70	3.2	2.8	6.5
4338/4340*	1.21	0.79	H barely detected		
Case T = $10^5$ K					
5876/5411	0.004	0.008	0.3	3.1	1.1
1640/4686	6.02	6.12	7.45	1.53	8.24
3203/5411	3.56	3.56	3.2	2.8	6.5
4338/4340*	5.40	2.92	H barely detected		

\* assuming  $N(H)/N(He) = 10$

Table 2  
 Predicted Energy Ratio He II 4338/H 4340

W	$T_*$ ( $10^4$ K)	$N_e$ (cm $^{-3}$ )	T = 3 ( $10^4$ K)	T = 5 ( $10^4$ K)	T = 10 ( $10^4$ K)
0.1 <sup>a</sup>	2.0	$10^{10}$	0.058	0.522	1.80
0.1 <sup>a</sup>	2.0	$10^{11}$	0.058	0.845	3.49
0.4 <sup>a</sup>	2.0	$10^{10}$	0.101	0.529	1.67
0.4 <sup>a</sup>	2.0	$10^{11}$	0.060	0.790	2.92
0.4 <sup>b</sup>	2.0	$10^{10}$	8.82	52.8	167.1
0.4 <sup>b</sup>	2.0	$10^{11}$	3.88	78.6	291.4

<sup>a</sup> $N(H)/N(He) = 10$ ;

<sup>b</sup> $N(H)/N(He) = 0.1$

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## DISCUSSION

Mullan: You found very large b-factors for He  $2^3S$  (namely  $b = 10^{10}$ ). Does this predict very strong He I 10830 in the Wolf-Rayet stars?

Underhill: I have not yet attempted to predict the energy emission from He I 10830; I cannot predict absorption lines with my rudimentary line-formation theory. Roughly, I would expect the ratio of the emission in He I 10830 to that in He II 5411 to be about 50x the ratio of He I 5876/He II 5411. Thus, roughly the maximum value of the rate would be of the order of 12/1. However, since  $\lambda 10830$  would be accompanied by a shortward displaced absorption trough, the numbers suggest (energy in  $\lambda 10830$ )/(energy in  $\lambda 5411$ )  $\sim 6$ . This is not greatly different from what is observed for Wolf-Rayet stars.

Linsky: One test of your calculations would be to estimate the He I 10830 line optical depths for Wolf-Rayet stars to see if the line should be in absorption or emission.

Underhill: It requires some radiative transfer theory to make a meaningful estimate. I have given "back-of-the-envelope" estimates to Mullan, namely I expect energy in emission in  $\lambda 10830$  to be roughly 6 times that radiated in emission by He II 5411.

Abbott: Two comments: (1) My understanding of your graph is that the level with  $n = 1$  of hydrogen is overpopulated and all the higher levels are underpopulated. Would that not lead to an observable Lyman-alpha absorption feature? At I.A.U. Symposium No. 99, A. Willis claimed his UV observations ruled out H I Lyman-alpha in several WR stars. (2) Your calculated line ratios appear to be calculated with an optically thin approximation, while in several cases some lines are undoubtedly optically thick.

Underhill: Typically, my fractional populations lead to about  $10^4$  H atoms  $\text{cm}^{-3}$  in level 1, and about 1 atom  $\text{cm}^{-3}$  in level 2. These densities would not lead to significant Lyman-alpha features which could be separated from the interstellar Lyman-alpha feature. I question Willis' analysis.

The idea that the commonly observed lines in the visible spectrum of WR stars are optically thick is a myth which is based, so far as I can see, on the arbitrarily large length and density scales adopted by Castor and van Blerkom (1970). My numbers suggest that observable details of the spectra can be predicted with at least 10x less material than Castor and van Blerkom suggest may be appropriate.

Castor I am surprised that such low  $b_n$ 's were found for high n; I would have expected  $b_n \rightarrow 1$  at  $n \sim 10$  or 15. I also would be happier to see an escape probability included for each line, based on its optical depth; I think some line optical depths are large.

Underhill: Level 1 is over populated by a factor of 250, while level 2 may be under populated by a factor 4. However, the fraction of neutral H is very small. Typically the fraction of all H present which is in level 1 is  $10^{-7}$ . With  $10^{11}$  H atoms and ions per  $\text{cm}^{-3}$ , you end up with  $10^4 \text{ cm}^{-3}$  in level 1. A next step is to predict absorption and emission lines using escape probability radiative transfer theory. I am attempting to do this now.

IS THE RATIO OF OBSERVED X-RAY LUMINOSITY TO BOLOMETRIC LUMINOSITY  
IN EARLY-TYPE STARS REALLY A CONSTANT?

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ABSTRACT

The observed X-ray emission from early-type stars can be explained by the recombination stellar wind model (or base coronal model). The model predicts that the true X-ray luminosity from the base coronal zone can be  $10^2$ - $10^4$  times greater than the observed X-ray luminosity. From the models, scaling laws have been found for the true and observed X-ray luminosities. These scaling laws predict that the ratio of the observed X-ray luminosity to the bolometric luminosity is functionally dependent on several stellar parameters. When applied to several other O and B stars, it is found that the values of the predicted ratio agree very well with the observed values ( $L_X^O/L_{Bol} \sim 10^{-7}$ ).

INTRODUCTION

Several surveys using the Einstein Observatory (HEAO-2) have found that essentially all O stars and many B stars are X-ray sources. The general result from these surveys is that the observed X-ray luminosities scale directly with the bolometric luminosities ( $L_X^O/L_{Bol} \sim 10^{-7}$ ) (Pallavicini et al. 1981).

One of the present unsolved problems concerning the atmospheres of early-type stars is determining the source and location of the X-ray emission. Models developed to explain the X-ray emission suggest that radiatively driven shocks occurring in the stellar wind may produce the observed X-rays (Lucy and White 1980; Lucy 1982), or that coronal zones at the base of the stellar wind may be responsible (Cassinelli and Olson 1979; Waldron 1984). It is quite possible that both processes may contribute to the observed X-ray emission. However, the recombination stellar wind (RSW) model of Waldron (1984) has shown that base coronal regions alone can reproduce the observed X-ray IPC spectral distributions and the corresponding observed X-ray luminosities for four early-type stars.

Using the results of these four models, scaling laws for the true X-ray luminosity ( $L_X$ ) and the observed X-ray luminosity ( $L_X^O$ ) can be found as a function of several stellar parameters. These scaling laws allow us to derive an expression for the ratio of  $L_X^O/L_{Bol}$ , and test the applicability of this expression towards other early-type stars.

SCALING LAWS FOR  $L_X$  AND  $L_X^O$

Several relations were investigated to determine the scaling of  $L_X$  and

$L_X^0$  with other known stellar parameters, using the results predicted by the four RSW models of Waldron (1984). The models suggest that the best scaling laws are

$$\log L_X/L_{\text{Bol}} = -2.60 + 1.49 \log \dot{M} v_{\text{es}} c / L_{\text{Bol}} \quad (1)$$

$$\log L_X^0/L_X = 25.92 - 1.30 \log N_w \quad (2)$$

where,  $\dot{M}$  is the mass loss rate ( $\text{gms}^{-1}$ ),  $v_{\text{es}}$  is the effective surface escape velocity ( $\text{cm s}^{-1}$ ),  $c$  is the speed of light, and  $N_w$  ( $\text{cm}^{-2}$ ) is the stellar wind column density ( $N_w \sim \dot{M} v_{\infty}^{-1} r_*^{-1}$ , see Cassinelli et al. 1981). The correlation coefficients for these scaling laws are both greater than 0.990.

The scaling law for  $L_X^0$  is not surprising, since one would expect  $L_X^0$  to be proportional to  $L_X$  times a frequency averaged attenuating factor (i.e.,  $L_X^0 = L_X \langle e^{-\tau_\nu} \rangle$ , where the stellar wind optical depth,  $\tau_\nu \sim N_w$ ). For the  $L_X$  scaling law, the results suggest that  $L_X$  and the rate of momentum deposition ( $\dot{M} v_{\text{es}}$ ) may be strongly correlated. However, the physical interpretation of this relation is presently unknown.

The dependence of the ratio of  $L_X^0/L_{\text{Bol}}$  on stellar parameters can be obtained via equations (1) and (2). The result is

$$\begin{aligned} \log L_X^0/L_{\text{Bol}} = & -7.93 + 0.19 \log \dot{M} + 1.30 \log R_* v_{\infty} \\ & + 1.49 (\log v_{\text{es}} - \log L_{\text{Bol}}/L_{\odot}) \end{aligned} \quad (3)$$

where the units are;  $\dot{M}$  ( $M_{\odot} \text{ yr}^{-1}$ ),  $v_{\text{es}}$  and  $v_{\infty}$  ( $\text{km s}^{-1}$ ), and  $R_*$  ( $R_{\odot}$ ). Therefore, the RSW model predicts that the ratio of  $L_X^0/L_{\text{Bol}}$  is not a true constant, but is functionally dependent on several stellar parameters.

#### COMPARISON WITH OBSERVATIONS

The stellar data required for this analysis has been collected from the literature for 67 O and B stars. Only 43 stars were found with quoted values for  $L_X^0$ . The results are shown in Figure 1, where the predicted values of  $L_X$  (filled circles),  $L_X^0$  (open circles), and the observed values of  $L_X^0$  (open triangles) are plotted versus the bolometric luminosity ( $L_{\text{Bol}}$ ). For the observed values of  $L_X^0$ , the scale is shifted down 2 orders of magnitude for clarity.

The agreement between the predicted values of  $L_X^0$  and the observed values of  $L_X^0$  is very clear. For  $L_{\text{Bol}} > 10^{38}$ , the values of  $L_X^0$  represent only a very small fraction of the true X-ray luminosities. As pointed out by Waldron (1984),  $L_X^0$  reflects the absorption properties of the stellar wind, and not the true nature of the X-ray source. For  $L_{\text{Bol}} < 10^{38}$ , the stellar wind optical depth becomes optically thin to the X-ray emission, and at this point, the optical depth of the interstellar medium can no longer be neglected (the effects of the ISM have not been included in Figure 1). For a few stars around  $L_{\text{Bol}} = 10^{37}$ , equation (2) gives unphysical results ( $L_X^0 > L_X$ ), and in this region,  $L_X^0$  would be very sensitive to the ISM optical depth values. It is

also important to note that the true X-ray luminosities ( $L_X$ ) can be quite significant ( $L_X \leq 10^{-3} L_{\text{Bol}}$ ), indicating that O and B stars may be very efficient producers of X-rays.

### CONCLUSIONS

It has been shown that the scaling laws derived from the RSW model results can be very successful in predicting the general observed X-ray characteristic of O and B stars, namely, that  $L_X^O/L_{\text{Bol}} \sim 10^{-7}$ . The results indicate that  $L_X^O/L_{\text{Bol}}$  is not a true constant, but a function of several stellar parameters which uniquely combine to form a "constant". This derived expression for  $L_X^O/L_{\text{Bol}}$  may also provide another means of estimating mass loss rates from O and B stars for comparisons with other methods.

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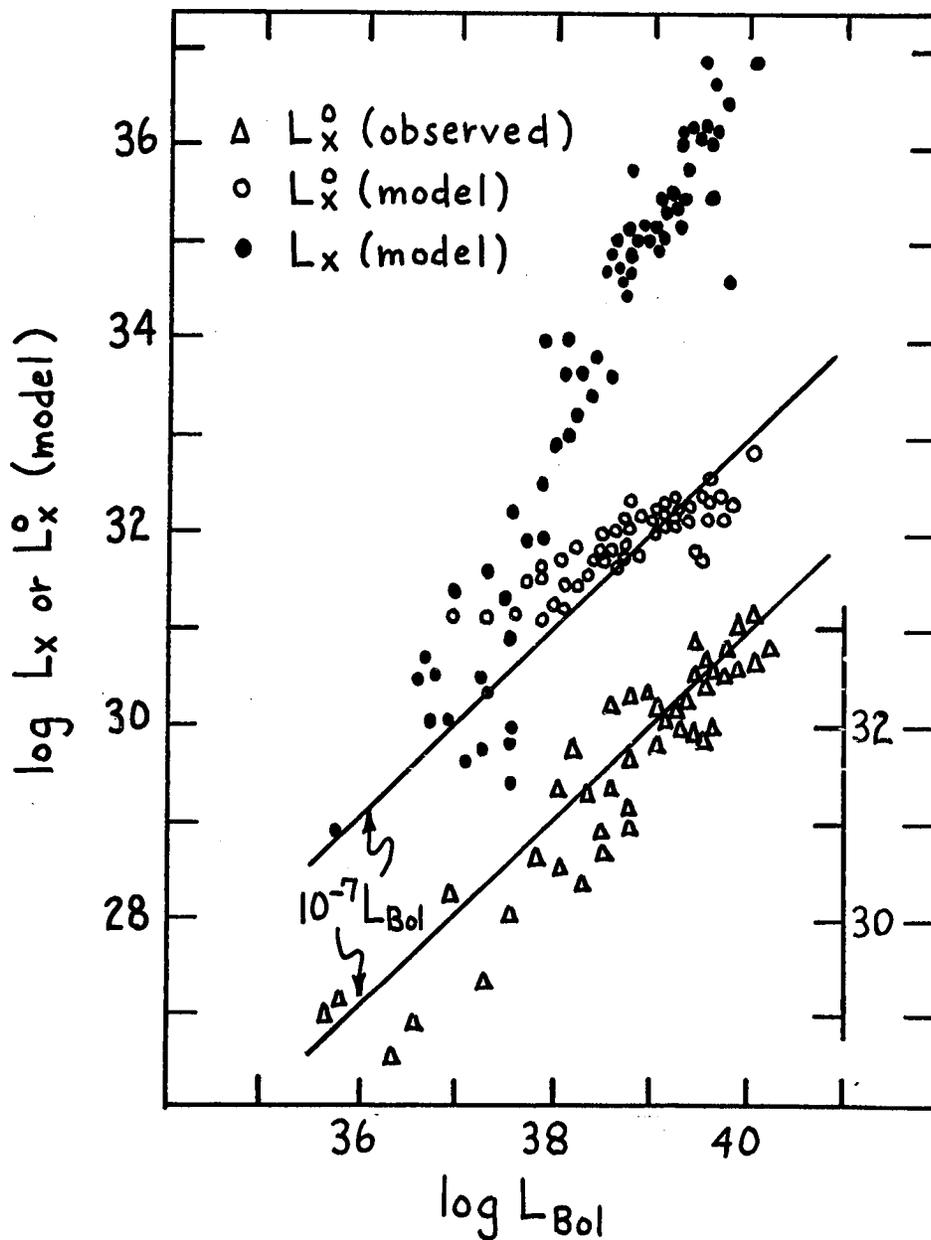


Figure 1. The predicted values of  $L_x$  ( $\bullet$ ),  $L_x^o$  ( $\circ$ ), and the observed values of  $L_x^o$  ( $\Delta$ ) are shown as a function of  $L_{\text{Bol}}$ . The scale for the observed values of  $L_x^o$  is shifted down 2 orders of magnitude for clarity. The results show that the predicted values of  $L_x^o$  are in very good agreement with the observed values.

## DISCUSSION

Abbott: The problem I see with your model is that the K shell cross sections of CNO are relatively immune to changes in the wind ionization balance. Thus, the conflict between SSS observations which show no K shell absorption dip, and the cool-wind plus coronae model remains.

Waldron: There can be changes in the K-shell opacities of CNO by factors of 2 - 4. The only conflict between the SSS observations and RSW model is at the oxygen K-shell edge (0.6 keV). Although the RSW model has reduced the absorption at this edge; the results are still not in agreement with the SSS. Possibilities for resolving this conflict include the following: If the wind is non-spherically symmetric, the absorption would be decreased, or if the base coronal X-rays are supplemented by X-rays produced by shocks occurring out in the wind, the absorption problem at 0.6 KeV may be eliminated.

Swank: What parameters did you determine in fitting the IPC spectra? With respect to Abbott's question, the SSS data would allow a jump in optical depth  $< \sim 1$  at the oxygen edge.

Waldron: The parameters determined were the emission measure and temperature of the base coronal region. The current RSW models predict an optical depth at the oxygen edge of  $< \sim 2$ .

R.L. White: Do the coronal X-rays change the ionization structure of the wind enough to be detectable in optical and UV spectra? For instance, is all the O and C so highly ionized that we wouldn't expect to see any low ionization states?

Waldron: The X-rays do affect the UV line profiles, as reported by myself at the IUE Symposium in April, 1984, when considering variability in X-rays, but the overall UV spectra are essentially unaffected. The corona produces highly ionized species close to the coronal region, but once the He II optical depth is  $\sim 1$ , the ionization structure returns to its expected normal state, except for the anomalous ionization (enhanced but not the dominant states) produced by the Auger effect. Therefore, it is expected that the optical spectra should not be affected significantly.

# NON-RADIATIVE ENERGY FROM DIFFERENTIAL ROTATION IN HOT STARS

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## ABSTRACT

A model of differential rotation is proposed for the upper radiative envelopes of hot stars, and it is suggested that the actions of such motions can be the source of energy for heating the coronae.

## INTRODUCTION

Sixty years ago, Von Zeipel (1924) posed his famous paradox on the inability to obtain local thermal energy balance in rotating barotropic stars. Mathematically, this paradox may be troublesome, but physically it may be a blessing. It provides a clue about the heating of hot-star coronae.

Observationally, it is clear that non-radiative energies are needed to drive the temperatures above  $10^6\text{K}$  in the coronae of hot stars. For example, x-ray luminosities  $L_x$  of the order of  $10^{-7} L_*$  (the bolometric luminosities of the stars) are commonly observed (Pallavicini et al., 1981). Yet, the outer convection zones of these hot stars are too feeble to supply the required energy. In a B5V star, the maximum power that can be produced by the unstable  $\text{H}_e^{++}$  layer is  $\rho V_c^3 \sim 10^{-9} L_*$ . In this estimate, the convective velocity  $V_c$  is computed from the mixing length theory of convection; two-dimensional computations solving the Navier-Stokes equations indicate that the powers of these convection zones are much weaker (Sofia and Chan, 1984). After all, there is no unstable ionization zone inside stars earlier than B0.

Considering the importance of magnetic activity in heating the solar corona, Underhill (1980) has suggested that magnetic fields carrying the actions of differential rotation may produce similar effects in hot stars. However, it was not clear how the differential rotation could be generated. Along this line of thinking, we develop a model for such differential rotation and show that the amount of power available may be enough to sustain the coronae of hot stars.

## DIFFERENTIAL ROTATION IN HOT STARS

The study of motion in rotating stars is a classical subject with vast bibliography [see Tassoul (1978) and references therein]. In this short note, we cannot elaborate on our mathematical approach and its relation to previous work. A more detailed discussion of our approach can be found in the recent paper by Mayr, Harris, and Chan (1984; MHC hereafter), and the application to stars will be expanded in a later paper. Here, we discuss the results which are particularly relevant to hot stars.

According to Von Zeipel's theorem, differential heating occurs between the pole and equator of a uniformly rotating (quasi-)barotrope. In terms of spherical harmonics, the rate of heating per unit volume can be expressed as

$$Q = -\frac{8}{3} \frac{F}{r} \left( \epsilon - \frac{3}{2} \frac{\rho}{\rho} \right) \epsilon \left( \frac{x}{m} \right)^2 P_2 (\cos \theta), \quad (1)$$

where  $F$  = the radiative flux,  $r$  = the radius,  $\epsilon = (V_\phi/V_e)^2$  = the ratio between the centrifugal acceleration at the equator and the gravitational acceleration,  $V_\phi$  = the rotational speed at the equator,  $V_e$  = the escape velocity at the stellar surface,  $\bar{\rho}$  = the mean density of the star,  $x = r/r_*$  = the normalized radius,  $m = M/M_*$  = the normalized mass inside  $r$ ,  $\theta$  = the colatitude, and the subscript \* denotes the stellar value.

As an example, we shall discuss the effects of such differential heating in a B5V envelope with  $V_\phi = 200 \text{ km s}^{-1}$ . We assume that the rotation is "initially" uniform, and the outer layer of the envelope ( $x \gtrsim 0.7$ ), where equatorial heating occurs, is treated as a single slab (see MHC). The behavior of this differentially heated, rotating layer can be summarized as follows:

(i) The number of spherical harmonic modes required to resolve the flow grows inversely with the square root of the Prandtl number  $Pr$ . At  $Pr = 10^{-6}$  (already an overestimate when only the radiative and molecular viscosities are considered), at least 200 modes should be included. Thus the need for a single-layer approximation.

(ii) The normalized distributions of the differential rotation ( $V'_\phi$ ) and the vertical components ( $V'_r$ ) of the meridional circulation for different values of  $Pr$  are plotted vs. colatitudes in Fig. 1 and 2, respectively. Curves a, b, c, and d correspond to  $Pr = 10^{-6}$ ,  $10^{-4}$ ,  $10^{-2}$ , and 1., respectively; the scaling factors are 1.5 (5), 1.5 (5), 1.3 (5), and 2.9 (4)  $\text{cm s}^{-1}$  for Fig. 1, and 3.7 (-4), 3.6 (-3), 2.9 (-2), 2.0 (-1)  $\text{cm s}^{-1}$  for Fig. 2. The integers inside the brackets represent exponents of 10. Notice that the peaks of  $V'_r$  near the equator are sharper for smaller  $Pr$ .

(iii) For small Prandtl numbers, the flow induced by the differential heating is mainly differential rotation (the geostrophic limit, Schwarzschild, 1947). When  $Pr$  approaches 0,  $V'_\phi$  approaches an asymptotic distribution, and  $V'_r$  decreases as  $Pr^{1/2}$ . One can say that the meridional circulation is induced by the viscosity.

(iv) For  $Pr \gg 1$  (not shown in Figs. 1 and 2),  $V'_\phi$  decreases as  $Pr^{-1}$ , but  $V'_r$  approaches an asymptotic distribution with a shape close to curve d of Fig. 2 and a scaling factor of  $0.28 \text{ cm s}^{-1}$  (pure Eddington-Sweet circulation).

#### SIGNIFICANCE TO THE HEATING OF HOT-STAR CORONAE

In the above model, the outer stellar envelope acts as an engine converting a fraction of the out-flowing radiative energy into mechanical energy; this provides a source of non-radiative energy (there is also dynamo action). To actually heat the coronae, it is necessary that this energy is

carried out to the coronal region where it is converted back into thermal energy. How this can be realized is the subject of extensive research and beyond the scope of this note. Apparently, wiggling of the magnetic field may play an important role (Stencel and Ionson, 1979).

When the magnetic field anchored in the envelope is sheared, the effective Prandtl number of the stellar fluid should increase. Thus we treat  $P_r$  as a variable parameter.

Eq. (1) provides an important estimate for the upper limit of power that can be delivered with this mechanism from the outer envelope layer. The maximum non-radiative flux that can be generated there is

$$L_{NR} \sim L_* \left( \frac{v_\phi}{v_e} \right)^4. \quad (2)$$

Therefore, it is a rather steep function of the ratio between the rotational and escape velocities. Based on the numbers listed in Table 1 of Nerney's paper (1980), the mean value of  $(v_\phi / v_e \sin i)$  for O-type supergiants is about 0.17, giving a value of  $\sim 10^{-3} L_*$  for  $L_{NR}$ . This is well above the required value to account for the x-ray luminosities usually observed in these hot stars. According to some recent calculations by Waldron (1984), the "real" values of the x-ray luminosities at the coronae may be close to this magnitude.

The fact that there is a  $\sin i$  factor in the observed rotational speeds seriously complicates the test of relation (2). However, there are indications that higher values of  $(v_\phi / v_e)$  produce more non-radiative energy. For example, Nerney's table of 35 supergiants from O4 to A5 yields a mean value of .12 for  $v_\phi \sin i / v_e$  (this value is also close to the median). If we use this value as a dividing criteria to make two groups of stars, the group with higher values of  $v_\phi \sin i / v_e$  shows more mass loss ( $\dot{m}$ ). The comparison is summarized in Table 1. To decrease the uncertainties caused by the  $\sin i$  factor, a larger sample with observed  $v_\phi \sin i$  values would be very useful.

Between  $L_{NR}$  and  $\dot{m}$ ,  $L_x$ , etc., the relationships need not be linear. Other complications like the strength of the magnetic field and the magnitude of surface gravity may come in. Quantitative models relating all these parameters have not yet been developed. The present note merely suggests a possible mechanism for the generation of non-radiative energy inside hot stars.

We appreciate the helpful discussions with Dr. Wayne Waldron.

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Table 1 Comparison of two groups of supergiants

	the group with $v_{\phi} \sin i/v_e > .12$	the group with $v_{\phi} \sin i/v_e < .12$
number of stars	18	17
$\langle v_{\phi} \sin i/v_e \rangle$	0.154	0.084
$\langle \dot{m} \rangle (M_{\odot} \text{yr}^{-1})$	4.62(-6)	0.92(-6)

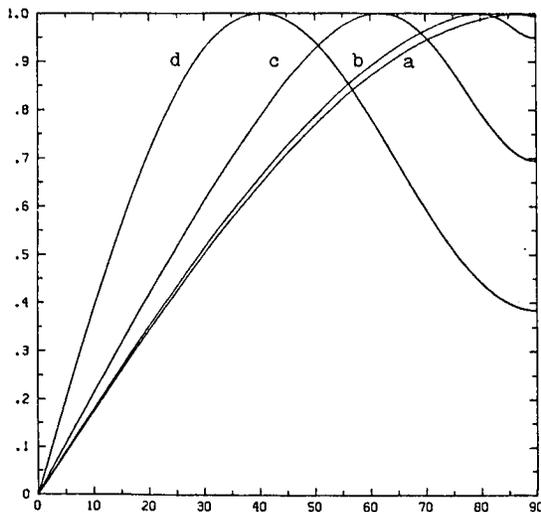


FIG. 1 Differential Rotations

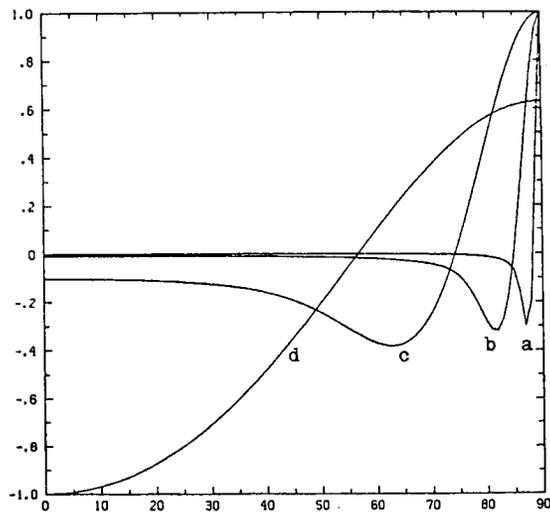


FIG. 2 Meridional Circulations

## DISCUSSION

Castor: The correlation of  $\dot{M}$  with  $(v_{\text{rot}} \sin i)/v_{\text{esc}}$  needs to be first compensated for the L variations in the sample. Lamers and others included  $v_{\text{rot}} \sin i$  with L in a least-squares analysis of mass loss rates. They found no dependence on  $v_{\text{rot}} \sin i$ .

Cassinelli: Barker, Marlborough, and Landstreet (in Six Years of IUE Research, 1984) have shown that for ordinary B stars the anomalous ionization of C IV 1548,1550 ceases at B2, while for Be stars C IV is seen as late as B9e. There is certainly a correlation of mechanical energy deposition with  $v_{\text{rot}} \sin i$ .

Mullan: The ratio of  $v_{\text{rot}}/v_{\text{esc}}$  also determines where CIR's form. The larger  $v_{\text{rot}}/v_{\text{esc}}$  is, the closer to the star the CIR's form, and the more material there is available in the CIR to create non-thermal lines (either in absorption or emission).

# BIPOLAR FLOWS AND X-RAY EMISSION FROM YOUNG STELLAR OBJECT

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**Abstract:** Production of both the large scale CO bipolar flows and the small scale optical bipolar jets from the star-forming regions is given interpretation in terms of a magnetic mechanism related to accretion model. It is shown by an axisymmetric 2.5-dimensional simulation that the large scale cold bipolar flow may be produced in the relaxation of the magnetic twist which is created by the rotational winding-up of the magnetic field in the contracting disk. In contrast, the small scale warm bipolar jets may be driven by the recoiling shocks which are produced in the crash at the stellar surface of the infalling material released from the inner edge of the disk through magnetic reconnections.

## 1. Introduction

Very young stars like the T Tau stars that emerge from dark nebulosities are known to exhibit vigorous activities observed as the large and rapidly varying blue and red shifts in the hydrogen lower Balmer lines (Strom, Strom and Grasdalen 1975, Mundt and Giampapa 1982, Hartmann 1982). Models to interpret these activities discussed thus far include the stellar wind models (Kuhi 1964, Hartmann and MacGregor 1982) and accretion models (Lynden-Bell and Pringle 1974, Ulrich 1976, Bertout 1979), but no ultimate success has been obtained.

Evidence of X-ray emission from the region near the stellar surface (Walter and Kuhi 1981), as well as of the large scale bipolar flows observed in millimetric CO lines (Snell *et al.* 1980, Bally and Lada 1983, also, Cohen 1982) came later and suggested the necessity of the global consideration of the problem. More recently, the presence of tiny warm bipolar jets also in the general direction of the large scale cold bipolar flows was reported (Mundt and Fried 1983), and added further problem to be solved.

In this paper, we propose a new picture in which the effect of the magnetic field in the contracting "proto-disk" plays important roles. This model explains the coexisting in- and outflows near the stellar surface, X-ray activities, and the small scale warm bipolar jets, as well as the origin of the large scale cold bipolar flows, in a consistent way.

## 2. Situation of the Present Model

The regions where the cold bipolar flows are found in millimetric CO lines are related to the regions of star formation in dense and cold nebulosity. We here concentrate ourselves to the bipolar flow L1551 (Snell

*et al.* 1980 ) which is a typical example in which the basic processes are most clearly seen in a nice projection. The lobe in the bipolar flow emanating from the central IR object , IRS-5 in this example, has a length of the order of 1 pc, the width of 0.3 pc, the ordered velocity of 30-50 km/s ( 15 km/s in the line of sight ), the density of  $10^{3-5} \text{ cm}^{-3}$  , and the temperature of a few tens K. The total mass,  $M_f$  , total energy of the flow,  $M_f V_f^2/2$  , and the mass loss rate,  $\dot{M}_f$  , of the flow, amount to  $0.3 M_\odot$  ,  $7 \times 10^{43}$  ergs, and  $10^{-4} M_\odot \text{ y}^{-1}$  , respectively ( Bally and Lada 1983 ). Warm optical jets have a size of 0.05 - 0.2 pc with a high velocity of 100 - 200 km/s ( Mundt and Fried 1983 ). A disk-like object surrounding the central IR source and perpendicular to the bipolar flow axis is observed in CS 49 MHz line ( Kaifu *et al.* 1984 ), and the rotation velocity of 0.35 km/s and the density of  $>10^6 \text{ cm}^{-3}$  , averaged at a radius  $\sim 0.1$  pc, are derived. The total mass of the disk is estimated to be  $\sim 3 M_\odot$  . The whole system is located at the edge of a dark cloud, and the interstellar polarization indicates that the general direction of the interstellar magnetic field is roughly parallel to the bipolar axis ( Vrba, Strom, and Strom 1976 ).

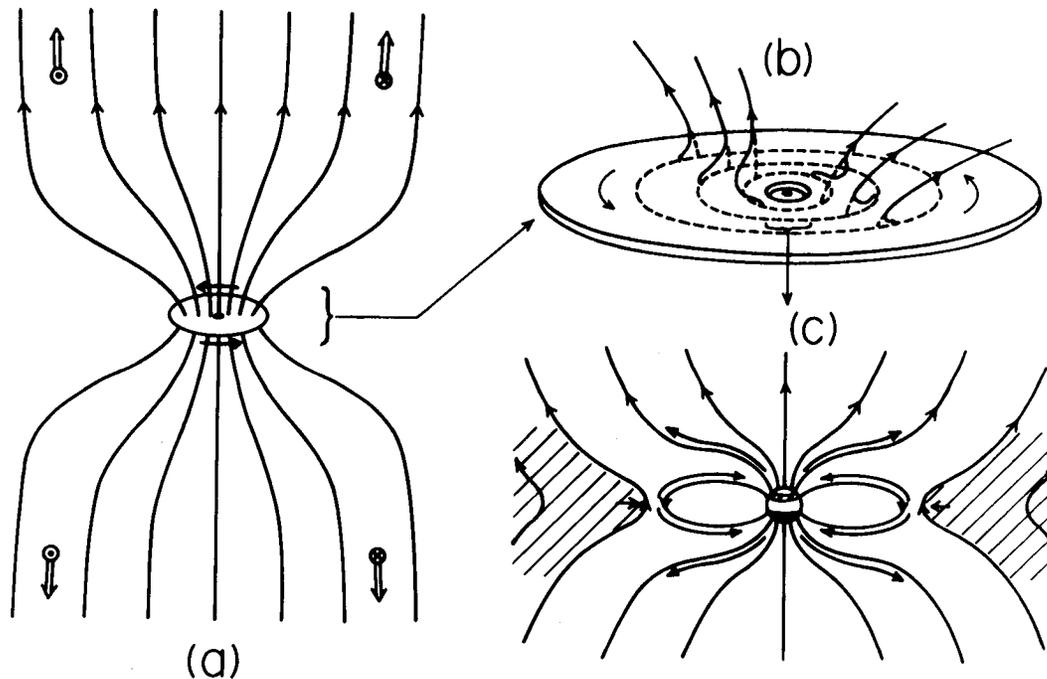


Fig. 1. Schematic presentation of the situation. *Left*: Global situation of large-scale bipolar flows and rotating disk. *Top*: Disk and the wound-up magnetic field lines. *Bottom*: Magnetic field configuration near the central object. Note the magnetic neutral points ( ring ) and the flow of material leaked by magnetic reconnection. ( Uchida and Shibata 1984a )

The model situation we deal with, in accordance with these observations, is schematically shown in Figure 1. A part of the nebulosity having a uniform magnetic field contracted by the gravitational instability, and brought the magnetic flux together with the mass into the condensation. Although a large part of the magnetic flux escaped in the cold molecular cloud phase ( Nakano 1979, Mouschovias 1979 ), some part remained until the time when the frozen-in state was restored as the temperature rose due to compression and stellar radiation. The field strength may be estimated to be of the order of 10 mG when  $n \sim 10^9 \text{ cm}^{-3}$  in the disk. The rotating material in the contracting disk pulls the field lines around the axis and twists them up. The dynamics in the relaxation of the twist thus created will be discussed in connection to the acceleration of the large scale bipolar flows in section 3.

In the vicinity of the central object, the situation is somewhat more complicated. As soon as the central object establishes the domain of its magnetic influence, there appears a magnetically neutral ring in the equatorial plane ( Uchida and Shibata 1984a ). This ring of magnetic neutral points is activated if the angular momentum of the inner disk material is carried away along the magnetic field and the rotation becomes sub-Keplerian, and the magnetic structure is overloaded. The magnetic reconnection at the neutral ring allows the leakage of the stored mass to the stellar surface, and the inflow of mass, its heating to an X-ray emitting temperature, and the outflow driven by the recoiling shock, may take place as described in Uchida and Shibata (1984a). These will be recapitulated in section 4, specifically with the application to the small scale warm bipolar jets in mind.

### 3. Large Scale Motion Induced by Interaction of Rotating Disk with Magnetic Field

In the large scale, the cloud rotating in the sub-Keplerian velocity forms a contracting "proto-disk" which exerts stresses on the magnetic field both in  $-r$  and  $\varphi$ -directions. We made an axisymmetric 2.5-dimensional simulation (  $\partial/\partial\varphi=0$  but  $B_\varphi$ ,  $v_\varphi$  are non-zero) for this state by assuming a simple initial situation in which the disk is imbedded in a constant magnetic field in the  $z$ -direction. A preliminary calculation, in which the parameters describing the system,  $\beta \equiv 8\rho T/(B^2/8\pi)$  and  $\varepsilon \equiv 8T/(GM/r)$  in the inner disk are tentatively taken to be 0.5 and  $3 \times 10^{-3}$ , respectively, is shown in Figure 2. A hydrostatic corona assumed to fill the space outside the disk has a density  $2 \times 10^{-3}$  times that of the disk at the border.

It is clearly seen from Figure 2 that as the disk, given  $0.5 \times$  local Keplerian velocity at each point as an example, contracts towards the Keplerian radius, the field lines are pulled around by this spiralling motion, and the twist in the motion begins to relax into  $\pm z$  directions. In such a relaxation of  $\varphi$ -component of the magnetic field into low- $\beta$  regions, the induced motions are helical outflows whose axes are in the  $\pm z$  directions ( Uchida and Shibata 1984b, Shibata and Uchida 1984 ). The flow is turned toward the  $\pm z$ -direction as the centrifugal force of the helically accelerated gas is given barrier by the magnetic field whose footpoints are anchored in the contracting disk. The front of  $B_\varphi$ -packet guided along the large scale field continues to accelerate the gas. The velocity of the flow is roughly the Alfvén velocity which is  $10 \sim 80 \text{ km/s}$  in the region far from the disk, coinciding with the observed range of velocities of CO bipolar flows ( Bally and Lada 1983 ).

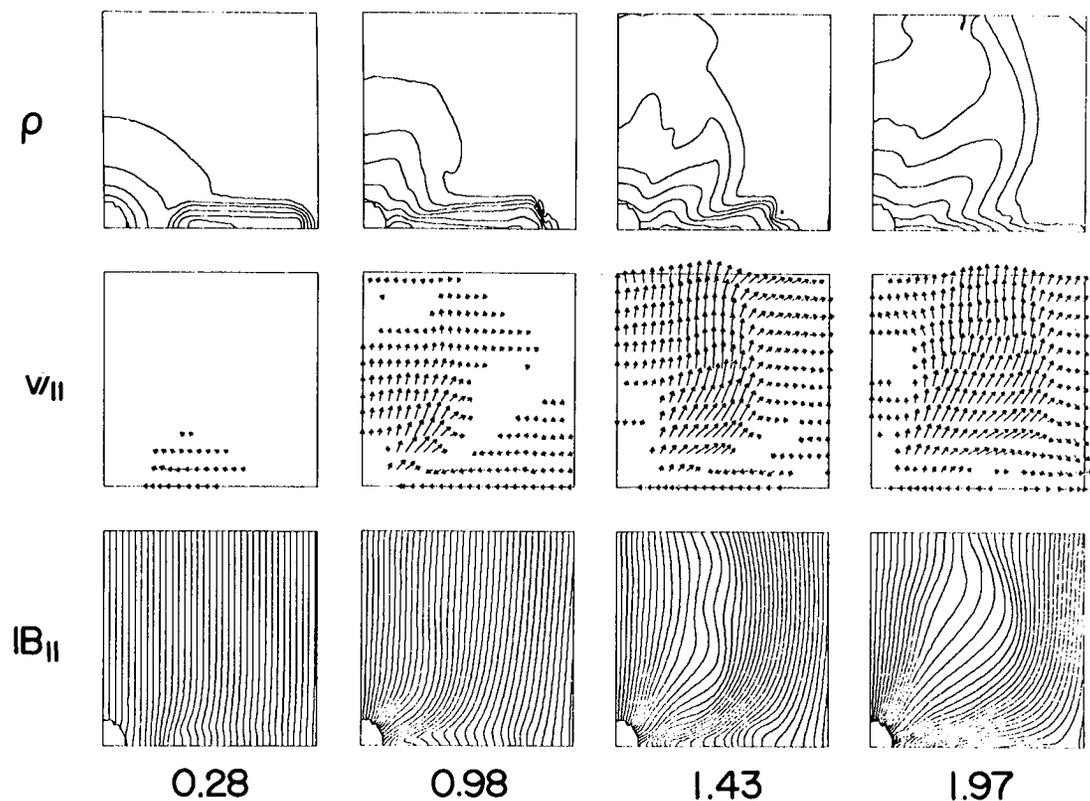


Fig. 2. Time variation of  $\rho$ ,  $v$ , and  $B$  (top to bottom). It is seen that the material is accelerated in helical paths on a conical surface with initially large but eventually small opening angle. ( see details in Uchida and Shibata 1984c in preparation )

#### 4. Flows Near the Central Object — Coexisting In- and Outflows, X-ray Activities, and Small Scale Optical Bipolar Jets

Now we consider the region near the central object. The magnetic structure by which the magnetized gas accreted later is suspended has a magnetically neutral ring located at several stellar radii ( $R_1 \sim 6r_*$  in the equatorial plane. Figure 1 of Uchida and Low 1981), if the established stellar polar field is several hundred gauss ( Nakano and Umebayashi 1982 ), and the physical parameters in the disk at the inner-most part are  $B \sim 5G$ ,  $n \sim 10^{11} \text{ cm}^{-3}$ , and  $T \sim 10 \text{ K}$  ( Uchida and Shibata 1984a ).

Leakage of the gas, which is once buffered by the magnetic structure, may take place if the rotation is sub-Keplerian and the magnetic reconnection occurs at the magnetically neutral ring ( Figure 1c ). The rate of mass

transfer through the neutral ring,  $\dot{M} \sim 2\pi R_1 h \rho_1 v_{eff}$ , where  $h$  ( $\sim R_1$ ) is the effective thickness of the disk with the density  $\rho_1$ , and  $v_{eff} \sim 0.1 V_A$  for the reconnection (Sato and Hayashi 1979), turns out to be  $\sim 2 \times 10^{-8} M_\odot/y$ .

The mass transferred will execute a free-fall along the flux tubes to the edges of the polar caps in both hemispheres and convert its potential energy ( $E = GM_* (R_1^{-1} - r_*^{-1}) \sim 6 \times 10^{14}$  erg/g) into kinetic energy, and eventually into heat in the crash at the stellar surface. The rate of energy liberation,  $L = \dot{M} E \sim 6 \times 10^{32}$  erg/s, may be sufficient for the X-ray emission from such stars.

A simulation calculation (Uchida and Shibata 1984a) shows that regions with a temperature as high as a few times  $10^7$  K is created at the surface and a rebound shock is sent out from the crash. The shock increases its strength as it propagates out into the decreasing density of the tail of the infalling material, and drives the material out along the field lines toward the polar directions. This outflow can coexist with the inflow because the paths of them are separated by the reconnection as shown in Figure 2 of Uchida and Shibata (1984a).

The lateral size of the flow is of the order of ten stellar radii, and the velocity and the temperature of the outflow near the star are 600 km/s and  $6 \times 10^6$  K, respectively, and therefore the observed values in the optical bipolar jets (Mundt and Fried 1983) of the order of  $2 \times 10^2$  km/s and  $10^4 \sim 5 \times 10^4$  K, respectively, at a distance from the star, may be reasonably explained as due to the gravitational deceleration and expansion.

## 5. Conclusion and Discussion

In our picture, the large scale cold bipolar flows are propelled by the relaxation of the magnetic twist (Uchida and Shibata 1984b) which is created by the rotation of the contracting "proto-disk". Since, in our picture, the cold bipolar flows do not come from the central star (cf, Draine 1983) but rather from the gravitationally contracting disk itself, they can have pretty large mass as well as mass-loss rate not restricted by the stellar mass itself. The energy source is gravitational energy of the contracting disk and the magnetic field plays an intermediary role in converting the energy into the energy of the flow directed to the polar directions.

In contrast, the small scale optical bipolar jets are related to the hot X-ray emitting region and the recoiled shock produced in the crash of the infalling material at the stellar surface. The flow is also directed towards the polar directions by the magnetic effect but at much closer distance to the star. X-ray emitting region produced nearer to the stellar surface than the  $H_\alpha$ -emitting regions (Walter and Kuhl 1981), and the coexistence of in- and outflows of large velocities at the stellar surface, are explained in a natural way in our picture.

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## DISCUSSION

Chan: The opening angle of your "jet" seems wide (~ 45 degrees)? Does it curve back later?

Uchida: Yes. As the slides show, the flow is guided by the external magnetic field toward the poles. The flow initially expands in the r-direction owing to the centrifugal force (due to induced rotation) which is caused by the angular momentum transmitted from the shrinking disk through the action of the magnetic field. As soon as the centrifugal force becomes small (as  $v_\phi$  gets smaller because of expansion in r), the flow is bent toward the polar directions as a result of the confinement by the external magnetic field. The opening angle at large distances is small.

Castor: Is the jet quasi-steady or episodic as lumps of matter fall through the neutral point?

Uchida: It can be either continuous or episodic. At least a continuous operation is possible without degrading inflows and outflows because of the automatic separation of the path of the magnetic reconnection. If the supply of the material changes, the heating and outflow can show a bursting profile.

Praderie: Can you sketch how the configuration which you compute for the magnetic field, jets, inflow and outflow evolves when the star comes nearer to the main sequence? Does the whole configuration become more spherically symmetric?

Uchida: I have not looked into the evolutionary problem in terms of the stellar-evolution time scale. The change in the configuration of the field in a short time scale can be told, however. When the amount of accreted material increases, the neutral ring shrinks, but as the material disappears, the neutral ring may regain a larger size through inverse reconnection.

Feigelson: May I comment that the available X-ray data generally do not directly address the very young stars to which your models refer owing to a selection effect. The stars that are undergoing initial contraction, or that are the source of Herbig-Haro objects and bipolar flows, are deeply embedded in the clouds, so that soft X-rays can not penetrate (see Pravdo and Marshall 1981 for a possible exception). We know only that (presumably older) stars which have emerged from the primordial collapsing cloud do emit X-rays.

Uchida: I agree. I mentioned the activity in the earlier stage mainly in the context of bipolar flows. The X-ray emission we are looking at may be the emission which occurs in the phase toward the end of the activity; the main phase may be hidden by the nebulosity.

Lafon: Could you comment on the coupling of the magnetic field and the fluid. The degree of ionization is highly variable in time so that magnetic fields may be lost at some stages.

Uchida: I think that the magnetic field and the fluid decouple in the cold-molecular-cloud phase and this lets a large fraction of the field escape. A certain fraction, however, is brought into the star, and this amount corresponds to the stellar dipolar field with  $\sim 10^3$  G at the pole, according to some people, in the case of the less massive stars. The part held by the disk may recover a frozen-in state as soon as the temperature increases owing to compression and/or to absorbing photons from the central star.

# NON-RADIATIVE HEATING AND ENHANCED MASS-LOSS DUE TO SHEAR TURBULENCE IN MASSIVE HOT STARS

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## Abstract:

Rotation in massive stars generates shear turbulence. This has the consequence of heating the outer layers of massive stars and enhancing mass-loss in the early spectral types. Model calculations are presented and discussed in support of these effects.

## I. INTRODUCTION

It is well known that additional mechanisms for heating the outer layers of massive stars are required to understand the presence of certain ions of Nitrogen and Oxygen in the spectra of early type massive stars exhibiting radiatively driven winds (Casinelli 1979). One also needs to understand the reasons for higher mass-loss rates in Wolf-Rayet stars as well as the more or less uniform rates of mass-loss in these stars which show a diversity of spectral features as contrasted by diverse mass-loss rates of otherwise common spectral features in O stars of comparable masses, (Conti 1983). We suggest that one of the reasons for these might be rotation and the attendant consequences such as an enlarged convective core and the generation of shear turbulence. We shall demonstrate the plausibility of this hypothesis with some computer models for massive stars.

## II. The Basic Physical Picture

It is known that massive stars exhibit considerable rotation (Conti and Ebbets, 1977). It is also known that the surface rotation of massive supergiants is of the order of  $\sim 50$  km/s. One knows from numerical computations that the convective core of massive stars shrinks as the models evolve off the zero age main sequence starting point (Sreenivasan and Wilson 1978a, Chiosi, Nasi and Sreenivasan 1978). One does not know however, the precise law of angular momentum distribution within the stars. Assuming that angular momentum per unit mass is constant throughout the star for purposes of illustration, the core will rotate faster than the surface layers according to:  $\omega_c r_c^2 = \omega_s r_s^2$ , where  $\omega_c$  and  $\omega_s$  are the angular speeds of the core and surface at  $r = r_c$  and  $r = r_s$  respectively.

When account is taken of the angular momentum carried off by the mass leaving the star, it can be shown that the surface layers will spin down by the time hydrogen is all converted into helium in the core (Sreenivasan and Wilson 1978b). One can also see that as the core shrinks in size, it will spin up to conserve angular momentum and that unless angular momentum transfer from the core to the mantle is taken into consideration the core will spin up to unreasonable speeds as it shrinks in radius to zero (Sreenivasan and Wilson 1982). A consequence of the spin-up of the core due to evolution and spin-down of the surface due to mass-loss is the generation of shear turbulence due to well-known rotational instabilities in Fluid Dynamics (Lin 1955). This instability gets worse with age and results in increased

shear turbulence.

We have recently modeled the transfer of angular momentum from the core to the mantle by generalizing the procedure given in 1978 (Sreenivasan and Wilson 1978b; Sreenivasan and Wilson 1984b). It can be shown that one of the effects of a rapidly spinning core is an enlarged size of the core due to reduction in the effective gravity. A rising bubble of convective element effectively travels farther as a result and causes an extended core. This has the dual consequence that the core spins up more slowly and the hydrogen burning lifetime of the model is increased due to the additional mixing of fuel. As a result, surface rotation lasts longer due to angular momentum carried over from the core, than the previous calculations indicated.

The mechanism envisaged for the heating is analogous to the one suggested many years ago by Biermann (1946) and Schwarzschild (1948) for the heating of the outer layers of the Sun by the non-thermal energy-flux generated due to noise in the hydrogen convection zone.

The amount of energy flux generated in the solar case was estimated using the theory of Lighthill (1952) and could be of the order of 1% of the radiative flux in the Sun. In the case of massive hot stars, we estimate the flux of energy generated by shear turbulence to be  $\sim 1/2 \rho (\Delta V)^2 v_s$ , where  $\rho$  is the average density in the mantle defined as the region outside the core and below the atmosphere ( $\tau = 2/3$ ) of the (star) model,  $\Delta V$  = difference between the rotational speeds of the core and surface, the constant of proportionality takes into account an efficiency factor and allowance for the latitude dependence of rotational speed, and  $v_s$  is the average of the sound speeds of the core and surface layers. This flux is at least comparable to the radiative flux of these models and thus represents a significant reservoir of non-thermal energy for the star.

As in the solar models, the non-thermal energy flux is carried in the form of progressive waves outward and dissipated in the outer layers to heat them. This results in a Corona. The temperature minimum, defined as the location where the velocity of the progressive waves is equal to the local speed of sound occurs at a few scale heights above the limb for the Sun. In the case of massive stars, this point could be much closer and indeed below the limb since the flux of non-thermal energy carried by these waves is much greater. Thus coronal conditions would exist right outside the limb.

### III. Model Computations and Discussion

We have made model computations for 40, 60, 80 and 100  $M_{\odot}$  zero age initial masses with composition  $X = 0.70$  and  $Z = 0.03$ . We have carried the calculations to the end of core helium burning. Details of the computations will be published elsewhere (Sreenivasan and Wilson 1984a). The increase in the shear as the models evolve result in an increase in the mass loss rate and provides a logical explanation for the enhanced mass-loss rates of WR stars. The scenario depicted results in a different explanation for the blue/red supergiant ratios, the existence of a WR phase for massive stars in the post blue/red supergiant phase, and the consequence of an extended convective core (analogous to but not the same phenomenon as convective overshoot). (Sreenivasan and Wilson 1984a,b). We have not yet, however, constructed a detailed model for the heating of the outer layers of the

massive stars using the non-thermal energy flux due to shear turbulence. It appears to be a promising possibility as one can understand the presence of the N V and O VI in the spectra of these objects and the existence of a hot Corona as well.

Other promising applications of the non-thermal energy reservoir due to shear turbulence in rotating stars are to the understanding of variability in supergiants such as  $\alpha$  Cyg and  $\beta$  Cephei stars (Narasimha et al, 1984; Sreenivasan and Wilson 1978c; Papaloizou and Pringle 1978; Ando 1981). In the case of low mass stars:  $1-3 M_{\odot}$ , results have been obtained towards an understanding of blue stragglers, enhanced mass-loss in red giants and the spectral peculiarities of p giants (Scalo 1981).

Fuller details of these studies will be reported elsewhere (Sreenivasan and Wilson 1984 c, d).

#### Acknowledgement

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TABLE I

$M_0 (M_\odot)$	$\dot{M}_0$	$\dot{M}_H$	$\dot{M}_{He}$	$(F_r)_0$	$(F_r)_H$	$(F_T)_0$	$(F_T)_H$	$V_r/V_c$	$\Delta \tau_{ms}$
40	1.14(-6)	26.3(-6)	2.8(-6)	1.9(14)	1.8(14)	1.0(21)	4.5(21)	0.16	-
60	3.16(-6)	28.4(-6)	3.0(-6)	2.9(14)	8.6(14)	0.2(21)	5.6(22)	0.28	0.3(6)
80	4.39(-6)	21.8(-6)	3.6(-6)	3.6(14)	1.0(14)	0.9(21)	3.5(21)	0.26	-
100	7.62(-6)	38.0(-6)	18.3(-6)	4.3(14)	2.6(14)	1.7(21)	5.0(21)	0.41	-

$M_0$  = Zero Age main sequence mass

$\dot{M}$  = Mass Loss rate ( $M_\odot \text{ yr}^{-1}$ )

$F_r$  = Radiative flux ( $\text{erg cm}^{-2} \text{ s}^{-1}$ )

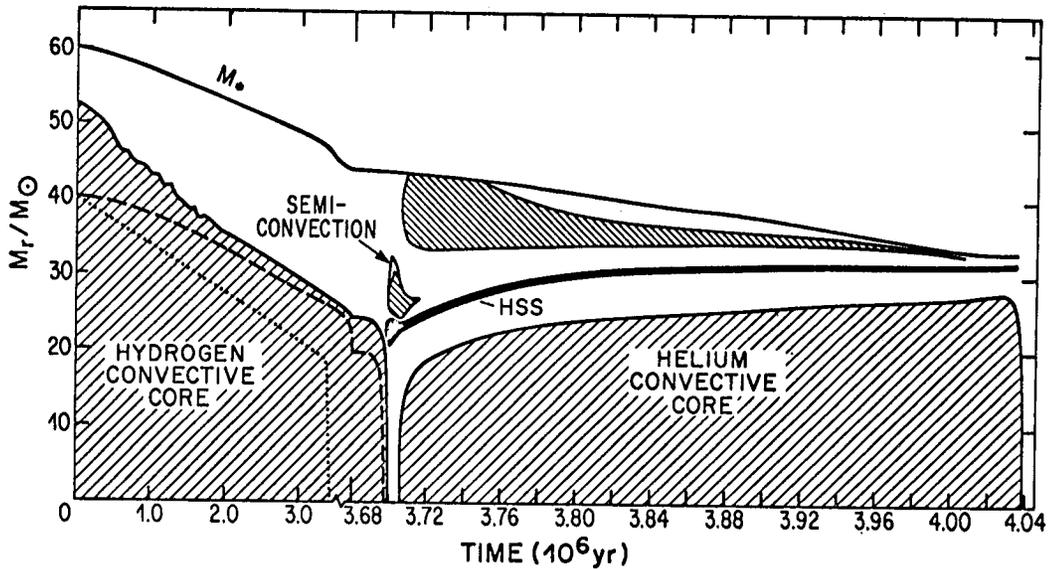
$F_T$  = Nonthermal flux due to shear turbulence ( $\text{erg cm}^{-2} \text{ s}^{-1}$ )

$V_r/V_c$  = Ratio of surface rotational speed to breakup speed =  $\left(\frac{GM_\star}{R_\star}\right)^{1/2}$

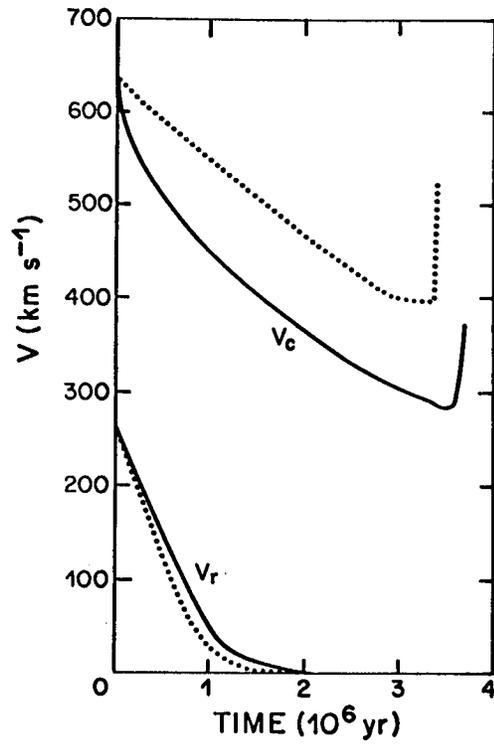
$\Delta \tau_{ms}$  = Increase in main sequence lifetime due to rotation (yr)

NOTE: (1) a subscript o refers to the ZAMS; H to central hydrogen exhaustion, and He to central helium exhaustion.

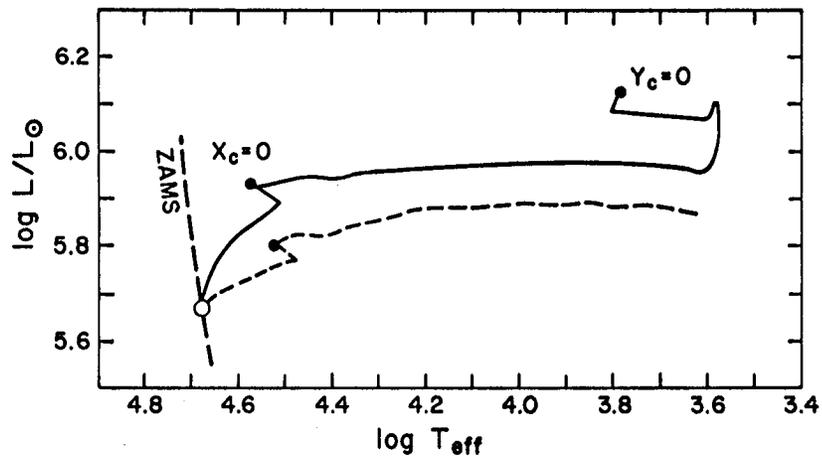
(2) A number in parentheses gives the power of 10 to which the preceding number is to be raised.



Change of internal structure with age (note increase in size of the Hydrogen burning core).



Spin-down of core and surface rotation.



Evolution of a  $60 M_{\odot}$  model.

## DISCUSSION

Mullan: It is clear that Wolf-Rayet stars may lose mass because of pulsational instabilities in helium burning stars. Do your models suggest that this can explain the high  $\dot{M}$  of Wolf-Rayet stars?

Sreenivasan: In our model the high mass loss rates are due to the combination of a radiation-pressure driven (cold) wind and the hot wind driven by shear turbulence produced by nonthermal energy flux. One can easily account for mass-loss rates of  $10^{-5} M_{\odot} \text{ yr}^{-1}$  this way. In addition, differentially rotating stars like our models show non-radial oscillations. Both g modes and r modes are excited. Resonant coupling between the frequency of rotation and the frequencies of the nonradial modes may yield high amplitude oscillations resulting in additional mass loss as well as in the observed variability of OB supergiants.

M.A. Smith: Did you mean to imply that you can get mass loss from r-modes (Rossby waves)? How could this drive off mass since these modes do not vibrate up and down?

Sreenivasan: Both r-modes and g-modes are excited. A Kelvin-Helmholtz instability also develops. As a consequence, the amplitudes of these modes grow as you go outward from the center of the star. Mass loss occurs through resonance with the rotational frequency of the star. One should remember also that there are progressive waves due to acoustic flux generated by shear turbulence. Non-radial pulsations, therefore, increase mass loss due to (a) radiation pressure, and (b) shear turbulence. They should also produce mixing.

Underhill: I prefer to use the word "mantle" for the outer part of the stellar atmosphere where the deposition of nonradiative energy and momentum determines the physical state of the plasma. A problem which I think should be addressed is how, by what mechanism, is a supply of energy in one form transferred to a low density plasma so that the plasma radiates in the way observed. It is necessary to provide extra nonradiative energy in the photosphere, but also to enable the energy to get into the mantle (my mantle) as heat.

Sreenivasan: Agreed.

# A LEAKY WAVEGUIDE MODEL FOR MHD WAVE DRIVEN WINDS FROM CORONAL HOLES

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## INTRODUCTION

High speed solar wind streams are now known to originate in discrete open field magnetic structures within the solar corona called coronal holes (Krieger et. al. 1973; Neupert and Pizzo 1974). Observations of the plasma state within coronal holes when combined with in situ measurements of solar wind properties by spacecraft in the interplanetary medium can provide enough information to allow a valuable test of solar wind theory. Results so far have indicated that classic solar wind theory with heat conduction as the sole energy transport mechanism cannot account for the observed properties of high speed solar wind streams (Holtzer and Leer 1981; Kopp 1981). Another mechanism is needed to transport energy from the base of the corona out to the wind acceleration region. Magnetohydrodynamic (MHD) waves, driven by the large scale convective motions of the photosphere have been suggested as a possible source of additional acceleration for the wind. Most of the turbulent power in a coronal hole is carried by MHD waves with periods of a few hundred seconds or longer. This is evident from direct observations of turbulence in the solar photosphere, as well as in situ observations of turbulence in the solar wind. But waves with periods this long have wavelengths which are typically as large as the transverse scale of the coronal hole flux tube itself. For these waves boundary effects are important and the coronal hole must be treated as a waveguide. The basic purpose of this paper is to briefly discuss the propagation of MHD waves using this waveguide approach. For more detail see Davila (1984).

## DISCUSSION OF RESULTS

Consider a MHD wave incident on the interface between two media characterized by different Alfvén speeds. Such a situation would be relevant at the boundary of a coronal hole like the one shown in figure 1. Each medium is assumed to be characterized by a different value of the transverse propagation constant  $\kappa$ . This variation of  $\kappa$  is the result of density variations in the model presented here. As one might expect a portion of the incident wave energy is reflected from the interface while the rest is transmitted. The distribution between reflected and transmitted

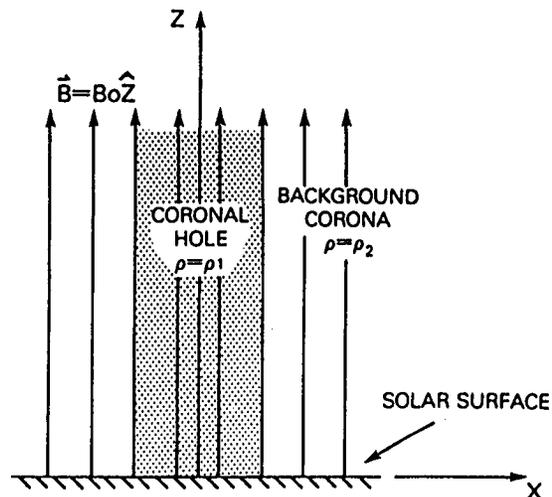


Figure 1: Model Coronal Hole with  $\rho_1 < \rho_2$ .

energy can be calculated by simply considering plane wave solutions along with the boundary conditions; (1) continuity of the normal component of the velocity and (2) continuity of the pressure. The reflection coefficient obtained in this way is completely analogous to the well known Fresnel coefficients of electromagnetic theory, and can be expressed as

$$\frac{A_r}{A_i} = - \frac{\kappa_1 - \kappa_2}{\kappa_1 + \kappa_2} = - \frac{\sin \theta_1 - \sqrt{N^2 - \cos^2 \theta_1}}{\sin \theta_1 + \sqrt{N^2 - \cos^2 \theta_1}}$$

where  $\theta_1$  is the grazing angle (not the usual angle of incidence measured from the surface normal) and  $N = v_{a1} / v_{a2}$  is the ratio of the Alfvén speeds of medium 1 to medium 2. This ratio,  $N$ , plays the same role as the ratio of refractive indices in the Fresnel equations. Graphs of the reflection coefficient are shown in figure 2 (3) for cases where  $N^2$  is smaller (larger)

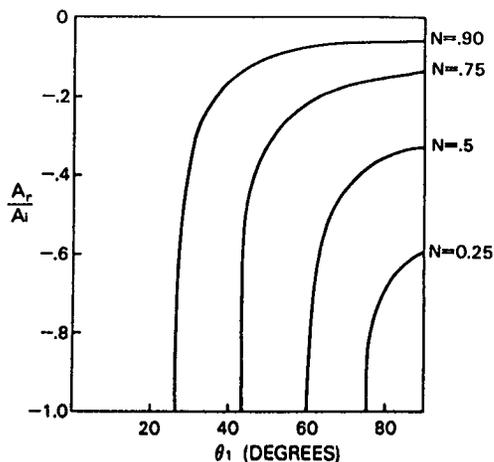


Figure 2: The Reflection Coefficient for a Coronal Loop where  $v_{a1} < v_{a2}$ .

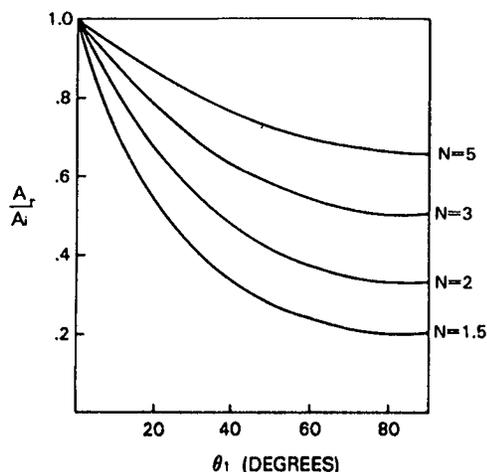


Figure 3: The Reflection Coefficient for a Coronal Hole where  $v_{a1} > v_{a2}$ .

than unity. The type of wave propagation implied by these two cases is qualitatively and quantitatively different. To see this consider first the case where  $N^2 < 1$ .

In this case when  $\cos^2 \theta_1 > N^2$  the incident wave is totally reflected. This phenomenon results in the fully guided modes of the dielectric waveguide. For these waves energy is trapped entirely within the guiding structure. Ionson (1982) has emphasised the importance of this phenomenon for heating closed loops within the solar corona. However, for coronal holes  $N^2 > 1$  so that there is no possibility of total internal reflection at the interface between the plasma inside and outside of the coronal hole. Nevertheless, as shown in figure 3 the reflection coefficient can become relatively large, approaching unity, when the grazing angle becomes small. The high reflectivity at grazing incidence allows the propagation of nearly guided leaky wave modes in the coronal hole flux

tube. Mathematically these waves are described by the same dispersion relation as the fully guided modes. The difference is that the propagation constant,  $k_z$ , within the flux tube is allowed to be complex. It is worthwhile to emphasize here that the imaginary part of the propagation constant is not due to damping of the wave since only dissipationless processes have been considered in this analysis. Instead, the imaginary part of  $k_z$  is a measure of the rate at which wave flux leaks through the boundary. Formally these leaky wave solutions are obtained as the complex generalization of the dispersion relation for fully guided modes.

A more rigorous mode theory of the coronal hole waveguide can be obtained as well. Solutions of the wave equation and were developed for the model coronal hole shown in figure 1 and the dispersion relations were obtained. Numerical solutions of the dispersion relation are presented for the lowest order symmetric wave mode in figures 4 and 5. Results of this solution can be

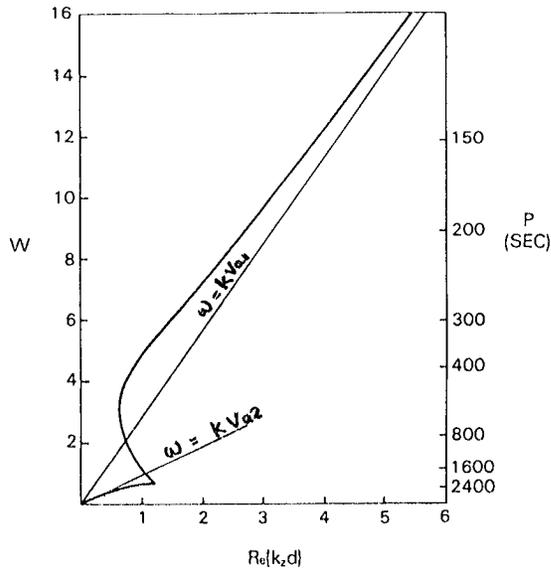


Figure 4: The Real Part of  $k_z$ .  
 $W^2 = (\omega^2 d^2 / v_{a1}^2)(N^2 - 1)$ .

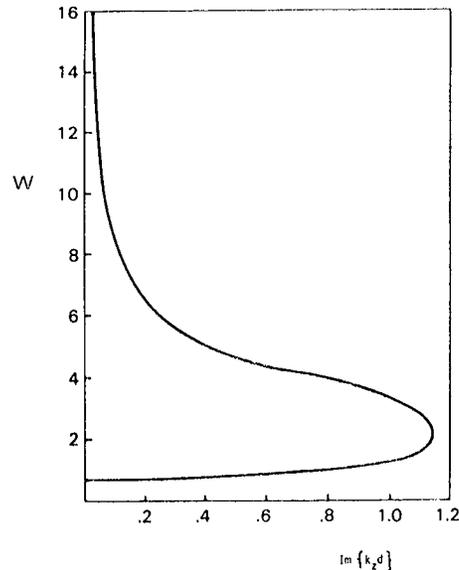


Figure 5: The Imaginary Part of  $k_z$

summarized as follows. High frequency, short wavelength, waves propagate inside the coronal hole at essentially the Alfvén speed of the interior. The boundaries are not important for these small scale disturbances. Very low frequency, long wavelength, symmetric waves can propagate at essentially the Alfvén speed of the external medium. These waves have scales large enough so that the coronal hole has little effect on their propagation characteristics. These waves are essentially the "infinite medium" modes of the external plasma. As one might have expected, when the wavelength is on the order of the transverse size of the coronal hole the waves propagate at a phase speed intermediate between the phase speed of the interior and exterior medium and the leakage rate is maximized. Finally, detailed

examination of the dispersion relation shows that for a band of wave periods near 100 seconds the group velocity is downward. Oscillations at the base of the corona with these periods cannot transfer energy upward into the corona. This is important since the turbulent power spectrum in the photosphere seems to peak very near this period due to the 300 second p-mode oscillations. These estimates of the wave period are based on nominal solar coronal parameters of  $v_a = 10^8$ ,  $d = 10^{10}$  and  $N=3$ . The model used in these calculations is a rather simplified one, so that more detailed calculations will have to be done before this effect can be quantified.

Using the solution for  $k_z$  obtained above, the time averaged force on the plasma due to the propagation of these leaky wave modes in the coronal hole waveguide can be evaluated. This force can be thought of as consisting of two terms, a magnetic wave pressure and magnetic wave tension. The balance between these two forces determines the direction and magnitude of the net force on the plasma. Calculations are presented in figure 6 of  $\epsilon_f$ , the ratio of the total wave force to the wave pressure force. These results show that when the leakage rate becomes large the tensile force can become significant. For some frequencies the tensile force can dominate the wave pressure force resulting in a net downward (i.e. negative) wave force.

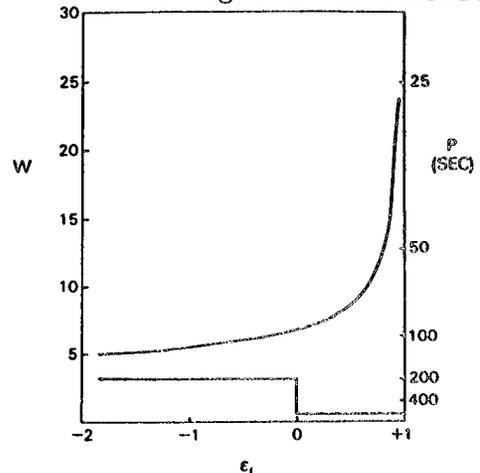


Figure 6: Ratio of Total Wave Force to Wave Pressure Force.

## CONCLUSIONS

The simple model presented in this paper demonstrates that coronal holes can act as waveguides for MHD waves. For typical solar parameters the waves are compressible and can generate a wave tensile force which tends to cancel at least part of the wave pressure force. This effect tends to decrease the efficiency of MHD wave acceleration. Additional work must be done to incorporate wave sources and more realistic models of the corona.

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## DISCUSSION

Uchida: You proposed a waveguide-type function for the open field region, but if we consider fast-mode waves even of 5-minute periods, the lateral wavelength is too long and the waves do not seem to fit into the waveguide.

Davila: For 5-minute wave periods and typical solar coronal parameters the Alfvén wavelength is  $\sim 10^{10}$  cm. This is roughly the transverse size of a coronal hole. Waves with longer periods have higher leakage rates. Perhaps this is the physical manifestation of long wavelengths: not fitting into the waveguide.

Martens: Do not these external structures also radiate energy into holes? You only talk about absorption. If not, why not?.

Davila: Since the structures outside the coronal holes are more dense, e.g. streamers, they act as traps for wave flux. Because of this, energy which escapes is not likely to return to the coronal hole.

Mullan: SKYLAB data suggested that in coronal holes mass ejection occurs from discrete sources. Maybe mass is ejected from discrete magnetic events at the base of the corona.

Davila: It has been suggested that mass can be ejected as discrete diamagnetic blobs over X-ray bright points. I have seen no evidence to rule out that mechanism at this time.

Wentzel: Can the "force" due to the tension be compensated by a corresponding term from the gas pressure? The discontinuity at the boundary requires a finite gas pressure somewhere.

Davila: Whenever the net force on the coronal-hole plasma is downward, there will be a modification of the zero-order pressure scale height to compensate this force. For first-order (wave) motions, thermal pressure is insignificant since it is strongly dominated by magnetic pressure.

## RADIATIVELY DRIVEN WINDS AND WHAT THEY IMPLY:

A review of radiative driven instabilities and their importance in hot stars.

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### 1. Introduction.

One of the aims of this workshop is to try and learn from what we know about other types of stars, such as the Sun and cool stars, and see if that experience and knowledge will help us in solving some of the problems existing in hot stars. In this workshop we are concerned in particular with the origin of non-radiative heating and momentum in hot stars, that is with problems of mass loss and the heating of gas to temperatures higher than a normal radiative equilibrium.

Hot stars have one property which is not shared with cool stars - they have a high effective temperature. This results in large radiative forces from the absorption of the photospheric radiation by gas in the outer layers of the star. The absorption comes from continuous opacity, such as bound-free, and free-free opacity together with Thomson scattering by electrons and from the opacity of many resonance lines of highly ionized impurity atoms such as carbon, nitrogen and oxygen. The resulting radiative forces are substantial. Typically they are half the force due to gravity when the absorption is continuous and are one hundred to one thousand times the force due to gravity if the absorption comes from just one unsaturated resonance line. The effects of these radiative forces in hot stars cannot then be deduced from studies of cool stars.

We know now that OB supergiants are losing mass at a rate typically a few times  $10^{-6}$  solar masses per year and that this mass flow is accelerated up to final velocities of 2000 - 3000  $\text{km s}^{-1}$ . The mass loss from OB main sequence stars is some orders of magnitude less.

Most workers in the field agree that the mass loss and acceleration of the mass flow comes, directly or indirectly, from the radiative forces of the resonance lines. These radiative forces can also cause instabilities to grow in the flow, and this is probably an important source of non-radiative heating and momentum in hot stars. In what follows the physical origin of these instabilities is described, and later some of the problems of hot stars where radiative driven instabilities may play a part are briefly discussed.

## 2. The types of instabilities.

The radiative driven instabilities which have been suggested fall into two main groups: drift instabilities and Rayleigh-Taylor type instabilities

### a) Drift instabilities.

The Drift instability grows and moves relative to the local fluid frame at a velocity about equal to the sound speed. A perturbation at one point thereby gives rise to a large amplitude disturbance at points down stream from the original perturbation. The radiative instabilities of this type that have been discussed all occur as an exponentially growing oscillations. In many cases they look very similar to a propagating sound wave which gains in energy with distance from its interaction with the radiative forces. If a sound wave propagates through an atmosphere with a steadily decreasing density, the amplitude of the wave increases. But this does not correspond to an increase in the flux of energy carried by the wave. In a radiative driven sound wave the flux of energy carried by the sound wave increases until non-linear processes cause dissipation to occur at a rate equal to or faster than the energy input from the radiative driving. A simple mechanical analogue of this instability can be seen in a driven pendulum. If a pendulum is set oscillating and then every time that the bob comes by in a given direction it is given an extra impulse, the amplitude of the pendulum oscillation will increase until some non-linear process causes energy to dissipate at the same rate as energy is fed into the oscillation by the impulses given to the pendulum bob.

In a sound wave, a given element of gas is undergoing simple harmonic motion like the pendulum bob. As the element of gas moves forward in the direction of the wave propagation it is compressed, and as it moves backwards it is rarefied. If one can increase the force on the element of gas during the compression and reduce it during the rarefaction, energy will be fed into the sound wave and it will be amplified. This extra force on the compression can be attained with radiative forces.

### b) Rayleigh-Taylor instabilities.

This is the classical instability of a dense fluid over a lighter fluid. One can find an equilibrium state, where all the hydrostatic forces are balanced, but the equilibrium is unstable. If one makes a perturbation of the fluids in the plane of the interface between them then the buoyancy forces are so changed that the perturbation continues to grow.

If the dense fluid is perturbed below the level of the original interface of the two fluids, it finds itself surrounded by lighter fluid. The buoyancy force is now reduced and dense fluid protrudes further into the lighter fluid. Similarly if the lighter fluid is perturbed above the level of the original interface of the two fluids, it finds itself surrounded by dense fluid and the buoyancy force is now increased and it continues into the dense fluid.

The Rayleigh-Taylor instability is essentially a two dimensional

instability unlike the radiative driven sound wave which is a one dimensional instability. In the classical Rayleigh-Taylor instability the short wavelength perturbations grow more rapidly than the long wavelength perturbations and the typical non-linear form of the instability shows fingers extending into the lighter fluid.

Again a Raleigh-Taylor type instability can be caused if the radiative forces act on a two dimensional perturbation so as to reinforce the movement of the perturbation. If the perturbation moves fluid upwards, the radiative forces in the upwards direction must be increased as a result of the perturbation.

### 3. Instabilities driven by radiative forces from continuous opacity.

#### a) Drift instability.

This radiative driven sound wave instability was suggested by Hearn (1972).

The radiative force acting on 1 gram of gas is  $\frac{H\chi}{c}$ , where H is the integrated radiative flux,  $\chi$  is the Rosseland mean opacity and c is the velocity of light. Consider a sound wave propagating outwards in a stellar atmosphere for which the optical depth corresponding to one wavelength of the sound wave is much less than unity. The perturbations to the atmosphere are then optically thin and have no effect on the radiative flux H. The atmosphere as a whole will of course be optically thick. Energy can be fed into the sound wave if the radiative force is increased in the compression. Since the radiative flux remains constant in an optically thin perturbation, the Rosseland mean opacity per gram must be increased.

The opacity from electron scattering is independent of the density, so it cannot cause a drift instability.

The other important opacity in the atmospheres of hot stars is the bound-free Lyman continuum opacity. Since the hydrogen is predominantly ionized the opacity is proportional to the number of atoms in the ground level, or proportional to

$\frac{\rho}{T} e^{-I/kT}$  where I is the ionization potential of hydrogen, T is the electron temperature and  $\rho$  is the mass density.

In an adiabatic compression the increase in the temperature reduces the opacity by more than the increase in the density increases it. This too cannot drive a drift instability. If the sound wave is isothermal the opacity is proportional to the density and a drift instability will occur. For the sound wave to be isothermal in a hot star atmosphere the period must be longer than about 1 second to allow for sufficient radiative cooling of the compression.

The growth time for this instability is long, typically a few thousand seconds. Berthomieu et al (1976) have pointed out that since the e-folding length for this instability is much greater than the density scale height in a stellar atmosphere, the final flux of energy is very small.

The same instability has been suggested independently by Mathews (1976) and Mestel et al (1976) in studies of radiation driven mass loss from Quasars.

b) Gradient instability.

This instability was suggested by Carlberg (1980). It is a two dimensional instability which is driven by the same mechanism as the preceding instability and occurs in a density gradient. The two dimensional isothermal perturbation causes an increase in the density with a consequent increase in the radiative force which drives the perturbation further. The instability is similar to a Rayleigh-Taylor instability and its growth time is also long, about  $10^5$  seconds.

4. Instabilities driven by radiative forces from resonance lines.

The radiative force resulting from one unsaturated resonance line is 100 to 1000 times greater than the force due to gravity. This is much larger than the radiative forces coming from the continuous opacity and the instabilities driven by the resonance lines are much more important.

Resonance lines are strong and saturate rapidly, so that at a given point in a stellar wind the flux of photospheric radiation will have a strong absorption line caused by the absorption of the resonance line of matter between that point and the star. Because a stellar wind is accelerating the mean velocity of gas forming that absorption line will be less than the velocity of the wind at the point being considered. Consequently the absorption line profile of the gas at this point is moved bluewards with respect to the centre of the absorption line formed in the flux of photospheric radiation. If the velocity of the gas at that point is now perturbed an increase in the velocity will move the absorption profile towards the continuum wings. Since the gas now experiences a higher flux of photospheric radiation at its absorbing line frequency, the radiative force is increased which drives the perturbation further. An instability is therefore possible.

Lucy and Solomon (1970) had suggested that an instability could result but they did not work it out further. A number of papers have now been written discussing details of these instabilities. The differences between them are mostly a matter of what approximation was made to calculate the dependence of the perturbed radiative force with the perturbation in the velocity. These papers divide into two groups, subsonic and supersonic flow.

a) Line driven instabilities in subsonic flow.

Nelson and Hearn (1978) have calculated the growth rate of a two dimensional Rayleigh-Taylor type instability in an accelerating subsonic wind. They assume that the vertical scale length of the perturbation is small compared with the vertical distance corresponding to a unit optical

depth and also that it is small compared with the pressure scale height. The perturbed radiative force is then a function of the perturbed velocity. This Rayleigh-Taylor type instability grows very rapidly. If there are one hundred resonance lines acting independently (which is the number of resonance lines needed in the Castor, Abbot and Klein (1975) theory of radiation driven winds to give a mass loss in agreement with the observations) the instability grows with a time scale of 50 seconds.

Martens (1979) showed that with the same physical assumptions a drift instability is also caused. This too is a rapidly growing instability with a growth time of 100 seconds.

b) Line driven instabilities in supersonic flow.

MacGregor et al. (1979) estimated the growth rate of a drift instability in a supersonic flow for an optically thin perturbation. They assumed that the distribution of the flux of photospheric radiation was a step function, representing a deeply saturated line profile. They assumed further that the unperturbed centre of the local absorption profile lies always one Doppler width from the step function. The radiative force then depends on the wing of the profile beyond one Doppler width. A perturbation in the velocity moves the local absorption profile closer towards the step function in flux and thereby increases the radiative force. They concluded that radiative driven sound waves grow rapidly in the supersonic flow of winds from hot stars.

Abbott (1980) used different assumptions and obtained different conclusions. The theory of Castor, Abbott and Klein (1975) calculates the radiative force driving the wind from the Sobolev approximation. Abbott (1980) assumed that the perturbations in the wind are optically thick and that the perturbed radiative force can be calculated from the Sobolev approximation, that is it is proportional to the perturbed velocity gradient. He found with these assumptions that sound waves propagate in the wind with a modified sound speed but that they are marginally stable. The sound waves do not increase in energy.

The different results of MacGregor et al. (1979) and Abbott (1980) caused some confusion. This has been resolved by Owocki and Rybicki (1984). They have studied the stability of a radiative driven wind but they assume neither that the perturbations in the flow are optically thin nor that they necessarily satisfy the Sobolev approximation. They find two limiting cases

If the wavelength of the perturbation is much less than the Sobolev length, they find the flows are unstable. The Sobolev length is the length over which the mean velocity of the flow increases by a thermal speed. They find a simple result that the growth time of the instability is approximately equal to the time for the mean radiative force to accelerate ions through a thermal speed, which is equal to the time for the wind to flow through a Sobolev length. So there are hundreds of e-folding lengths for the instability in the wind.

If on the other hand the wavelength of the perturbation is much longer than the Sobolev length, then the perturbations become asymptotically stable.

This result of Owocki and Rybicki (1984) bridges the different conclusions of MacGregor et al. (1979) and Abbott (1980).

The conclusion of Owocki and Rybicki (1984) has been criticised by Lucy (1984) for the neglect of scattered photons in the calculation of the perturbed force. Owocki and Rybicki (1984) assumed that the scattering would be isotropic and should not contribute to the perturbed radiative force. Lucy (1984) has analysed the effect of the scattered photons assuming coherent scattering in plane parallel geometry, using the same analysis as in his calculation of the P Cygni line profiles (Lucy 1971). This analysis uses the Sobolev approximation and so assumes that the velocity gradients are large. He finds a damping effect from the scattered photons which exactly cancels the destabilizing effect found by other authors. Lucy calls this damping line drag. In an optically thin perturbation, ions which are moving faster than the adjacent mean flow find themselves coupled radiatively only to ions ahead of the perturbation and not to ions behind. They see only a negative flux of scattered line photons and experience a radiative drag.

Lucy points out that this analysis specifically assumes  $\frac{dv}{dr} \gg \frac{v}{r}$ . This does not hold in the outer layers of the wind. A radiative driven wind accelerates very rapidly close to the star and then the acceleration is much less. Since the velocity gradient condition is not satisfied beyond the inner region of the wind, the short wavelength instabilities will be present.

Finally a rather different type of instability in a supersonic wind has been proposed by Kahn (1981). He considers a two dimensional velocity perturbation in a radiatively driven wind. He assumes that the perturbations are optically thick and that the radiative force is proportional to the velocity gradient, the Sobolev approximation. He finds a perturbed radiative force which is not radial and there is an unstable mode which describes a large scale convective motion superposed on the mean flow, which grows with distance. But this instability only occurs if the mass loss is greater than half the maximum mass loss which can be obtained if all the momentum of the radiation is transferred to the wind. Why this threshold should occur is physically obscure.

## 5. Problems of hot stars where radiative driven instabilities may be important.

### a) The origin of mass loss.

In the Castor, Abbott and Klein (1975) theory of mass loss from hot stars the momentum transfer from the radiation to the wind is responsible not only for accelerating the wind to the final velocity but also for specifying the magnitude of the mass loss. Hearn (1975), Cassinelli, Olson and Stalio (1978) and Olson (1978) have suggested that a small corona might exist at the base of the wind of hot stars, heated perhaps by radiative driven instabilities. The heating of the small corona would then determine

the magnitude of the mass loss and the momentum transfer from the radiation to the wind determines the final velocity of the wind. Whether a small corona exists at the base of the wind of hot stars or not remains an open question. Recent work on reconciling the theory with observations has been discussed by Cassinelli in this workshop.

If the mass loss from hot stars is determined by a small corona heated by radiative driven instabilities, then it is the resonance line radiative driven instabilities in the subsonic flow which are important. Unfortunately most attention has been given to radiative driven instabilities in the supersonic flow, mainly because the applicability of the Sobolev approximation makes the work much easier. Consequently far more work needs to be done on the theory of radiative driven instabilities in the subsonic part of a stellar wind.

b) X-ray emission.

Since the failure of the original small corona plus cool wind model of Cassinelli and Olson (1979) to explain the X-ray observations, there have been several attempts to provide an explanation of the X-rays. Stewart and Fabian (1981) and Waldron (1984) have modified the physics associated with the small corona model, while Lucy and White (1980) and Lucy (1982) have suggested that the X-rays are emitted in shocked regions generated by radiative driven instabilities. None of these suggestions has been entirely successful. (See the review by Cassinelli in this workshop). However it seems likely that the source of the non-radiative mechanical heating needed to explain the X-ray emission will be radiative driven instabilities, even though the details of the production of X-rays are not fully understood at present.

c) Variability of the wind.

The variability of the wind from hot stars is now well established. For example de Jager et al. (1979) found variations in the absorption edge velocity of the CIV and NV lines from  $\alpha$  Cam(09.5Ia) of  $100 \text{ km s}^{-1}$  within half an hour. These short term changes may well reflect instabilities in the wind, and radiative driven instabilities are probably important. The most extreme variations with time are seen in the Be stars, and these changes have a random character over times of years or decades (Doazan 1982).

The coming and going of the narrow absorption components in the U.V. P Cygni line profiles of hot stars, not only from Be stars, present a great puzzle. Henrichs et al. (1983) have suggested that the observations of the narrow absorption profiles of  $\gamma$  Cas(B0.5IVe) could be explained by episodes of increased mass loss lasting a day occurring every few weeks. The relaxation oscillations of a corona described by Hearn, Kuin and Martens (1983) give a possibility of converting radiative driven instabilities into stochastic changes of the wind with very long time scales.

### Acknowledgement.

I am very grateful to Drs. P.C.H. Martens, S.P. Owocki and G.B. Rybicki for a number of discussions which have been very helpful in preparing this review.

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## DISCUSSION

Uchida: I think we have to know the radial structure of the flow in order to tell about the heating. It really matters whether the "bullet" is snow-ploughing or whether the first-accelerated one goes faster than the ones coming later. This is because in the latter case no shocks will be formed in the flow no matter how fast the flow goes because no blobs collide. Furthermore, in order to tell something about the heating, the non-linear development of the flow initiated by these instabilities is more important than whether there is an instability or not.

M.A. Smith: The nonradial oscillations in B stars seem to peak around the  $\beta$  Cephei (early B) stars. This observation and theoretical eigenfunctions suggest that the oscillations are not all superficial but that some may extend deeply into the star, or at least into the envelope. Other modes are more superficial, probably, but the low- $\ell$  modes probably contain too much energy to be driven by radiative instabilities in the atmosphere.

My question is to ask you to clear up some confusion which I have. If the instabilities have small wavelengths and short time scales would not the instabilities be "invisible" in the UV lines? Put another way, would it not be difficult to explain the observed UV line variability (discrete components, changes in terminal velocity, etc.) in terms of radiative instabilities?

Hearn: For lines formed in the subsonic region what you say is probably true, the instabilities would contribute to microturbulence. But I think the instabilities could explain the variations in the shortward edge of the P-Cygni profiles.

Rybicki: Some observational support for multiple shock models comes from the deep absorption troughs seen in the strong P-Cygni lines. As Lucy has shown (1983, Ap.J., 274, 372), the explanation for such features is easy in terms of the shock models, but very difficult when one assumes smooth, monotonic velocity fields.

Underhill: There is an important observational fact about discrete components which you do not seem to realize. All stars of a given spectral type, e.g. B1 Ia, do not show discrete components, although all have about the same  $T_{\text{eff}}$  and wind (inferred from shapes and strengths of wind profiles). If the discrete components were generated solely by instabilities in a radiatively-driven wind, all stars with similar  $T_{\text{eff}}$  and similar wind should show closely similar discrete components. The theory of Underhill and Fahey (1984) takes account of the observed behaviour of discrete components in both supergiants and rapidly rotating mainsequence stars.

Owocki: Perturbations with  $\lambda < L \sim R_*/100$  are linearly unstable and so one would not necessarily expect that they would be associated with X-ray variability. The non-linear result of such instabilities is, however, still entirely unknown, and so needs to be investigated.

Zirker: The growth of instabilities and their eventual dissipation seems an important problem for further study. At one extreme, the instabilities may be damped to give only a warm wind. At the other extreme, they may completely disrupt a radiatively-driven wind to give a large hot corona.

Rybicki: Lucy (1984, preprint) has recently shown the importance of a "line-drag" force which tends to suppress any instability near the base of the wind. Perhaps nonlinear heating in the subsonic region by the growth of perturbations may be more difficult to achieve than you suggest.

Abbott: Regarding the lack of X-ray variability, I believe there is a simple explanation. Spectral line observations have a high signal-to-noise ratio, they resolve frequencies, and they see a small volume of the wind projected in front of the star. The variability seen in spectral lines never amounts to more than 10 % of the total energy absorbed in or emitted by the line. X-ray observations see the entire emitting volume; they have limited frequency resolution, and they have low signal-to-noise ratio. Therefore, I do not think you should expect to detect the variability seen in line profiles in existing X-ray data.

Swank: I agree with Abbott's explanation of why one might expect more variability in line profiles than in the X-ray fluxes. The frequency information in line profiles gives a form of spatial information.

Castor: Let me add to Abbott's comment. The line profile variations, for instance in H $\alpha$  of  $\alpha$  Cam and  $\zeta$  Pup, are seen to be strongest at low velocity - 200 - 300 km s<sup>-1</sup>. But most of the X rays come from farther out where the variability in H $\alpha$ , at least, seems to be less.

Hearn: The variations of the shortward edge of the P-Cygni lines of  $\alpha$  Cam measured by de Jager et al. were 100 - 200 km s<sup>-1</sup> in an hour or so.

Wentzel: If concepts such as co-rotating interaction regions or shock acceleration of electrons are attractive, then one must include non-radial magnetic fields, which make qualitative and difficult changes in the theory.

Is there any indication whether a single instability suffices for all hot stars? Conversely, might two instabilities compete in a single star so that small surface inhomogeneities cause a highly structured wind?

Hearn: There is no theoretical indication of which instability or instabilities are important.

Mullan: As regards Castor's comment, variations in line profiles are not confined to low velocities. Discrete components occur at  $(0.7 - 0.8)v_{\infty}$ . Therefore winds are varying at high velocities. Lamers et al. (1982) rejected the Lucy-White idea because they believed L-W blobs would produce discrete components at  $(0.3 - 0.35)v_{\infty}$ , rather than at  $(0.7 - 0.8)v_{\infty}$ .

R.L. White: The original Lucy/White model generated most of its X rays near  $v \sim (0.3 - 0.5)v_{\infty}$ . One might be tempted to infer from this that the

discrete components would occur in the same velocity range, although there have not been any calculations to substantiate this. In any case, the more recent Lucy model produces X rays much farther out in the wind, so there would be no reason to expect X-ray induced features only at low velocities.

Underhill: What is meant by "close in" and "far out"? According to the typical velocity laws adopted for OB supergiants, one reaches  $0.75v_{\infty}$  at about  $4 R_{\star}$  and about  $0.99v_{\infty}$  at  $10 R_{\star}$ . The sonic point (critical point) is usually believed to lie inside about  $1.5 R_{\star}$ .

R.L. White: Shocks persist all the way to infinity in Lucy's model.

M.A. Smith: I would like to beat the drum for nonradial pulsations one more time. Epsilon Persei is a normal B0.3 star near the main sequence. It shows variations in the UV continuum at  $\lambda 1000$  over a few hours of 40%! Gry et al. (1984, Astr. Ap., in press) also find evidence for circumstellar neutral hydrogen moving at moderate velocities. The only other remarkable property of this star is that it shows nonradial oscillations of enormous amplitudes in its line profiles, so much so that this star has been mistaken for decades for a double-lined spectroscopic binary.

Sreenivasan: Two comments: (1) I agree that attention needs to be paid to the subsonic region in the flow. Some observational diagnostics in that region would help. Do you have any specific ideas on the kind of diagnostics that would aid? (2) Some observations are explainable if there is a variable mass-loss rate such as you referred to in your talk. Do you have any ideas regarding what might produce variable mass-loss rates?

Hearn: I think it is very important that all wavelength regions are observed. Diagnostics come from the comparison of different wavelength regions, such as the comparison of infrared and radio observations described during this meeting by Abbott.

Uchida: You did not mention the scale sizes for which the growth rate becomes maximum, but I presume that it is pretty small compared with the stellar size. I do not, therefore, understand how these small-scale perturbations produce a macro effect representing discrete line component which you are referring to as due to blobs. (They must be huge ones.)

Lafon: All of these instabilities are linear and they are analysed in media not much perturbed by them. This means that the analyses are relevant only so far as the disturbances remain perturbations and do not upset the overall structure of the winds. A non-linear approach is crucial for determining whether this remains true or not over several growth times and lengths. In any case, which non-linear phenomena can be expected to break the exponential growth rates?

Hearn: Non-linear effects are difficult to calculate, but they must exist. The work of Lucy and White was a good attempt to suggest, using physical intuition, what the final non-linear result might be.

MAGNETIC EFFECTS IN THE HEATING AND MODIFICATION OF FLOWS  
IN THE OUTER STELLAR ATMOSPHERES  
WITH APPLICATION TO EARLY TYPE STAR CASE  
( Invited Review Paper )

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**Abstract:** Possible magnetic effects in the heating and modification of flows in early type star atmospheres are discussed by referring to the physically related phenomena dealt with for late type stars, young stars, and close binary systems. It is pointed out as the result that the magnetic field may play important roles also in early type star atmospheres in converting the energy of the radiatively driven outflow into heat, or in modifying the outflow by nozzling or by initial modification of temperature and/or momentum by which the effect of the radiation pressure may be made the most of in accelerating the outflow.

## 1. Introduction

The effects of the magnetic field in the outer stellar atmospheres were clearly shown by the Skylab X-ray and EUV observations for the case of the sun, which is an example of isolated, slowly rotating G2 type main sequence star. The corona was shown to be highly inhomogeneous, and the hot and dense parts were found to be consisted of aggregates of fine loops and threads (Sheeley *et al.* 1974). In contrast, there were also parts lacking appreciable X-ray emissions, called coronal holes (Krieger *et al.* 1973, Vaiana *et al.* 1973). Hot loops were shown to coincide with the coronal magnetic field lines calculated from the photospheric magnetic field distributions as boundary values (Sakurai and Uchida 1977, Figure 1), while the coronal holes were found to be the source of the fast solar wind streams (Nolte *et al.* 1976).

These discoveries caused a change of the paradigm in the solar coronal research from the classical acoustic shock heating picture (Biermann 1948, Schwarzschild 1948, Schatzman 1949, de Jager and Kuperus 1961, Osterbrock 1961, Uchida 1963, Ulmschneider 1966, Kopp 1968) to the magnetic heating picture, since it was difficult for the acoustic heating theory to reproduce the observed inhomogeneities (loops, threads, and holes) and the correlation of the coronal structures to the magnetic field. The possibility of the magnetic heating of the corona was stressed by Piddington (1973) and Uchida and Kaburaki (1974), and mechanisms were proposed and developed by a number of authors along the line. We will come back to this point and discuss them in more detail in section 2.

The classical acoustic heating picture, however, was transplanted in the meantime to the stellar case before the paradigm change in the solar coronal

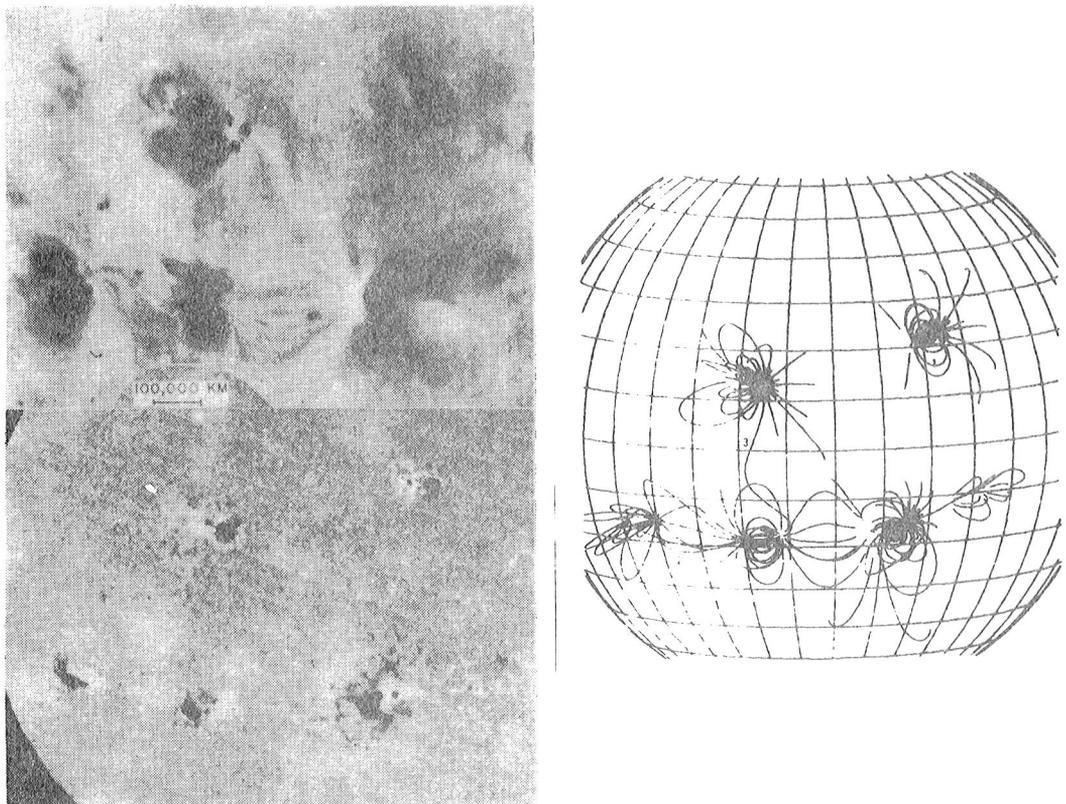


Fig.1. *Left top*: Skylab EUV picture in FeXV ( Sheeley *et al.* 1974 ). *Left-bottom*: Magnetogram of the same day ( Kitt Peak ). *Right*: Coronal magnetic field calculated from the photospheric distribution of magnetic field ( Sakurai and Uchida 1977 ).

research took place ( Kuperus 1969, de Loore 1970, Landini *et al.* 1975, Hearn 1975, Mullan 1976 ). The prediction made there was that the corona should be expected mainly in F and G type dwarfs which have surface convection vigorous enough to produce turbulence, as well as strong enough gravity to hold back the heated plasma to the stellar surface.

Observations by HEAO-1, Einstein, Copernicus, IUE, and VLA etc., however, revealed in contradiction to this expectation that stars of almost every type on the HR-diagram, ranging from late type dwarfs to early type stars, from very young stars emerged from nebulosities to much evolved late type giants, exhibit strong X-ray emissions ( Vaiana *et al.* 1981 ). The new results were striking because, (i) late type giants without strong enough gravity have X-ray emitting regions, (ii) early type stars without surface convection layer show X-ray emissions, and (iii) the luminosity of X-ray emission from the stars having the same spectral type and luminosity class has a scatter as large as  $10^3$ . Observational fact (i) suggests strongly the possible role of the magnetic confinement of the heated plasma, (ii) indicates that the heating

may not be due to the acoustic heating mechanism but rather due to some magnetic-field-related mechanism, and (iii) indicates that there may exist some hidden parameter(s) controlling the heating, and again the mechanism is not likely to be the acoustic heating. In the classical theory of stellar structure, the mass, the chemical composition, and the age of the star, completely specify the state of the star including the convection, and the acoustic heating theory, which is a quite deterministic theory, uniquely specifies the special range of the star having the corona on the HR-diagram. The hidden parameter may be the rotation of the star, which was out of the scope of the classical theory, and is again related to the magnetic field.

## 2. Magnetic Effects in the Stellar Atmospheres

There are thus strong reasons to think that the magnetic field may also play important roles in the stellar atmospheres as in the solar atmosphere. No simple transplantation of the solar picture to other stars, however, is allowed since there are very large differences in the physical conditions in other type stars. The gravity, gas and radiation pressures and temperature at their surface, the states of surface convection zone and of rotation, and therefore, of the magnetic field, in other type stars, all differ markedly from those of the sun. Also, the effect of the duplicity, or the influence of the companion star in close binary systems can be another important factor which did not exist in the case of the sun. What is to be sought for is, therefore, not the simple similarity of the apparent phenomenology, but of the physics underlying these phenomena.

The effects of the magnetic field in the outer stellar atmospheres may include the following. (a) Magnetic field may provide a low-loss channel (Osterbrock 1961, Uchida and Kaburaki 1974) for the non-thermal energy supply (eg., in magnetic mode waves) to the rarefied part of the atmosphere. The rarefied atmosphere, which is a poor radiator and has a small heat capacity, can be heated to an X-ray emitting temperature if the energy is dissipated into heat there. (b) Magnetic field can sustain the plasma out of the mechanical equilibrium of the non-magnetic case. For example, it can sustain the plasma in a high gravitational potential state. It can also contain the heated plasma which may escape away from the star without it. (c) Magnetic field can modify the flow in a pattern different from the one without it, and this may modify the velocity, density, etc., of the flow (Bernoulli flow with de Laval point. Parker 1963, Holzer and Axford 1970). (d) Magnetic field can insulate the heated plasma from the surrounding low temperature part because of the reduction of the heat conduction perpendicular to the field lines. (e) Finally and most conspicuously, the magnetic field can make drastic transitions from such a high energy state to another lower energy state through a variety of instabilities. The sudden reconfiguration of the system in a short Alfvén-crossing time scale,  $\tau_A \equiv L/V_A$ , can release the potential energy into the kinetic energy drastically, and into heat in shocks, or by Joule dissipation with anomalously enhanced resistivity. If the magnetic reconnection is involved, there can be transfer of mass and momentum, as well as of the magnetic twist to the newly connected part of the flux tubes, either open or closed. If the injection is into an open tube, the jet-like ejection occurs, and if it is into a closed loop the resulting phenomenon may be loop

flares ( Uchida and Shibata 1984b ).

We first see in the following the examples of these in the cases of late type stars, young stars, and binaries ( we confine ourselves to binary systems composed of normal stars in this paper ), and then go to the case of early type stars in section 3.

## 2.1. Magnetic Effects in Late Type Stars

The sun is the best studied sample of isolated, slowly rotating late type dwarf stars, but there are also a number of late type dwarfs whose quiet and bursting X-ray and radio emissions have been detected. Typical ones are dMe flare stars like UV Cet, YY Gem, etc, emitting  $L_x \sim 10^{27-29}$  erg/s. The flux ratio of X-ray emission to the visual, amounts to  $10^{-3\sim-1}$  which is very large partly due to the dark optical luminosity of the star itself. Also flares are observed in X-rays, and analysed in detail, for example, in the case of Prox Cen ( Haisch *et al.* 1982 ).  $L_x$  amounts to  $10^{28.3}$  erg/s (  $E \sim 3 \times 10^{31}$  ergs ) and the time variations in the temperature and the emission measure mimic very closely those of solar disarition brusque type flares.

Among late type dwarfs, also spotted stars ( EQ Peg, CR Dra, BY Dra, etc ) as well as the rapid rotators,  $\pi^1$  UMa, etc, are X-ray emitters. In view of the fact that the X-ray luminosity is correlated with the rotational velocity (  $L_x \propto (v \sin i)^2$  ; Pallavicini *et al.* 1980 ) and that physical conditions are similar to those of the sun, it is highly likely that the X-ray emitting regions in the late type dwarfs are similar to those in the magnetic corona of the sun. Namely, the corona of these stars probably have loopy structures closely related to the magnetic field, and the magnetic field in turn is produced by the dynamo mechanism in which the cooperative action of rotation and a non-axisymmetric motion like the convection is essential. Furthermore, the magnetic field should not be a mere potential field but need be agitated, eg., by the convective motion in order to produce heating. In this context, it is interesting to see that the chromospheric activity measured by MgII h and k lines ( Ayres and Linsky 1980 ) is correlated to the period of rotation derived from Wilson's CaII H, K intensity variation ( Wilson 1976 ), and the activity is nicely a unique function of a parameter related to the Rossby-number ( Noyes *et al.* 1983, Mangeney and Praderie 1983 ).

Giants and supergiants, of F, G, and K type also have X-ray emissions. For example, an F0 type supergiant Canopus has  $L_x \sim 10^{32}$  erg/s, and  $f_x/f_v \sim 10^{-6\sim-7}$ . Since  $r\Omega T/GM > 10$  for giants, it is difficult for the gravity alone to hold the X-ray emitting high temperature plasma back to the stellar surface, and the picture will be the hybrid model in which the magnetically confined hot loops are imbedded in the outflowing cool mass ( Linsky 1983, Dupree and Hartmann 1981 ) which escapes from the magnetic field-free part of the stellar surface already with much lower temperature. The heating process of the hot loops may be an analogue of the solar active region loops as in late type dwarfs.

A problem arises about the dynamo process for giants or supergiants, however. The dynamo action is expected to become weak since the star spins down as it expands due to the evolution into the giant stage. The chromospheric activity for giants seems to be maintained, however ( Linsky

1980 ). Uchida and Bappu (1982) proposed one possible solution for this difficulty by considering the following : In the evolution, the core of the star contracts and spins up while the envelope expands and spins down, and the convection zone invades deeper into the envelope from the surface inwards as the envelope expands in the evolution. An internal dynamo layer equipped with the convection and a strong shear in rotational velocity will appear around the rapidly spinning core. The surface active region with magnetic flux lifted by the convective or buoyant transport will be diffuse and large in size, reflecting the large depth of the convection zone.

Magnetic effects, enumerated in § 2 as (a) through (c), may come into action in these stars basically in a similar way as in the case of the sun, in heating the corona, and in controlling the flow in low- $\beta$  ( $\equiv p_g/p_m$ ) regions. Thus, we survey here the mechanisms proposed in the context of the solar case.

As for the heating is concerned, magnetic mode energy carriers attracted attention as soon as the loop structures of the corona were revealed by Skylab, and Piddington (1973) suggested that the energy might be carried into the corona by Alfvén waves. Uchida and Kaburaki (1974) pointed out the "transparent window" character of the photospheric magnetic regions and suggested that the Alfvén-type waves coming out to the corona through such regions would get involved with the compression ( wave-mode coupling by non-linear effects ) as soon as the amplitude of the wave grows large enough, and might contribute to the heating. Wentzel (1974) suggested that the Alfvén-type waves would decay into shorter waves by wave-mode coupling and would become easier to dissipate. These treatments dealt with the body-waves of large amplitude and suffered by objections that there were no specially large amplitude waves observationally discernible in the coronal loops above the active regions ( Beckers and Schneeberger 1977 ).

Other possibility suggested by Ionson (1977) was to rely on the Alfvénic surface waves which propagate on surfaces of loops having a jump in Alfvén velocity, and dissipate energy at the point of resonance with the ion gyro frequency. This mechanism was based on the treatment of the Alfvén waves by using kinetic equations ( KAW treatment ) by Hasegawa and Chen (1976).

An interesting point in the extension of the notion of the dissipation on discontinuous surfaces was made more recently by Heyvaerts and Priest (1983) and also by Sakurai and Granik (1983) that in the presence of the gradient in the magnetic field strength perpendicular to  $B$  itself, a body wave in Alfvén mode would experience phase discrepancy with the neighboring part of it due to the accumulation of the effect of the difference in the propagation velocity. By this effect, a steep gradient in the field would appear after the wave propagates a large enough distance. Phase discrepancy in the neighboring part gets large and very finely nested surface will appear, and the energy dissipation both by viscosity and by resistivity would increase. This process may work for short period waves for which the loop is long enough in terms of the wavelength and the phase discrepancy can grow large enough even with a reasonably small gradient in the magnetic field strength. One has to have large enough power in the short period range in the turbulent convection.

In another group of mechanisms proposed for the heating of loops, the anomalous dissipation of the steadily flowing current which is caused by plasma turbulence due to microscopic plasma instabilities is dealt with, since the normal resistivity at the coronal temperature is too small to do the job

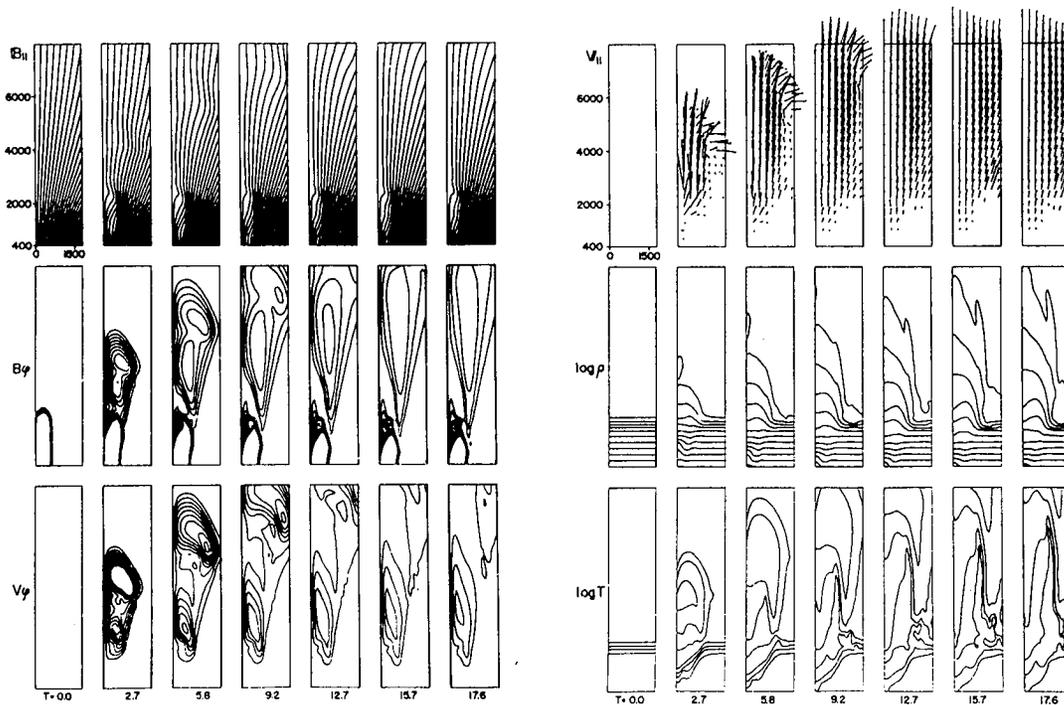


Fig.2. Acceleration of jets by magnetic twist relaxing into low- $\beta$  regions. *Left top*: Magnetic field lines in  $r$ - $z$  plane. *Left middle*: Contour of  $B_\phi$ . *Left bottom*: Contour of  $v_\phi$ . *Right top*: Velocity vectors in  $r$ - $z$  plane. *Right middle*: Contour of density. *Right bottom*: Contour of temperature. Left edge in each figure is the axis of symmetry, and numbers on abscissa and ordinate are in km. It is shown that a high velocity jet is formed as the packet of  $B_\phi$  relaxes into low- $\beta$  regions (Uchida and Shibata 1984b).

(Spicer and Brown 1980). Dissipation in the current sheet was suggested by Levine (1974), but a more likely configuration is the tube current whose dissipation was discussed by Rosner *et al.* (1978), Hinata (1979), Vlahos (1979) and Carlqvist (1979) and others also in relation to flares. The corona in the loop shape can be considered as a weaker version of loop flares. It was pointed out (Kuperus *et al.* 1981), however, that at least for the heating of the corona, too large a value of the current or too large a twist in the field is needed to start a current-driven instabilities. It is claimed that the tearing mode instability in the field will occur before anomalous resistivity sets in (Spicer 1976), but here again the necessary shear seems to be too large.

A different type suggestion was made recently by Uchida and Shibata (1984b). They considered the dynamical effects in the transiency in which the magnetic twist stored under the photosphere relaxes along a loop. It may be

worth mentioning that this is the transient version of the currented loop mentioned above. Previous treatments of the loop-current have dealt with the decay of an already built up current constantly flowing along a loop. An intermediate statistical building-up process was discussed by Sturrock and Uchida (1981). Uchida and Shibata (1984b) showed that the incidence into a weaker field loop of the packet of magnetic twist, created, for example, by the rotational motion in the convection zone, produces dynamical effects and sweeps up the mass with it in propagating upwards along the loop ( Figure 2 ). The mass carried attains a velocity of the order of the local Alfvén velocity. This will produce quite a conspicuous effect on colliding with another packet coming up from the other footpoint of the loop ( or a preceding wave reflected from the other footpoint ), especially if the sense of the twist in the latter packet is opposite to that in the former. The twists "annihilate" (unwound) leaving in the loop the mass and the kinetic energy converted to heat in the collision of wave packets. A strong version of this process may explain flaring loops, and the weak version may correspond to coronal loops.

## 2.2. The Case of Young Stars

Another stellar category of strong emitters of X-rays is the very young stars. T Tau stars are known to be strong X-ray emitters emitting  $L_x \sim 10^{30-31}$  erg/s. The steady component is known to fluctuate, and enhanced variability is seen in T Tau, SU Aur, GW Ori, etc., and the flaring, which is characteristically different from those of dMe flare stars, is detected, eg., in DG Tau ( Feigelson and De Campli 1981 ). T Tau stars are also known to show widely separated optical spectral lines ( Hartmann 1982, Mundt and Giampapa 1982 ) which may be interpreted to be due to the coexisting in- and outflows. More recently, T Tau stars are shown to relate to the bipolar flows observed in CO molecular lines in millimetric radio wavelength ( Snell *et al.* 1980, Bally and Lada 1983, Cohen 1982 ), and to the high velocity small scale optical jets which lie also in the general directions of the bipolar flows and sometimes connect the T Tau star with Herbig-Haro objects ( Mundt and Fried 1983 ).

The activity in these young stars were already known from the variability in optical spectral lines alone, corresponding to the controversial behavior of the spectral line profiles. Stellar wind models ( Kuhi 1964 ) as well as accretion models ( Lynden-Bell and Pringle 1974, Ulrich 1976, Bertout 1979 ) have been discussed to interpret these. The origin of the outflow was attributed to the unknown process of energy liberation of still unsettled magnetic configuration in the star after the formation ( Gershberg 1982 ), or to the vigorous generation of Alfvén wave whose dynamic pressure may drive the outflow ( Hartmann and McGregor 1980 ). In order to explain the coexistence of the X-ray emitting region and the outflow of cool material emitting  $H_\alpha$ , also a hybrid model in which active region loops and coronal hole coexist as in the sun, is discussed ( Imhoff and Giampapa 1982 ).

The magnetic effects in the stars of this category, if ever, can be pretty different from that of the sun, however. Uchida and Shibata (1984c,d) recently proposed a model to explain the activity on the star, optical bipolar jets, as well as the large scale CO-bipolar flow in a consistent way, based on the global magnetic picture. They first point out that the magnetic field

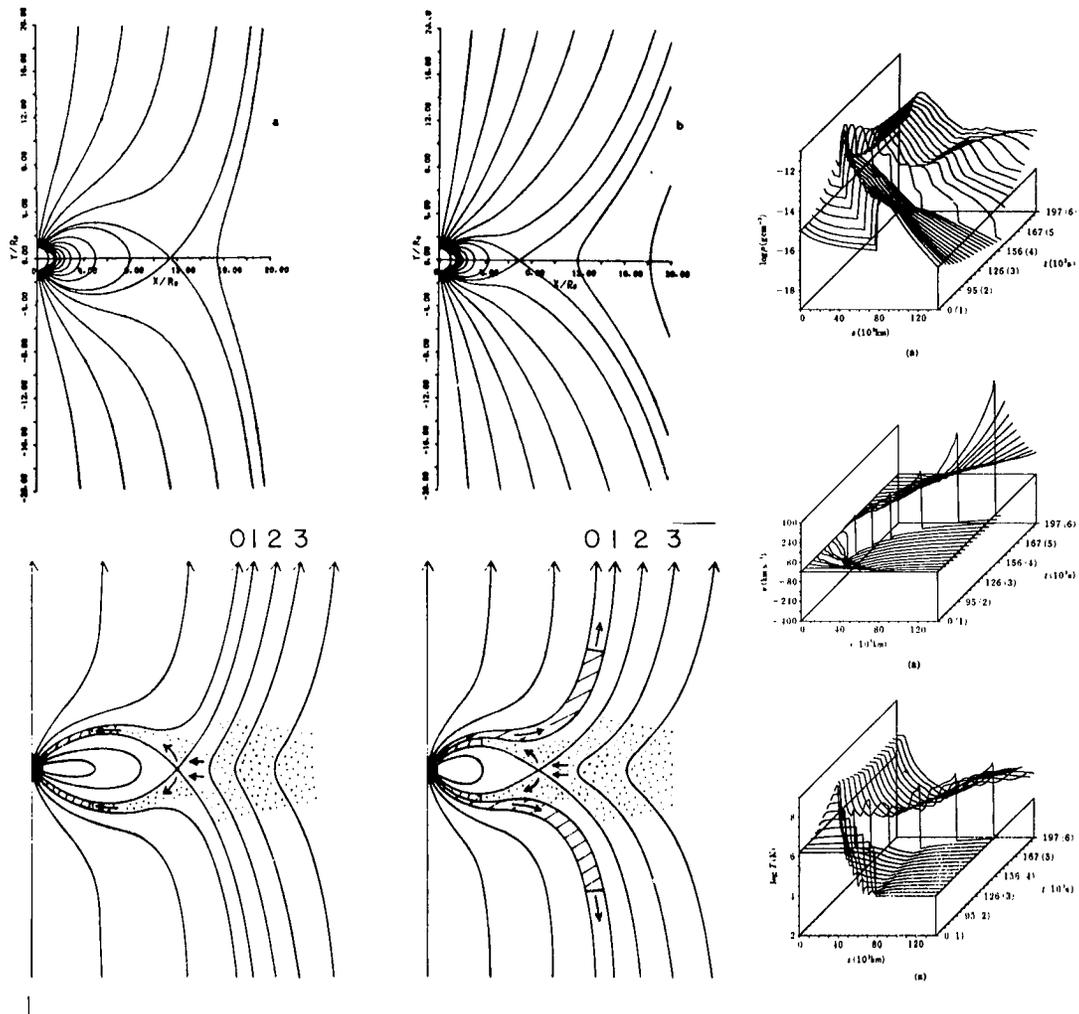


Fig.3. *Left top*: Calculated magnetic field structure around a star loaded by the accreted nebular mass ( Uchida and Low 1982 ). Magnetic fields of the star and the accreted mass are assumed to have a common origin in the large scale nebula. *Left bottom*: Schematic figure explaining the behavior of the mass leaking by magnetic reconnection occurring at the neutral ring ( Uchida and Shibata 1984a ). *Right from top to bottom*: Density, velocity, and temperature as functions of  $t$  and  $s$  ( coordinate along the curved flux tube in which the flow takes place ) ( Uchida and Shibata 1984a ).

configuration around a young stellar object formed in a magnetized nebula has a magnetically neutral ring in the equatorial plane around the star ( Figure 3, Uchida and Low 1982 ), and the accreted magnetized material will be supported by the magnetic structure having this ring of magnetically neutral points at its base. It may be noted that the field configuration may be

considered as a global version of the magnetic configuration supporting a solar prominence.

The nebular mass accreted to the star after this stage is once buffered by this magnetic structure, and falls onto the stellar surface by being transferred to the stellar field through magnetic reconnections taking place at the neutral ring. For the star having the polar magnetic field strength of the order of  $10^3\text{G}$  ( Nakano and Umebayashi 1982 ) the distance of the neutral ring from the star is estimated to be several stellar radii, and the potential energy of the accumulated material is  $\sim 6 \times 10^{14}$  erg/g. The free fall time is of the order of  $10^4\text{s}$ , the terminal velocity in the free fall is roughly 300 km/s, and the temperature attained by the conversion of this kinetic energy is  $3 \times 10^6$  K.

The problem is whether the rate of mass release,  $\dot{M}$ , by the magnetic reconnection from the reservoir is large enough. A simulation of an MHD flow in the magnetic reconnection by Sato and Hayashi (1974) shows that the flow is most like that of the Petcheck's (1964) earlier suggestion in which the velocity of the inflow is  $\sim 0.1V_A$ . By using this,  $\dot{M}$  is estimated to be

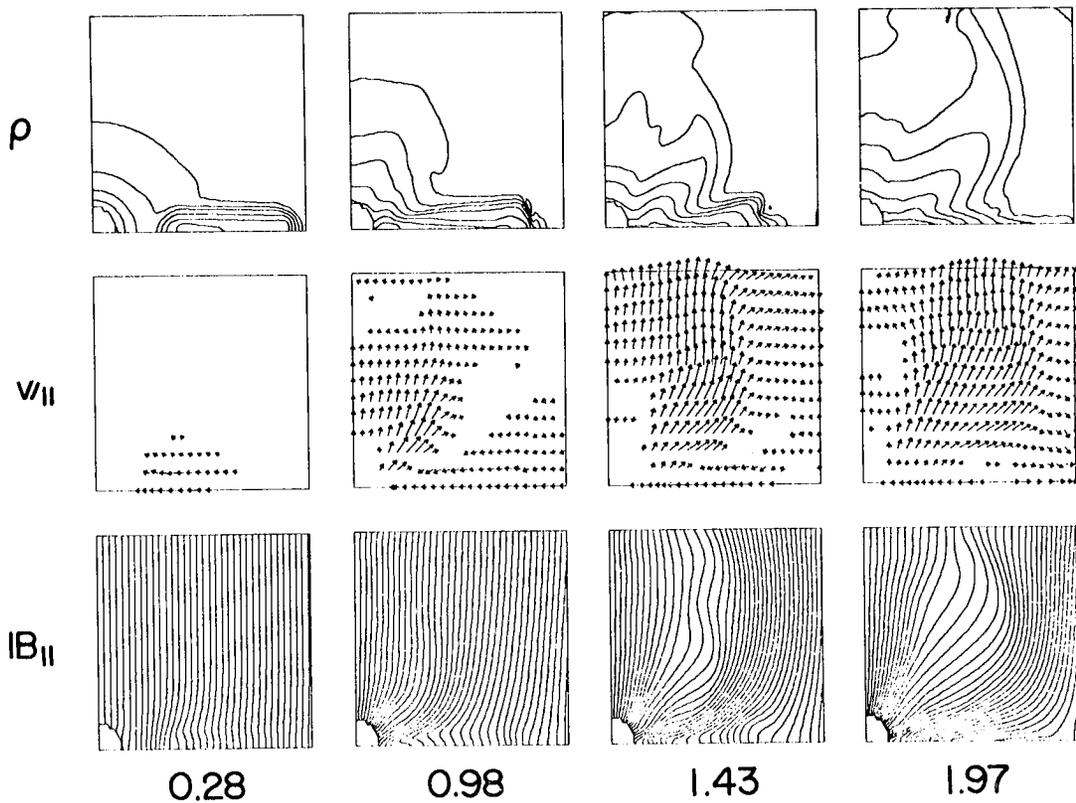


Fig.4. Formation of cold bipolar flow of large scale. Top to bottom: Contour of  $\rho$ ,  $\mathbf{v} = (v_r, v_z)$ , and  $\mathbf{B} = (B_r, B_z)$ . It is seen that a flow ( helical when combined with  $v_\phi$  ) is caused by the relaxing  $B_\phi$ -field created by the rotation of the disk ( Uchida and Shibata 1984c, d ).

$10^{18}$  g/s, or  $2 \times 10^{-8} M_{\odot}/y$ , and this corresponds to the luminosity of  $6 \times 10^{32}$  erg/s (Uchida and Shibata 1984a,c,d). These numbers suggest that this buffered accretion may explain the observed inflow and the production of the X-ray emitting region closer to the stellar surface than  $H_{\alpha}$ -emitting region (Walter and Kuhi 1981). The outflow is explained in Uchida and Shibata (1984a) by the mass driven out by the recoiled shock which is created in the crash of the infalling mass at the stellar surface and strengthen itself in propagating upward along the tail of the infalling mass (Figure 3c). The paths of in- and outflows are separated by the reconnection process, and in- and outflows can exist separately without being degraded into turbulence (Figure 3b).

On the other hand, the cold bipolar flow whose scale is of the order of a pc, but also coming from the general region of the new-born star, is explained as coming from different part of the star-nebulosity system which we are dealing with, again in magnetic picture (Uchida and Shibata 1984c,d). In the outer part of the magnetic configuration discussed above, there is an extended part of the accretion disk in which the large scale magnetic field of the original cloud is bundled and twisted up in the rotating motion of the disk around the central object. It was shown that, as the magnetic twist created by the rotation of the contracting disk relaxes into the low- $\beta$  regions above and below the disk, the gas is accelerated (Uchida and Shibata 1984b) along the helical paths toward  $\pm z$ -directions (Figure 4). The large mass as well as the large rate of mass loss,  $\sim 10^{-4} M_{\odot}/y$ , which is difficult to explain otherwise, can be explained in this model in a natural way (see details in Uchida and Shibata 1984c in these Proceedings).

### 2.3. The Case of Close Binaries

It is well-known that close binaries form a category of strong X-ray emitters among others especially when they have collapsed component (X-ray binaries with a neutron star, or AM Her type with a white-dwarf). The availability of the mass supply either by the overflowing Roche lobe of the low-mass primary, or by the mass-loss flow from early type massive primary, allows the mechanism of the mass accretion to operate. Uchida and Shibata's mechanism for the X-ray emission in very young stars mentioned above corresponds to a very soft version with small surface gravity and with the accreted nebular mass reservoir as the mass source. Here, without going into the well-haunted problems of the very close binaries having mass accreting collapsed star in the system (X-ray binaries; eg., Rappaport and Joss 1981), or those having a non-degenerate star but with heavy mass exchange (W UMa type; cf Dupree 1982), we confine ourselves to the case of RS CVn type binaries which are detached systems consisted of normal stars of our concern here without apparent mass exchange.

RS CVn stars (UX Ari, RS CVn,  $\sigma$  CrB, AR Lac, HR 1099, etc) are strong X-ray emitters (Walter *et al.* 1980). The steady component of X-rays from UX Ari, for example, is claimed to consist of two thermal components, one with  $T \sim (3-7) \times 10^6$  K and  $EM \sim 10^{53} \text{ cm}^{-3}$ , and the other with  $T \sim (1.5 - 10) \times 10^7$  K and  $EM \sim 10^{54} \text{ cm}^{-3}$  (Swank and White 1980). The extension of the sources was examined (Walter *et al.* 1980) and the latter component had the binary scale while the former had more normal extension as a stellar corona. The rough

configuration of the X-ray emitting region was deduced by using eclipses in the case of AR Lac (Walter *et al.* 1983) and it was found in this case that the corona existed on the foreside of both components with respect to the direction of rotation. Flares in RS CVn's are seen to occur both in X-rays (HR 1099, SAO 15338, HD 8359, etc; Walter *et al.* 1980) and in radio (HR 1099, HR 5110, UX Ari, etc; Gibson *et al.* 1978, Feldman *et al.* 1978). Since there is no apparent mass exchange, a softer version of the mechanism of X-ray binaries with degenerate component can not be applied to the present case, and some magnetic mechanisms are suggested.

RS CVn binaries have features favorable for the magnetic interpretation of their activities. These include the so-called photometric wave (=PW) which drifts across the light curve to the direction of smaller phase once in a cycle with a period of 8~10 y (Rodono 1981). The variation of the depth of the dip with phase in the cycle and also the color change accompanying PW suggest that this darkening may actually be due to something like sunspot. Thus the gigantic star-spot model was proposed by Hall (1972), and the possibility that it is a cumulative effect of many smaller spots was discussed by Eaton and Hall (1979). In these models, the drift in the phase is attributed to the increasingly faster rotation of the lower latitude zones into which the spot migrates down with the phase in the cycle.

Since the rate of the drift, one rotation on the stellar surface in 8~10 years, is actually very slow, the rate of differential rotation  $\Delta\Omega/\Omega$  estimated with this is two orders of magnitude smaller than that scaled from the sun by using Durney and Robinson's (1982) scaling law. Although it is generally thought that the tidal effect caused by the companion tends to bring the rotation of the star into a synchronized rotation (Zahn 1977), this seems to be too perfect an effect.

Is the migrating gigantic spot picture correct? Although it is a fascinating picture, does it have a good enough ground? In this connection, it is worth noting that the spot in the case of the sun does not migrate itself to lower latitude although the gigantic starspot hypothesis claims the analogy to the solar case. It is the latitudinal zone in which the spots appear that migrates equatorward. Furthermore, the sign of  $d\phi_{min}/dt$  should be negative in the solar analogy, but in some of the RS CVn systems it is not negative. For example, in HK Lac the sign is positive, and  $d\phi_{min}/dt$  even changes sign in the cases of SS Boo, V711 Tau, etc., indicating that the migration picture, if applicable, introduces a rather irregular behavior of spots.

The very slow drift, either eastward or westward, or even changing direction, reminds us of a solar feature called "active longitude belt" (Bumba and Howard 1969), and Uchida and Sakurai (1983) proposed that PW may correspond to the active longitude belt ( $\equiv$  ALB) rather than to a gigantic starspot. It is a longitudinal zone on the sun in which many spot-pairs appear, drift across, and disappear before its preceding edge is reached, and it was actually seen either to stand still, or to drift as a whole either eastward, or westward with a slow drift velocity relative to the solar surface (Gaizauskas *et al.* 1982) of the magnitude similar to that of the PW on RS CVn's.

The introduction of the notion of ALB gives us a much activated situation while a single gigantic super starspot which scarcely moves in the corotating frame would be quite static in nature. Now, spot pairs are born in, drift

across, and disappear from this belt, and thus the magnetic field configuration of the system invariably changes, with magnetic reconnections taking place from time to time. Furthermore, the rather stringent restriction imposed on the magnitude of the differential rotation by the small drift rate of PW is now relaxed, and the stars can have considerable differential rotation with synchronized latitudes at medium latitudes in north and south hemispheres. Uchida and Sakurai (1983, 1984) discussed the possible magnetic field configurations and reconnection in them by taking RS CVn itself as an example ( Figure 5 ). They showed that there can be reconnections of the field mediated by the field of the companion star, and reconnections may transfer the hot and dense plasma in an emerging spot to-spot connection into the newly formed spot-to-companion star connection on the foreside of the K star, for example, by the process of the relaxation of magnetic twist from highly twisted loops into less twisted weaker field loops ( Uchida and Shibata 1984b ) to form the hot loops of the binary-size.

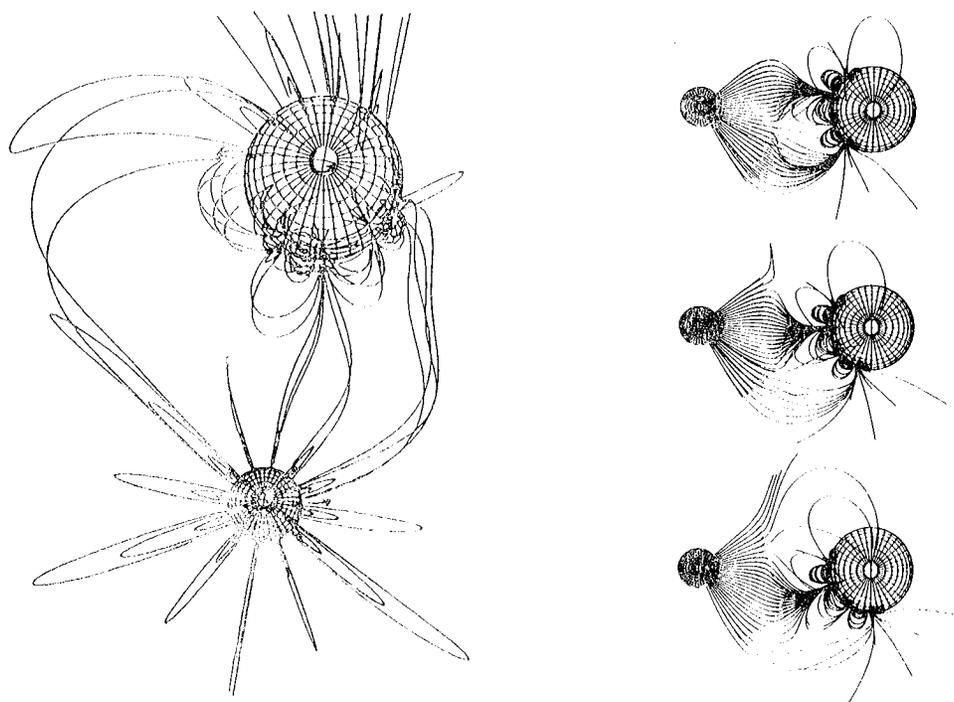


Fig.5. *Left*: Model magnetic field calculated for RS CVn in ALB picture. *Right*: Top views of magnetic field connection and reconnections as spot-pairs drift in the ALB.

### 3. Magnetic Heating and Modification of Flows in Early Type Star Atmospheres

Early type stars (O and B types) are also found to be strong X-ray emitters. Their X-ray emission amounts to  $L_x \sim 10^{31\sim34}$  erg/s and fulfills a nice linear relation with  $L_{bol}$  (Pallavicini *et al.* 1981).

In the case of the early type stars, there is a strong mass outflow (Morton 1967) which is believed to be due to the strong pressure of their photospheric radiation exerting on resonance lines (Lucy and Solomon 1970). It is, therefore, possible that some instability inherent to this driving mechanism may disturb the flow and generate turbulence and shocks and thus converts the energy of the mean flow into heat (Lucy and White 1980, Owocki and Rybicki 1983).

Underhill, however, has been claiming that there must be mechanisms other than radiative, and the magnetic field may play important roles also in the atmospheres of early type stars (Underhill 1980, 1983, Underhill and Doazan 1982). Her argument is based on (i) the presence of non-thermal radio emission and emission lines in some of the early type stars like WR stars (Underhill 1984), (ii) the evidence of anisotropic mass ejection from early type stars (Underhill and Fahey 1984), and (iii) the fact that  $v_\infty$  is not a unique function of  $L_{bol}$ , and there may be some other hidden factors controlling the outflow. (i) and (ii) are not supposed to exist in a spherical symmetric star in purely radiative regime.

From the theoretical point of view, there are a number of ways in which the magnetic field, if ever, may interact with the outflow and contribute either in converting certain part of the flow energy into heat, or modifying the momentum of the flow by providing excess heating to boost up the flow (Hearn 1979), or by providing excess momentum by waves (Hartmann and MacGregor 1980), or modifying the flow by nozzling (Holzer and Axford 1970, Cannon and Thomas 1977), or transmitting angular momentum to the flow (MacGregor and Friend 1984), or converting the rotational energy to that of the the energy of the flows in the polar directions (Uchida and Shibata 1984a, c, d). We here concentrate ourselves on the magnetic effects in the early type star atmosphere, and refer the reader to eg., "Mass Loss and Evolution of O-type Stars (1979)" concerning the radiatively driven flow and mechanisms proposed for the heating along this line.

The situation with the magnetic field in early type stars, however, seems to be very different from that of the late type stars. For example, early type stars do not have surface convection zones, and therefore, no dynamo mechanism like that in the solar case (= self-regenerative, oscillating dynamo) can operate. We have to start by asking even whether there is a magnetic field in early type stars at all.

#### 3.1. Magnetic Field in Early Type Star Atmosphere

##### — Its Existence and Configuration

The first question here is thus whether there is a magnetic field in early type stars. Unfortunately, it is not possible to answer this question based upon the observation yet due to the difficulty in measuring the Zeeman effect hindered by the large width of the spectral lines in early type stars. Absence of the observation, however, *does not* mean that there is no magnetic

field. We have to guess theoretically in such a case, but the observation of the magnetic field in A-type stars strongly supports our guess that O and B type stars may also have magnetic field.

Condensation of interstellar cloud with magnetic field has been discussed by several authors and it is argued that a large part of the magnetic flux must escape from the condensing gas ( Mestel and Spitzer 1956 ) probably in the cold molecular cloud phase due to ambipolar diffusion ( Monschovias 1979, Nakano 1979 ), leaving a small fraction behind. The remaining part of the flux is taken into the star and becomes the stellar primordial field (Nakano and Umebayashi 1982).

Whether the effect of the wholly convective Hayashi phase is to enhance or to destroy the magnetic field is not yet clear since there is an unsettled debate about the dynamo effect. The presence of the strong convection together with rotation seems at a glance to favor the growth of the magnetism, but it is also claimed that the presence of the radiative core which anchors the flux tube is necessary in strengthening and keeping the field ( cf, Schussler 1983 ). We may assume, however, that even if the Hayashi phase has a destructive effect on the magnetic field, some part of the primordial magnetic flux survives in early type stars. This stand point is supported by the fact that there is a magnetic field at least in A-type stars which may also have passed a similar phase.

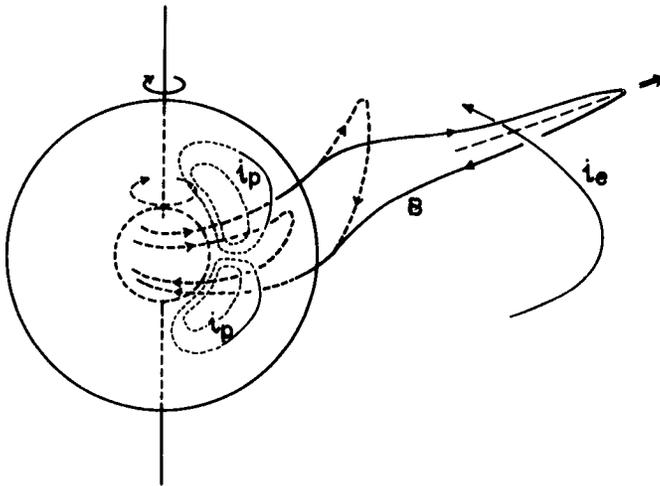


Fig.6. Schematic presentation of the system of magnetic field and current in a rotating early type star with strong wind. The magnetic field outside the star which is otherwise to be dragged by rotation is stretched outwards by the strong wind, and an equatorial sheet current is formed.

But there may be an objection saying that there is no surface convection zone and thus no dynamo action ! The presence of the regenerative dynamo process is indeed the must for the presence of the magnetic field in less massive main sequence stars having an exceedingly long life. In early type stars whose life is only of the order of  $10^{6-7}$  y which is short compared with the magnetic decay time,  $\tau_D = 4\pi\sigma L^2/c^2$ , the regenerative dynamo process is not necessarily indispensable in maintaining the magnetic field. Furthermore, some of the functions in the dynamo mechanism are in operation even without the effect of the convection. For example, the strengthening of the  $B_\phi$ -field by

the differential rotation in  $r$  may take place, and the  $B_\theta$ -component would increase continuously if there is no dissipative effect. The differential rotation in  $r$  may be maintained if the magnetic field extending out of the star exerts a braking effect on the outer shells of the rotating star ( Figure 6 ). In such a case, a toroidal magnetic field of a considerable strength may be expected in the star, and some parts of the flux tube may float up to the surface in the low latitude zones. There is a poloidal current system induced inside the star corresponding to the toroidal field component, and if the current closes its path inside the star, the magnetic field outside will be a potential field. It should be noted, however, that the potential field here is not a dipolar field because the surface distribution of magnetic field which is the source of the potential field outside differs from that of the dipole field. If the magnetic field lines continue to be dragged outside the star, the current does no longer close its path inside, and the field outside becomes a currented field. This rotational drag may be superseded by the effect of the outflow, and the field lines are pulled outward at the equatorial part, and this causes an equatorial sheet current flowing in the azimuthal direction.

### 3.2. Heating by Magnetic Mechanism, and Magnetic Reconnections

Heating to an X-ray emitting temperature occurs if the current in the rarefied part is destroyed in certain efficient ways. This is equivalent to releasing free part of the magnetic energy, and the distortion in the magnetic field pattern deviated from that of the potential field will disappear. The process can either occur as a steady process or non-steady process ( Uchida *et al.* 1984 ). The former can take the form of the dissipation with a slippage of the plasma through the magnetic field where the radius of curvature becomes small as the tip of the pulled out field lines in the top figure of Figure 7. The field line which would otherwise be pulled out indefinitely in  $\sigma = \infty$  plasma, recedes to the location by slippage if the resistivity is finite. The region is heated due to the Joule dissipation in the slippage.

If the process takes place non-steadily, a blob of warm or hot plasma may be produced by magnetic reconnection and carried away by the outflow. The part of the flux tube on the stellar side shrinks in Alfvén velocity as the rubber belt in a sling-shot, and will be heated up due both to resistive heating and to compression and shocks as in the solar post-flare loops ( Kopp and Pneuman 1976 ). The process of the reconnection may be enhanced by the enhanced resistivity which may be due to the plasma turbulence caused by drift-instabilities induced when the current density in the sheet current increases by some squeezing as in the case of the earth's magnetic tail ( Galeev 1982 ). This process of forced reconnection ( Sato and Hayashi 1979 ) may take place if the disk-like magnetic structure in Figure 7 is exerted pressure from above and/or below. This may occur if the star is a so-called oblique rotator in which the axis of rotation is not parallel to the axis of magnetic field, and the stream in the open field region presses the face of the disk-like structure rotating rigidly with a tilt angle. Then, the directions of the intersecting lines of the equatorial planes of the rotation and of the magnetic field may become the preferred directions of ejection of warm blobs as observed by Underhill and Fahey (1984).

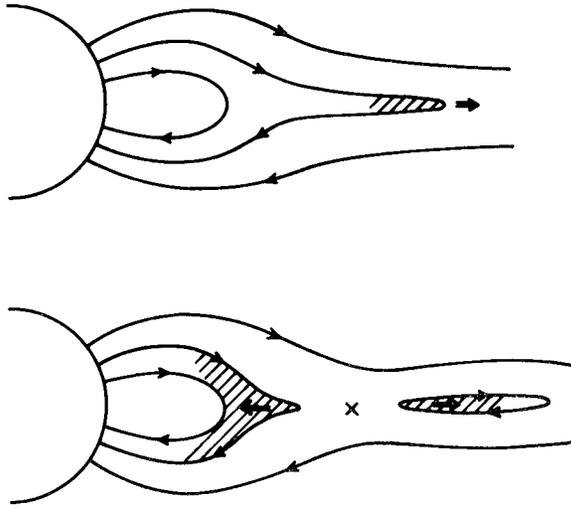


Fig.7. Outflow interacts with the closed field and stretches it in the magnetic equatorial plane. *Top*: In the steady state, a diffusive leak of the flow may take place from the tip of the stretched loop with weak heating. *Bottom*: If the process is helped by the tearing mode instability and magnetic reconnection occur at the squeezed point, a magnetic blob with heated plasma is ejected while the loop on the stellar side shrinks as a sling-shot, and a very hot loop is formed as in the solar post-flare X-ray emitting loops.

### 3.3. Modification of Flows by Magnetic Field

Although we refrained from going into the details of the non-magnetic heating mechanisms most of which relies on the instabilities of the flow driven by the strong radiation pressure from the early type star photosphere, we should mention that there is a difficulty in setting up the radiatively driven wind as pointed out by Marlborough and Roy (1970). Their point was that, if the outward force by radiation dominates gravity from the beginning, there is no critical point in the Parker-flow (Parker 1963) would appear in the flow, and thus a subsonic flow stays subsonic all the way, contradicting the observed velocity of 1000 - 2000 km/s. This point was argued further by several authors (eg., Nerney and Suess 1975). It should be mentioned here that the difficulty may be avoided if the initial acceleration takes place in a region in which  $dT/dr > 0$  (Rogerson and Lamers 1975) and this may be possible if the initial heating is somehow realized by the magnetic effect as in other type stars. If this is the case, magnetic effects can be very essential in helping the radiation pressure to produce the major effect in the early type star atmosphere, namely, the radiatively driven flow.

Other magnetic effects which may modify the outflow include the nozzling effect (Holzer and Axford 1970, Cannon and Thomas 1977). This is the early type star analogue of the origin of solar wind fast and slow streams (Kopp and Holzer 1977), and may be expected if the magnetic field is strong enough to control the flow pattern of the initial part of the flow. Polar fast stream seen in the sun (Svargaad 1975) may thus be expected also in early type stars. Alfvén wave driving (Hartmann and MacGregor 1980) may be ineffective due to the lack of the surface convection which buffets the footpoints of the

magnetic field to produce the Alfvén waves. Instead, a flow in the polar direction is expected by the interaction of rotation and magnetic field (Draine 1983, Uchida and Shibata 1984b, c, d). The mechanism is essentially due to the pressure of the torsional Alfvén wave which is created continuously by rotation instead of convection. This again may provide the initial acceleration by which the fluid begins to receive stronger radiation of the continuum from the photosphere by Doppler shift.

Finally, the flow steadily slipping out of the stretched magnetic field, or the magnetic blob produced in the reconnection, may add warm or hot components to the outflow, and modify the thermal state of the outflow as discussed in section 3.2. These may contribute to the X-ray emission from the extended source around early type stars which is considered to be due to the collision of the high speed outflow with the surrounding cloud.

#### 4. Conclusion

Magnetic effects in early type star atmospheres are discussed with reference to those in other type stars, and it is argued that the magnetic field may play important roles in the heating and modification of the outflows in their outer atmospheres.

Although the situation in early type stars without surface convection is not suitable for the dynamo process to perform the regeneration of the field, a pretty strong magnetic field may exist in them partly due to the short life of these stars and partly due to the strengthening of the toroidal field by differential rotation. Magnetic processes in the outer atmosphere, converting the energy of the outflow to heat, modifying the outflow by providing effective de Laval nozzles, or converting the rotational energy to the energy of the outflow in polar directions, are discussed by taking also the effect of magnetic reconnection into account. It is concluded that the magnetic effects may play important roles also in the atmospheres of early type stars as in the atmospheres of other type stars showing activities in X-rays and radio, like some of the late type stars, young stars, or stars in RS CVn systems.

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#### DISCUSSION

Linsky: The picture you are presenting implies that the magnetic fields in early-type stars will look very different from a simple dipole, and will change with time. However, the only early-type stars for which we have magnetic-field data (the Ap stars) appear to have very strong dipole-like fields that are not very time varying. Could you comment on this discrepancy?

Uchida: I do not think that there is a discrepancy except that the source distribution on the stellar surface is not a dipole type. The source distribution can be belts in each hemisphere, and it can be bipolar if the strong parts in each belt are separated by a large angle in longitude. The variations which I talked about may be quick in the front of the outer atmosphere, but variations of the internal field may be quasi-static once the rotation-diffusion balance is established.

Underhill: Is not the question which Linsky is asking one of what happens when the magnetic energy density is small relative to the motion energy as opposed to being strong (high magnetic energy density relative to the energy in motion)?

Uchida: I am not claiming that the magnetic field is dominating. Rather, it may be relatively weak and be opened up by the flow. It may be noted in this connection, that which field line is opened up is determined by the strength of the flow relative to the strength of the field. A "sling-shot arch" occurs in a strong field line when the flow is strong, and in a weak field line when the flow is weak. The strength of X rays to be emitted is, therefore, strong (weak) for strong (weak) flow. Thus  $L_X$  can be a function of  $L_{\text{Bol}}$  alone, and the strength of the magnetic field does not enter into the resulting expression for  $L_X$ .

Chan: The  $B_\phi$  generated by your picture is mainly due to the differential rotation between the core and the outer envelope. Would the build up of  $B_\phi$  stop this type of differential rotation in a relatively short time? Could magnetic buoyancy evaporate this field in a relatively short time?

Uchida: The value of  $\beta (= p_g / p_{\text{mag}})$  will be very large inside the star, so that it will not damp the internal rotation in a short time. As for the escape of the flux owing to magnetic buoyancy, I think that the flux will not perish so long as some of the lines of force are trapped in the core. The part of the magnetic flux escaping from the surface has zero net flux. The only thing you worry about is the diffusion in the core. However, the time scale for diffusion is longer than the evolutionary time scale in the case of young stars.

Wentzel: In the Sun, the "typical" field strength depends on the phenomenon observed. Active regions indicate fields of under 100 gauss; spots, flares, and thermal microwave gyroradiation several 100 gauss. Magnetic phenomena proposed for hot stars imply an enormous range in field strength. Heat conduction along the field (leading to the P-L-T scaling law) is possible for  $B \ll 1$  gauss; wave transport of energy and magnetic effects on thermal and radiation instabilities occur if  $B^2/8\pi > p$ , and typically  $B > 10$  gauss; the control of supersonic flows needs  $B^2/8\pi > \rho v^2$ ; microwave gyroradiation from electrons at  $10^8$  K needs merely  $B \sim 10^2$  gauss; but from electrons at  $10^6$  K it needs  $B \sim 5 \times 10^2$  gauss, which has many other dynamic implications.

Uchida: I agree.

Sreenivasan: Is the amplification of a seed magnetic field affected by the Eddington-Sweet currents? Is not the pattern of flow indicated in your diagram what one expects in the absence of magnetic fields? Your flow would be modified by the field present. Then the question is whether you can get a dynamo to increase the field strength effectively.

The question of how much of a fossil field is present in these OB stars (without an outer convection zone) in view of their young age is still open theoretically. If one is talking about supergiants which develop outer convection zones in the H-shell burning and He-core burning stages, you then have an outer convection zone, and dynamo amplification of a remnant fossil field is a possibility that should be confirmed by means of a theoretical analysis.

Martens: I disagree with the conclusion of the Marlborough and Roy paper. The only conclusion that can be drawn from it is that at the point where the net force changes sign, the flow velocity must equal the sound velocity. Of course, the net force must be zero somewhere in the atmosphere, for if not, there would not be a star. This point may be, of course, deep down in the photosphere, but it must be there, as, for example, shown by the Castor, Abbott, and Klein paper.

Castor: As Martens says, in a radiatively-driven wind model the magnitude of the radiative acceleration must change with radius so that it approximately balances gravity at the sonic point, being smaller than gravity inside the sonic point and larger outside. Furthermore, it does not require a lucky accident for this to happen; it is a natural consequence of saturation of the driving lines. The Sobolev-approximation models of CAK have this property; so do Steve Weber's wind models, which use accurate radiative transfer rather than Sobolev theory. In Weber's models the gravity balance condition at the sonic point is imposed.

Abbott: To correct a minor point, when you solve the equation of motion, you do not expect  $v_{\infty}$  to scale with  $T_{\text{eff}}$ , so the fact that the observed values do not scale with  $T_{\text{eff}}$  should not be cited as a "missing factor" which requires magnetic fields.

Uchida: Thank you. What I meant is that the property of the outflow should be determined uniquely if the flow is purely the result of radiative pressure.

Praderie: Coming back to the RS CVn stars, could you specify whether the active-longitude belt which you assume on the active star is somehow always in the direction of the companion? Also, is there a reason to find polar spots, as has been suggested by several authors?

Uchida: To the first point, the answer is no. The active longitude drifts, but only very slowly, namely, once in ten or so years. Such a velocity is seen for the active-longitude belt in the solar case. To the second point, it may be said that in the superspot picture, a spot very much elongated in the north-south direction is difficult to explain, but in the active-longitude picture, the active region can be a distribution of small spots ranging over a certain width in latitude.

# EFFECT OF SCATTERING ON INSTABILITIES IN LINE-DRIVEN STELLAR WINDS

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## I. INTRODUCTION

Owocki and Rybicki (1984; paper I) showed that line-driven O-B stellar winds of the type proposed by Lucy and Solomon (1970) and Castor, Abbott and Klein (1975; CAK) are unstable to perturbations of short spatial wavelength and that the growth rates for such instabilities are very rapid, corresponding to approximately 100  $e$ -folds in a characteristic outflow time. The nature of the nonlinear development of this instability is unknown at present, but might possibly be one of blobs of gas being driven through ambient gas (Lucy and White 1980) or a quasi-regular train of outward moving shocks (Lucy 1982). In either case the resulting dissipation of mechanical energy might explain the observed anomalous heating in O-B stars as evidenced by their X-ray emission and high ionization state. It also might explain the observed fine structure of the absorption lines and their time variability.

The analysis of paper I considered the driving due to the absorption of the stellar continuum flux and neglected the effects of the diffuse, scattered radiation field. This neglect of scattering was criticized by Lucy (1984), who showed that under certain special conditions the effect of scattering could reduce the instability growth rate to zero.

We have done a new stability analysis that includes scattering, but that uses the more physically realistic assumption of complete redistribution instead of coherent scattering, and that includes the effects of transverse velocity gradients, which become important as the flow moves away from the stellar surface. We find that the instability is indeed eliminated right at the base of the wind, but that as the flow moves outward the instability rate rapidly becomes equal to a substantial fraction of the value calculated in paper I, the fraction asymptotically reaching 80% at large radii. Since this still implies many  $e$ -folds in a characteristic outflow time, the primary conclusion that these winds are highly unstable is unchanged.

## II. OUTLINE OF THE ANALYSIS

The treatment of the instability follows in large part that of paper I, with the following changes:

1. The diffuse radiation field is included under the assumption of isotropic scattering with complete redistribution.
2. The finite solid angle of the stellar continuum is taken into account, assuming no limb darkening.
3. In addition to the radial velocity gradient  $v'(r)$ , the transverse velocity gradient  $v(r)/r$  is included.

The general analysis following from the above assumptions is rather difficult. Fortunately, since our main interest is in the short wavelength limit, where the instability is strongest, we may specialize the discussion to the case of optically thin perturbations.

We assume spherically symmetric geometry, with an outwardly directed velocity  $v(r)$  at radius  $r$ . Also we assume a flat stellar continuum radiation field of intensity  $I_c$  with no limb darkening, so that at any radius  $r$  the incident intensity field is equal to  $I_c$  within a cone of half-angle  $\cos^{-1}(\mu_*)$ , where

$$\mu_* = \sqrt{1 - \left(\frac{R}{r}\right)^2}, \quad (1)$$

and  $R$  is the stellar radius. We also define at each radius

$$\sigma = \frac{d \ln v(r)}{d \ln r} - 1. \quad (2)$$

which measures the ratio of the radial velocity gradient relative to the transverse velocity gradient.

As in paper I we linearize the mass, momentum and radiative transfer equations and make the WKB approximation. We have found it convenient, following Lucy (1984), to use the co-moving frame representation for the transfer equation. The perturbed (first-order) radiation force then contains two new terms compared to paper I: The first represents the effect of the perturbed scattered radiation field on the unperturbed material; in the optically thin limit this term is negligible. The other term is due to material moving with perturbed velocity through the unperturbed scattered radiation field; this term represents a kind of "photon drag", and persists even in the optically thin limit.

The results of the calculation may be conveniently stated in terms of the ratio  $\omega/\omega_I$  of the true growth rate to that calculated in paper I for the same mean line force. For the case

of optically thin perturbations,

$$\frac{\omega}{\omega_I} = \frac{2}{1 + \mu^*} \left[ \frac{(1 + \frac{1}{3}\sigma)(E_3 + \sigma E_5) - (\frac{1}{3} + \frac{1}{5}\sigma)(1 + \sigma E_3)}{(1 + \frac{1}{2}\sigma(1 + \mu^2))(1 + \frac{1}{3}\sigma)} \right], \quad (3)$$

where

$$E_3 = \frac{1 + \mu^* + \mu^2}{3}, \quad E_5 = \frac{1 + \mu^* + \mu^2 + \mu^3 + \mu^4}{5}. \quad (4)$$

For the velocity law

$$v(r) = v_\infty \sqrt{1 - \frac{R}{r}}, \quad (5)$$

which approximates the CAK law, we find from equation (2) that

$$\sigma = \frac{\frac{3}{2} - \frac{r}{R}}{\frac{r}{R} - 1}. \quad (6)$$

Using equations (1), (4) and (6) we can express all quantities in equation (3) as functions of  $r/R$ . The result is graphed in the figure. It can be seen that the ratio of  $\omega/\omega_I$  is zero at the stellar surface ( $r/R = 1$ ), but that it quickly approaches its asymptotic value of  $4/5$  as  $r/R \rightarrow \infty$ .

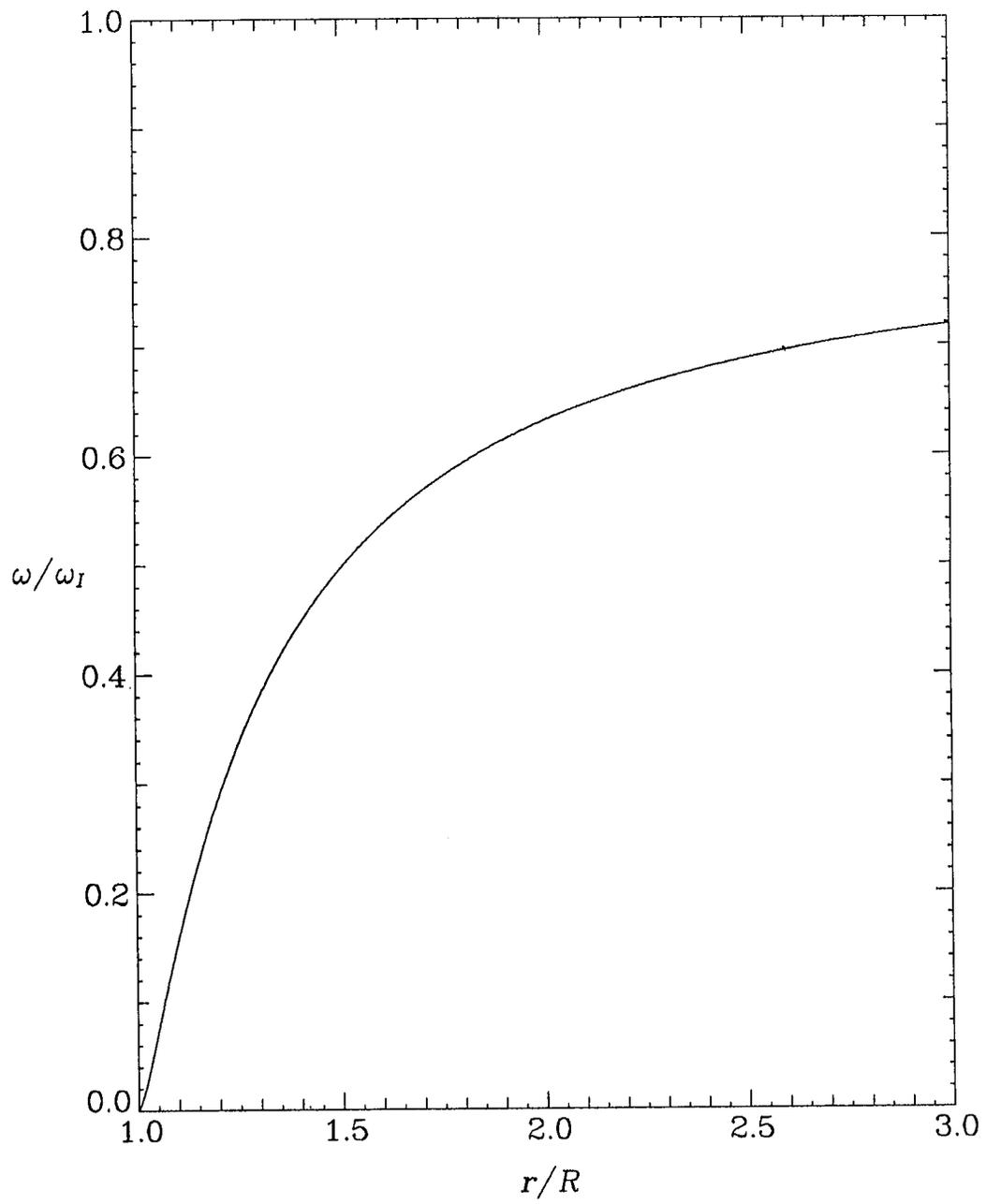
### III. CONCLUSIONS

We have confirmed the result of Lucy (1984) that the stabilizing effect of scattering in line-driven winds can be important near the stellar surface, but we have also found that once the wind leaves the surface the growth rates rapidly become a substantial fraction of those found neglecting scattering. Owing to the great strength of the non-scattering instability found in paper I, the primary conclusion remains that these winds are highly unstable and perturbations will surely grow to nonlinear amplitude.

We are currently extending our analysis of the effects of scattering to the whole range of perturbation wavelengths in order to find the appropriate "bridging law" between the optically thin and thick regimes. Some preliminary work has also been done on using a numerical hydrodynamics code to investigate the nonlinear growth of perturbations.

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## DISCUSSION

Cassinelli: Regarding your difference from Lucy's results, which new effect is more important, the spherical geometry or the noncoherent scattering?

Owocki: Both are important. If you assume complete redistribution (CRD) instead of coherent scattering, the growth rate still approaches zero at the stellar surface (where the flow is nearly planar), but only if there is no limb darkening. Both the coherent scattering treatment and the CRD treatment give large growth rates as you move away from the stellar surface to places where the flow is no longer plane parallel.

# NEW INSTABILITIES IN LINE DRIVEN WINDS

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## 1. Introduction.

The physical mechanisms potentially leading to instabilities in line driven winds which have been discussed in the review of Hearn at this workshop are the drift instability and the line-shape instability. In this contribution I will discuss these mechanisms applied to situations which have not been treated in the literature sofar. Further I will propose a general three-dimensional treatment of the stability problem of line-driven winds, which leads to the general dispersion equation. From this dispersion equation automatically a third physical mechanism driving instability in stellar winds is deduced; an instability which I will call the 'Thermal Drift Instability'. It is related to changes in absorption of radiation caused by temperature perturbations. This mechanism results in growing inwardly propagating sound waves.

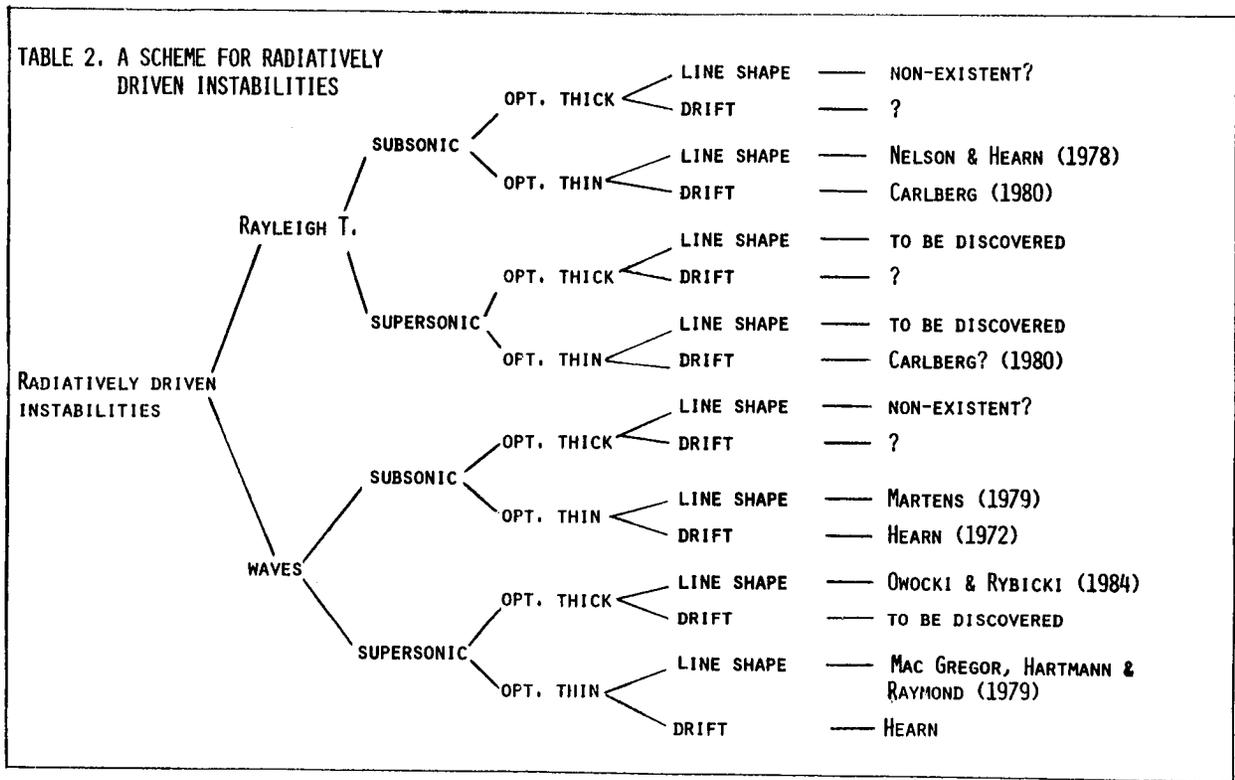
## 2. The line-shape and gradient instabilities.

The growth rate - if any - of these instabilities depends strongly on the details of the specific physical situation in the wind that is assumed in the analysis. One may distinguish between the subsonic and supersonic parts of the wind, between optically thin and optically thick perturbations and between propagating (sound-wave type) and non-propagating (Rayleigh-Taylor type) instabilities. Table 1 summarizes the work in the literature on these instabilities that is known to me.

The approach of Table 1 may be reversed and an investigation can be made of all possible combinations of these assumptions about the specific situation. This leads to the 'tree' of instabilities of Table 2. The branches of the tree that carry the leaves 'to be discovered' can be shown to represent combinations of assumptions that result in instability of the wind from straightforward extension of the existing results. The branches rated 'non-existent?' probably relate to stable physical situations, while the full question marks require further consideration.

	HEARN	NELSON & HEARN	MARTENS	MACGREGOR HARTMANN & RAYMOND	ABBOT	CARLBERG	KAHN	HEARN KUIN & MARTENS	OWOCKI & RYBICKI
YEAR	1972	1978	1979	1979	1980	1980	1981	1983	1984
SUBSONIC (-)	-	-	-	+	+	+	+	+/-	+
SUPERSONIC(+)	-	-	-	-	+	-	+	-	+/-
OPTICALLY THICK (+)	-	-	-	-	+	-	+	-	+/-
OPTICALLY THIN (-)	-	-	-	-	+	-	+	-	+/-
SOUND WAVE (+)	+	-	+	+	+	-	-	-	+
RAYLEIGH-TAYLOR(-)	+	-	+	+	+	-	-	-	+
LINE SHAPE(+)	-	+	+	+	+	-	+(?)	0	+
DRIFT(-)	-	+	+	+	+	-	+(?)	0	+
THERMAL(0)	-	+	+	+	+	-	+(?)	0	+
UNSTABLE(+)	+	+	+	+	-	+	+	+	+
STABLE(-)	+	+	+	+	-	+	+	+	+
1-D RAD. TRANSP.(-)	-	-	-	-	-	-	+	N.A.	-
3-D RAD. TRANSP.(+)	-	-	-	-	-	-	+	N.A.	-
GROWTH RATE (SEC.)	1000	50	100	2	NONE	10000	?	?	50

TABLE 1: PREVIOUS RESULTS ON INSTABILITIES IN STELLAR WINDS



### 3. The general dispersion equation.

The motion of the plasma in the wind is described by the equations of conservation of mass, momentum and energy and by the gas law. In the wind of a typical OB supergiant the external forces are gravity and radiation pressure, while the energy exchange is determined by radiative heating and cooling and by conduction. The radiation pressure and the energy budget depend strongly on the abundance of impurity ions, their ionization balance, and further on the details of the radiative transfer. These terms determine both the nature of the steady state wind and the occurrence of instabilities. Greatly different results may be obtained with different physical assumptions (see Table 1).

Hence I will make as little assumptions as possible on the physics of the wind in order to state the problem in its most general form. I consider perturbations with a wavelength that is small compared to the density and temperature scale-height in the wind and to the length related with deviations from spherical symmetry. Then all perturbations can be expressed as superpositions of modes of the form  $\sim \exp(i\vec{k}\cdot\vec{r} - i\omega t)$ . The equations of conservation of mass, momentum and energy respectively read

$$-i\omega \frac{\rho_1}{\rho_0} + i(\vec{k}\cdot\vec{v}_1) = 0 \quad (1)$$

$$-i\omega \vec{v}_1 = -ik c_s^2 \left( \frac{\rho_1}{\rho_0} + \frac{T_1}{T_0} \right) + \boxed{\delta \vec{g}_r} \quad (2)$$

$$-i\omega \left( \frac{T_1}{T_0} - \frac{2}{3} \frac{\rho_1}{\rho_0} \right) = \frac{1}{\frac{3}{2} \rho_0 T_0} \left( \boxed{\delta \mathcal{L}} + \boxed{\delta(\vec{\nabla} \cdot \vec{F}_c)} \right) \quad (3)$$

Here,  $\rho$ ,  $T$  and  $\vec{v}$  represent the density, temperature and velocity of the flow, while the subscripts 0 and 1 refer to the unperturbed situation and first order perturbations.  $c_s$  is the sound velocity. The terms in boxes are respectively the perturbation in the radiative acceleration, that in the sum of radiative energy gains and losses and the perturbed conductive flow.

It has been shown by Owocki and Rybicki (1984) that under very mild assumptions the influence of the terms  $\delta \mathcal{L}$  and  $\delta(\vec{\nabla} \cdot \vec{F}_c)$  may be represented by a complex generalization of the ratio of specific heats  $\gamma(\omega, \vec{k})$ , which depends only on two parameters, corresponding to the radiative and the conductive timescale of the plasma. This result will be used in the following without further derivation.

The perturbation in radiative acceleration depends on the variations in the fluid variables.

$$\delta \vec{g}_r = \underbrace{\begin{pmatrix} \partial \vec{g}_r \\ \partial \vec{v} \end{pmatrix}}_{\parallel \vec{A}} \cdot \vec{v}_1 + \underbrace{\begin{pmatrix} \rho_0 \partial \vec{g}_r \\ \partial \rho \end{pmatrix}}_{\parallel \vec{B}} \frac{\rho_1}{\rho_0} + \underbrace{\begin{pmatrix} T_0 \partial \vec{g}_r \\ \partial T \end{pmatrix}}_{\parallel \vec{C}} \frac{T_1}{T_0} \quad (4)$$

The tensor  $\vec{A}(\vec{k})$  represents the line-shape instability, the vector  $\vec{B}(\vec{k})$  the drift instability and  $\vec{C}(\vec{k})$  the new 'thermal drift instability'. These quantities need to be calculated for each specific situation. In most previous work only one element of  $\vec{A}$  has been calculated,  $A_{zz}$ , and generally also only one element of  $\vec{B}$  and  $\vec{C}$  is considered,  $B_z$  and  $C_z$ . Here the formal treatment is pushed to the limit by the elimination of  $\rho_1/\rho_0$  and  $T_1/T_0$  and the use of  $\gamma(\omega, \vec{k})$ . The problem reduces to the determination of the eigenvalues of the complex tensor  $\vec{T}$ .

$$\vec{T} = i\omega\vec{A} - \omega^2\vec{I} + [i\vec{B} + i\vec{C}(\gamma-1) + \gamma\vec{k}c_s^2]\vec{k} \quad (5)$$

where it is understood that  $\vec{B}\vec{k}$  is a tensor with  $\vec{B}$  forming the columns and  $\vec{k}$  the rows and analogously for  $\vec{C}\vec{k}$  and  $\vec{k}\vec{k}$ .

It may be shown that  $\vec{T}$  has five physically relevant eigenvalues of which at least one corresponds to a heavily damped thermal wave. Further consideration of this dispersion equation shows that there may be types of solutions that cannot be found in the limited one-dimensional treatment of most previous papers (Table 1). For example, it is easily demonstrated that under very mild conditions on the tensor  $\vec{A}$  there are growing transversal wave solutions, which is a rather unexpected feature in the absence of magnetic fields.

#### 4. The thermal drift instability

In order to demonstrate a simple example of this instability I ignore the line-shape instability ( $\vec{A} = \vec{0}$ ) and I assume purely radial perturbations such that  $\vec{B} = B\hat{z}$  and  $C = C\hat{z}$ .  $\hat{z}$  is the unit vector pointing radially outwards. Suppose now that bound-free transitions are a dominant source of opacity, i.e.

$$\chi = \chi_0 \rho T^{-1.5} \exp(I_n/kT) \quad (6)$$

The radiative acceleration is proportional to the opacity, so with (4) I find

$$C = -(1.5 + I_n/kT)B \quad (7)$$

Using the model of Carlberg (1980) for the supersonic portion of a typical hot-star wind I find that in the wave length range  $6 \times 10^5 \text{ cm} < \lambda < 4 \times 10^8 \text{ cm}$  sound waves propagate adiabatically, hence  $\gamma(\omega, \vec{k}) = 5/3$ . Inserting this in (5) I find

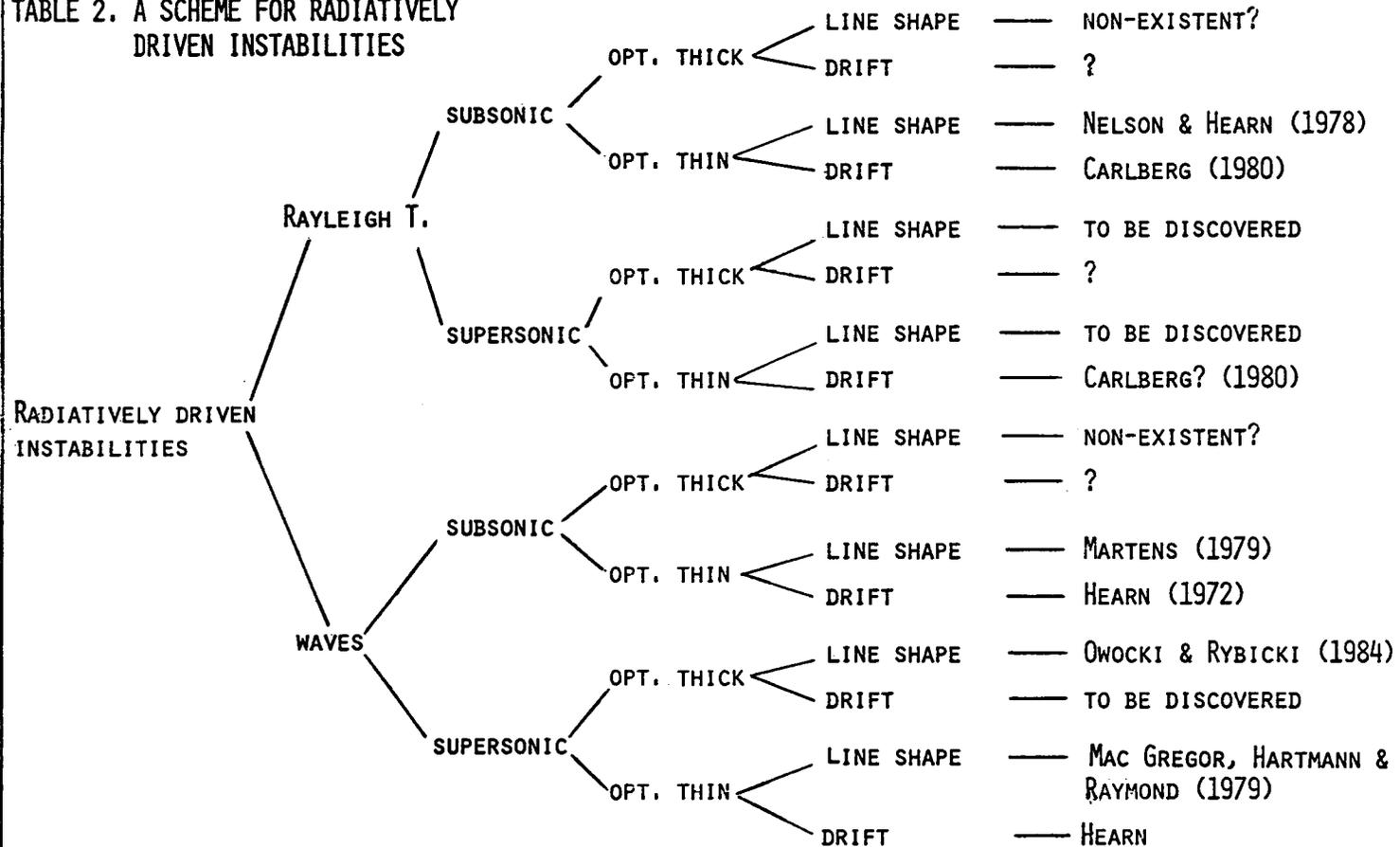
$$\omega^2 = \frac{5}{3} k_z^2 c_s^2 - i(I_n/kT)Bk_z \quad (8)$$

which means that inwardly propagating sound waves grow in amplitude at a rate comparable to the growth rate of the outwardly propagating isothermal drift waves. The model of Carlberg yields periods for these thermal drift waves between 0.2 and 130 seconds and an e-folding time of about 1000 seconds. In contrast to what has been shown by Berthomieu et al. (1976) for the outwardly propagating drift waves, these thermal drift-waves are not restricted in amplification.

	HEARN	NELSON & HEARN	MARTENS	MACGREGOR HARTMANN & RAYMOND	ABBOT	CARLBERG	KAHN	HEARN KUIIN & MARTENS	OWOCKI & RYBICKI
YEAR	1972	1978	1979	1979	1980	1980	1981	1983	1984
SUBSONIC (-)	-	-	-	+	+	+	+	+/-	+
SUPERSONIC(+)									
OPTICALLY THICK (+)	-	-	-	-	+	-	+	-	+/-
OPTICALLY THIN (-)									
SOUND WAVE (+)	+	-	+	+	+	-	-	-	+
RAYLEIGH-TAYLOR(-)									
LINE SHAPE(+)									
DRIFT(-)	-	+	+	+	+	-	+(?)	0	+
THERMAL(0)									
UNSTABLE(+)	+	+	+	+	-	+	+	+	+
STABLE(-)									
1-D RAD. TRANSP. (-)	-	-	-	-	-	-	+	N.A.	-
3-D RAD. TRANSP. (+)									
GROWTH RATE (SEC.)	1000	50	100	2	NONE	10000	?	?	50

TABLE 1: PREVIOUS RESULTS ON INSTABILITIES IN STELLAR WINDS

TABLE 2. A SCHEME FOR RADIATIVELY DRIVEN INSTABILITIES



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## DISCUSSION

Hearn: In your first analysis you have an instability proportional to terms in  $(d g_{\text{rad}}/d v)$ ,  $(d g_{\text{rad}}/d \rho)$ , and  $(d g_{\text{rad}}/d T)$ . The first term is the basis of the existing line-driven instability. If one looks at the physical mechanisms which can contribute to the instability, it would seem that the contribution of the last two would be very small in comparison with the  $(d g_{\text{rad}}/d v)$  term.

Martens: Yes, that is true in the outer parts of the wind, but at the base of the wind, the line-shape-instability growth rate may be greatly reduced as was shown in the previous contribution, so there the other two terms can be as important as the first term. In addition, the line-shape instability quickly saturates as the wave-amplitude reaches the thermal velocity. Then the other two mechanisms may become important.

Owocki: I agree with Hearn that modes associated with the perturbed density should lead to only very weak instabilities because these terms are of order  $L/R_* \sim 1/100$  (here  $L = v_{\text{th}}/v_o' = \text{Sobolev length}$ ) when compared to the terms associated with what you call "line-shape" instability.

The velocity amplitude being greater than the thermal speed does not imply that the instability will stop. It means only that the perturbed force will saturate to the value for an optically thin force, which is still much larger than the force on the mean fluid.

Martens: The first is true only in the supersonic portion of the wind. The second may be true, but then the linear approximation is no longer correct and all sorts of things may happen.

Castor: Can you clarify the relation of the instability you talked about at the last to Hearn's original overstable sound-wave instability?

Martens: In the physical explanation in Hearn's 1972 paper, only isothermal waves were mentioned, and it was said that they would be amplified because of the density dependence of the absorption. The instabilities of this paper depend on the changes in ionisation equilibrium associated with the temperature perturbations. The "thermal drift" waves propagate inward, the drift waves propagate outward. Actually the right expressions can be found in Hearn's 1972 paper; only the physical explanation was incorrect.

## RADIATIVE AMPLIFICATION OF ACOUSTIC WAVES IN HOT STARS

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Since the discovery of broad P Cygni profiles in early-type stars and the detection of X-rays emitted from the envelopes of these stars it has become clear, that a considerable amount of mechanical energy has to be present in massive stars.

Several attempts have been made in order to explain the observed phenomena, the most famous of which are the cool wind model by Lucy and Solomon (1970) and Castor, Abbott and Klein (1975), the warm wind model of Lamers, Morton, Snow and Rogerson (1976, 1978) the coronal model by Hearn (1975) and Cassinelli and co-workers (1977, 1984) and the shock-wave model by Lucy and Lucy and White (1980, 1982). Whereas the first models have difficulties in explaining the observed X-ray emission, the last ones lack close agreement between the observed and calculated X-ray spectrum.

So we propose another attack on the problem, an attack which has proved successful when applied to late-type stars. We claim that acoustic waves form out of random fluctuations, amplify by absorbing momentum from the stellar radiation field, steepen into shock waves and dissipate. We constructed a stellar atmosphere, initially in radiative equilibrium without macroscopic mass motions, and introduced sinusoidal small-amplitude perturbations of specified Mach number and period at the inner boundary. The partial differential equations of hydrodynamics as well as the equations of radiation transfer for grey matter were solved numerically. Here the equation of motion was augmented by a term describing, in an averaging way, the absorption of momentum from the radiation field in the continuum as well as in lines, thereby including the Doppler effect and allowing for the treatment of a large number of lines (actually 465) in the radiative acceleration term.

The results of our calculations can be summarized as follows:

- 1) Owing to the existence of an extended radiative damping zone up to  $\tau = 10^{-5}$ , shocks that may eventually form in the inner layer of the atmosphere do not grow. So the shocks are comparable in strength at the end of the radiation damping zone, irrespective of the magnitude of the initial perturbation at the inner layer.
2. The amplification is greatest for periods of  $1/3 - 1/4$  of the cut-off period.
3. Continuous opacities alone do amplify acoustic waves, but the amplification is generally less than 10 per cent. When we include line opacity, the amplification rate drastically rises about an order of magnitude. So the main amplification mechanism is the Doppler effect.

4. Beyond the radiation damping zone shocks soon attain temperatures of 500,000 K - 1,000,000 K, thereby heating the gas between them to an average temperature of 100,000 K to 400,000 K.
5. The thin zones of rather high temperature in and immediately behind the shocks are responsible for the X-ray emission.
6. In the warm gas between successive shocks UV resonance lines form. That is why resonance line analyses yield temperatures adequate for a warm wind model.
7. The shocks push the matter forward; the radiation momentum absorbed in the compression zone of the waves locally reduces the gravity, so matter is moving outward at a speed of approximately  $100 \text{ km s}^{-1}$  and a rate of  $10^{-8} - 10^{-7} M_{\odot} \text{ yr}^{-1}$ .

These results give encouraging support to investigate further the interaction of acoustic waves with their stellar environment in order to improve our understanding of the wealth of phenomena associated with early-type stars.

## DISCUSSION

Castor: Can you describe how you treated the radiation transfer in the lines?

Wolf: We did not treat the radiation transfer in lines correctly since we cannot afford a lot of frequency points in a line-dependent hydrodynamical calculation. So we developed a crude method based on several assumptions such as LTE, rectangular shape of line profile, and so on. We finally arrived at a formula for the radiation pressure in lines, part of which can be tabulated because it depends only on pressure and temperature, while the rest of it is a simple function of the velocity and accounts for the Doppler effect.

Owocki: I do not understand your neglect of lines. I believe that the radiative force will greatly exceed gravity if you include lines, and it will not be necessary to drive the atmosphere with a piston to start things moving.

Wolf: If macroscopic motions are absent, lines help in reducing the gravity a great deal, but they do not sum up to an effective acceleration that points outward.

Underhill: When you are estimating the force due to the absorption of radiation in lines, you should recall that inside an atmosphere the net flux in the line frequency is very small whenever the material is nearly stationary. The net flux in a line frequency at depth  $\tau = 0.001$  is much less than that which emerges from the atmosphere at the level where  $\tau = 0.000$ . Here  $\tau$  is the nominal or continuum optical depth. This statement can easily be confirmed by using a model-atmosphere program to calculate the net spectrum at  $\tau = 0.001$  instead of at  $\tau = 0.000$ .

ON THE ROLE PLAYED BY LINES IN RADIATIVELY DRIVEN STELLAR WINDS  
DEPENDING ON THE POSITION OF THE STARS IN THE HR DIAGRAM

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Though it is now well established that the radiative force due to transfer in ultraviolet lines is always an important mechanism for driving hot star winds (Lucy and Solomon, 1970; Castor, Abbott and Klein, 1975; Weber, 1981, Leroy and Lafon, 1982), it is still not clear when it is the dominant mechanism and which parameters are crucial for this. In order to investigate the efficiency of purely radiative momentum/energy transfer in hot star winds and in various regions of the HR diagram, we have improved the model built up by Leroy and Lafon (1982) and put it to its limits; we have looked for correlations between the mass loss rate, the luminosity and other parameters and compared the theoretical and the observational results, looking for observed stars "violating" the model.

MODEL It is that of Leroy and Lafon (1982) improved in order to investigate a wide range of physical conditions with the minimum number of free parameters. The basic assumptions are steady state, spherical symmetry, radiative driving, radiative equilibrium. We have used the "radiative intensity" formalism i.e. we have solved the radiative transfer equation for one or two "typical lines" shifted at frequencies in two non-overlapping intervals by the expansion velocity, which is assumed increasing with the radial distance (accelerated wind); then we have multiplied each radiative force by "typical number of lines"  $N_i$ ; the ratios  $N_i/\Sigma N_i$  are data of the problem (derived from the results of Abbott (1982) that give the fractions of radiative force due to lines on both sides of the Lyman discontinuity at one given optical depth). The total number of lines  $N_1+N_2$  is left free and is a result of the computations: it is better to fix  $v_\infty$ , on observational grounds; since it is highly sensitive to  $N_1+N_2$ , we obtain a much faster convergence of the numerical iteration.

The frequency of one of the typical lines is chosen close to the maximum of the Planck function; the other is taken on the other side of the Lyman discontinuity. Indeed, for  $T_{\text{eff}} < 2 \cdot 10^4 \text{K}$  the contribution of lines with wave lengths  $\lambda < 912 \text{ \AA}$  is negligible; for  $T_{\text{eff}} > 4 \cdot 10^4 \text{K}$  all lines are formed at the photosphere. By contrast, in the intermediate range, the continuum opacity in creases in the inner layers of the wind, lines with  $\lambda < 912 \text{ \AA}$  are formed at larger radial distances and their contribution is not negligible. Details of the physics will be discussed in forthcoming papers; the main point is that antagonistic effects produce roughly compensating results. The effect is maximum for  $T_{\text{eff}}$

about 25000K and in this case the computed mass loss rate is enhanced by a factor 1.3 (for same  $v_{\infty}$ ).

Finally, at each frequency, we have used lines with different total line opacities  $\kappa_l$  distributed according to a power law (number of lines  $\sim \kappa_l^{-\alpha}$ ).

The temperature is that corresponding to a stationary gray atmosphere in radiative equilibrium, as in Weber's work (1981), but with a different boundary condition (the photosphere is fixed at  $T = T_{\text{eff}}$ ).

Of course the system of equations is solved using numerical iteration :

The input parameters are : The effective temperature, the luminosity and the mass of the star, and also the terminal velocity  $v_{\infty}$  and  $\alpha$ . The total number of lines and the mass loss rate are output data derived from the computations together with the temperature, the force and the velocity profiles.

An important point is that a self consistent solution, limit of a fairly fast converging numerical iteration, can be found only in a small range of  $\alpha$  (less than  $0.1\alpha$ ), which "calibrates" the model.

THE STARS We have choosen a sample of stars from various regions of the HR diagram, including spectral types O, B, A, and one Wolf Rayet star, for which both the mass loss rate  $\dot{M}$  and the terminal velocity  $v_{\infty}$  are available. The parameters are given in table 1.

Star	Spectrum	$T_{\text{eff}}$	$\log L/L_{\odot}$	$M/M_{\odot}$	$R/R_{\odot}$	$v_{\infty}$ (km/s)
9 Sgr	O4	50119	6.12	97	15.3	3440
$\lambda$ Cep	O6	38019	6	65	23	2670
$\lambda$ Ori	O8	34754	5.24	29	11.5	3050
$\alpha$ Cam	O9	30000	5.81	48	30	1890
$\epsilon$ Ori	B0	24831	5.59	37	34	3320
$\eta$ Cen	B1	24000	3.98	11	5.7	810
$\epsilon$ Cma	B2	21000	4.68	16	16.6	700
$\rho$ Leo	B1	20893	5.21	24	31	1580
P Cyg	B1	19300	5.86	30	76	300
O <sup>2</sup> Cma	B3	15488	5.23	26	58	580
$\alpha$ Cyg	A2	10351	5.07	22	106	280
92740	WN7	30200	5.56	32	22	2070

THE RESULTS The results of the numerical computations, displayed in table 2, show in general a fairly good agreement between the computed and the observed mass loss rates  $\dot{M}$ , except in two cases indicated by †. For all but these stars a correlation appears between  $\dot{M}$  and L (fig. 1), which can be described, using a least squares fit, by the relation

$$\dot{M} = 1.26 \cdot 10^{-12} (L/L_{\odot})^{1.17} M_{\odot}/\text{year}$$

which can be compared with the relations derived from observations by

Barlow and Cohen (1977)  $\dot{M} = 6.8 \cdot 10^{-13} (L/L_{\odot})^{1.1} M_{\odot}/\text{yr}$  (O stars)

$$\dot{M} = 5 \cdot 10^{-13} (L/L_{\odot})^{1.2} M_{\odot}/\text{yr}$$
 (B, A)

Waldron (1984, this vol.)  $\dot{M} \sim (L/L_{\odot})^{1.1}$  ( $T_{\text{eff}} > 2600\text{K}$ )

Peppel (1984)  $\dot{M} \sim (L/L_{\odot})$  (OB stars)

It could be noted that the two stars for which the discrepancy between the computed and the observed value of  $\dot{M}$  is obvious have particular values of the ratio  $\Gamma$ .  $\eta\text{Cen}$  has a very small  $\Gamma$  so that many lines would be necessary to drive the wind up to the observed  $v_{\infty}$  (the model needs a large number of lines), which produces an unexpectedly high mass loss rate. By contrast, the very high  $\Gamma$  of  $\rho\text{Cyg}$  minimizes the role of the lines and produces a very small mass loss rate.

Table 2

Star	$\Gamma$	$\dot{M}$ ( $M_{\odot}/\text{yr}$ ) Observed	$\dot{M}$ ( $M_{\odot}/\text{yr}$ ) Computed	$\alpha$	
9 Sgr	0.45	2.5 $10^{-5}$	5.13 $10^{-5}$	1.6	
$\lambda$ Cep	0.5	3 $10^{-6}$	7 $10^{-6}$		
$\lambda$ Ori	0.2	7 $10^{-7}$	9.22 $10^{-7}$	1.6	$\Gamma$ is the ratio of the radiative force due to the continuum to the gravity force.
$\alpha$ Cam	0.46	3.5 $10^{-6}$	4.31 $10^{-6}$	1.6	
$\epsilon$ Ori	0.36	3.1 $10^{-6}$	5 $10^{-6}$	1.2	
$\eta$ Cen	0.03 †	2.85 $10^{-10}$	1 $10^{-5}$	3	
$\epsilon$ Cma	0.1		1.22 $10^{-6}$	3	
$\rho$ Leo	0.23	9 $10^{-7}$	3.31 $10^{-7}$	1.4	
$\rho$ Cyg	0.8 †	2 $10^{-5}$	4 $10^{-7}$	1.8	
O <sup>2</sup> Cma	0.22	3 $10^{-7}$	4.38 $10^{-7}$	1.8	
$\alpha$ Cyg	0.18	7 $10^{-7}$	1.98 $10^{-6}$		
92740	0.19	3 $10^{-5}$	2.95 $10^{-5}$	1.6	

## CONCLUSIONS

Not in all cases but in a widespread region of the HR diagram, line driven models are consistent with observations, the radiative equilibrium physics is relevant throughout the expanding atmospheres and the mass loss rate is quasi-linearly correlated with the luminosity.

Nevertheless, in some cases additional momentum or energy sources are necessary and other mechanisms are probably active.

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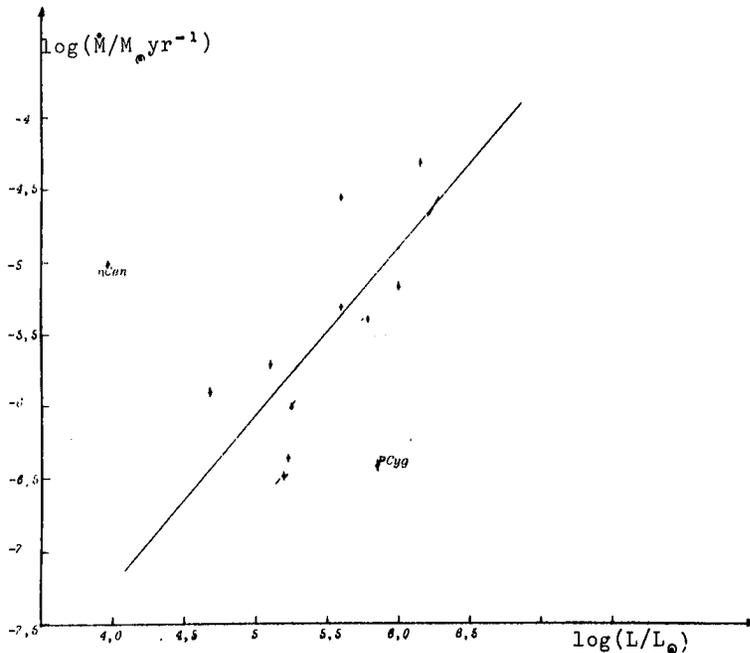


Fig.1 Correlation  
between  $\dot{M}$  and  $L$

Communication presented by J.-P. J. Lafon

## DISCUSSION

Castor: I have two questions. (1) Is it correct that you adjusted  $\alpha$  to get the observed  $v_{\infty}$ ? (2) Can you clarify the relation between the 1 to 2 "typical lines" and the  $\alpha$ -power strength distribution? In what respect do the "two typical lines" differ?

Lafon: The quantity  $\alpha$  is not truly "adjusted". In fact, self-consistent models can be found by converging iteration only for the indicated value of  $\alpha$  and within a very small range about it (without major changes in the numerical results). We think that this can be explained by the respective roles of the weak lines (mainly efficient close to the photosphere) and the strong lines (mainly efficient in the outer parts of the wind). In some way  $\alpha$  is a measure of the distribution of the line strength between strong and weak lines. For too large a value of  $\alpha$  weak lines can produce an excessive radiative force at the bottom of the wind (cf. the paradox of Marlborough and Roy (1970, Ap.J., 160, 221); for too small a value of  $\alpha$ , the strong lines dominate, but are saturated at the bottom and cannot produce a trans-sonic wind.

The  $\alpha$ -power strength distribution is disconnected from the "two typical lines" assumption. A strength distribution is assumed (usually but not necessarily the same one, with the same  $\alpha$ ) for each typical line. The difference between the typical lines is that one is taken close to the maximum of the Planck function, depending of  $T_{\text{eff}}$  and on the elements present and the other is taken on the other side of the Lyman discontinuity.

Underhill: There is good reason to believe that the effective temperature of P Cygni is near 13000 K, see Underhill (1979. Ap.J., 234) and Chapter 4 of "B Stars with and without Emission Lines" (NASA SP-456). Would a lower  $T_{\text{eff}}$  than the value which you assumed remove some of your difficulties with P Cygni?

Lafon: Of course, complete numerical computations would be necessary to give a quantitative answer. However, the fact, mentioned in our talk, that higher  $\Gamma$  values (or higher luminosities  $L$ ) tend to decrease the computed mass-loss rate, whereas lower  $\Gamma$  values tend to increase it suggests that this might be true. We shall look at this pretty soon.

MULTI-LINE TRANSFER AND THE DYNAMICS OF STELLAR WINDS\*

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A Monte Carlo technique for treating multi-line transfer in stellar winds is described and tested. With a line list containing many thousands of transitions and with fairly realistic treatments of ionization, excitation and line formation, the resulting code allows the dynamical effects of overlapping lines to be investigated quantitatively, as well as providing the means of directly synthesizing the complete spectrum of a star and its wind. As a direct result of this improved treatment of multi-line transfer, the computed mass loss rate for  $\zeta$  Puppis is now found to agree with the observed rate. The synthesized spectrum of  $\zeta$  Puppis also agrees with observational data. This confirms that line-driving is the dominant acceleration mechanism in this star's wind.

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\*To appear in The Astrophysical Journal.

## DISCUSSION

Cassinelli: Could you explain again how you iteratively derived the  $\dot{M}$ 's for your models?

Abbott: Given a value of  $\dot{M}$ , you calculate the work done on the wind. You then compare this work to the energy of the wind,  $\dot{M}(v_{\infty}^2 + v_{\text{esc}}^2)/2$ , and iterate on  $\dot{M}$ .

Linsky: I should bring to your attention that the absolute flux scale in the 900-1200 Å region has recently been revised from that used by the Johns Hopkins rocket people (Brune *et al.* 1979, *Ap.J.*, 227, 884). Recently the Voyager far ultraviolet spectrometer instrument has been calibrated on an absolute flux scale using hot subdwarfs and white dwarfs.

R.L. White: Did you calculate the radiative acceleration as a function of radius? If you did, how does it compare with the radiative acceleration implied by the velocity laws which you assumed?

Abbott: We have not yet solved the equation of motion.

Linsky: I think that the worst thing which could happen for the progress of this or any other field would be the agreement between theory and observation.

## SUMMARY OF THE ORIGIN OF NONRADIATIVE HEATING/MOMENTUM IN HOT STARS

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### INTRODUCTION

We have met for three days to hear about nonradiative heating in the atmospheres of stars and about the deposit of nonradiative momentum in the stellar atmosphere. We have discussed the implications of what we have heard and we have, at times, emphasized opposing points of view. Now it is my turn to summarize what we have heard. Naturally, this summary is biased to some extent by my particular interests.

Observations made from space have been very important in changing our concept of what a star is like. In order to interpret the spectroscopic information gained in the wavelength region inaccessible from the surface of the earth, that is, chiefly in the domain of X rays and of ultraviolet radiation, we have to revise in many ways the assumptions which underlie the theory of stellar atmospheres. The observations made from space drive the change, but change is demanded also when one considers the interpretation of modern observations made from the surface of the earth in wavelengths from approximately 3100 Å to 20 μm and in the radio range.

At this conference we have not discussed instrumentation, but improved observing facilities are one major reason why we need to consider new ideas for interpreting the spectra of stars. It is a fact that the photometric precision and sensitivity for observing at high and at moderate spectral resolutions have increased by a large amount in the last 15 years. Modern observing procedures and modern data analysis methods have put into our hands information which was undreamed of when the theory of stellar atmospheres and stellar spectra began to bloom some 40 years ago. That blossoming period was driven, in part, by the development of high-dispersion, high-resolution spectrographs for observing stars. It is not in the least surprising that now when we have many more types of observation to consider, it is desirable to re-think the basis for the theory.

### MODELING

Every interpretation of spectroscopic observations is made by combining knowledge of the physics of gas and radiation to produce a model, and then comparing the predictions of the model with what is observed. In the case of the spectra of stars in the mainsequence band of the HR diagram and of giants and supergiants, one needs to use only nonrelativistic physics to understand observations in the wavelength band from 1 Å or so to 10 cm or so. Such spectra are what I am talking about.

Model stars and model atmospheres are assemblages of numerical data which describe the physical state at every depth in the star. We shall focus our attention chiefly on the properties of model atmospheres. The starting point for making a model atmosphere is provided by the three conservation laws: conservation of energy, momentum, and mass. The equation of state for the matter present is that of a perfect gas.

The conservation laws are very general. To make progress one must use a few constraints to reduce the equations which represent the conservation laws to simple enough forms that numerical solutions can be found. One wants to know the particle density, the degree of ionization, the electron density, and the radiation field at each distance  $r$  from the center of the star. The star is assumed to be spherically symmetric. The solutions are defined by specifying boundary conditions at the inside of the model atmosphere where it joins a model representing the interior layers of the star, and at the point in space where the model stellar atmosphere joins to a model interstellar medium.

The traditional constraints used when one is modeling the atmosphere of a hot star are two in number: hydrostatic equilibrium and radiative equilibrium. When one uses the geometry of plane parallel layers, one specifies that the acceleration of gravity in the atmosphere is constant at some appropriate value. This enables one to find the particle density as a function of radius by working with the equation which results from the principles of the conservation of mass and the conservation of momentum. Traditionally model stars do not lose mass;  $M$  is put identically equal to zero. When one uses spherical geometry, the local value of the acceleration of gravity is determined by the mass of the star, the radius to the level in the atmosphere being considered, and the constant of gravitation.

Use of the constraint of radiative equilibrium and the principle of conservation of energy allows one to find how the temperature depends on the distance from the center of the star. Radiative equilibrium means that the total amount of energy present in the radiation field at any level  $r$  is constant. The value of the constant is specified by giving the effective temperature of the model atmosphere.

The spectrum emerging from the model atmosphere is calculated by solving the equations of radiative transfer. One tests the model atmosphere for relevancy by comparing specific details of the predicted spectrum with features in observed spectra from stars of the spectral type it is desired to interpret. In the early work, because of limited computing facilities, one had to adopt the simplification that the degree of ionization and excitation of the atoms and ions in the model atmosphere could be calculated as if local thermodynamic equilibrium (LTE) existed. Later, when large fast computers became available, this severe simplification was replaced by the statement that statistical equilibrium exists in the atmosphere. However, if use of the principle of statistical equilibrium is to yield representative results, one must make use of realistic model atoms.

Model atmospheres and predicted spectra, as I have described them, allow one to obtain an acceptable interpretation of many features in the parts of the spectra of hot stars observed from the ground. Careful use of accurate observations, however, shows that the predicted spectra do not match well much of what is observed. This is particularly serious for O and Wolf-Rayet stars because many of the spectral features selected empirically as spectral classification criteria are not predicted accurately by the existing methods. The areas of discrepancy are increased when observations made in space are compared with the predictions of the traditional theory.

#### AREAS OF DISCREPANCY

When one compares the predictions from the best available traditional model atmospheres with the best observations made from the surface of the earth and from space, one finds 9 areas of discrepancy. They are the following:

1. The presence of strong emission lines in the spectra of many hot stars;
2. The presence of an infrared excess, specially for Wolf-Rayet stars, Be stars, and supergiants;
3. The presence of suprisingly strong radio emission from hot supergiants and Wolf-Rayet stars;
4. The great strength and width of the leading members of the series of H, He I, and He II lines observed in the spectra of O stars; "microturbulence" of the order of  $100-150 \text{ km s}^{-1}$ ;
5. The superheating which is inferred from the presence of strong absorption lines from the high ions of C, N, and O;
6. Outflow of low-density gas to form a wind;
7. Emission of X rays by most B, O, and Wolf-Rayet stars;
8. The presence of rather sharp, shortward displaced absorption components in the profiles of the ultraviolet resonance lines of relatively abundant ions (C II, C IV, N V, O VI, Si IV, Al III, Mg II) for some stars.
9. Irregular variation of the light from O and B supergiants which can be interpreted to be a result of the rotation of a slowly changing spotted disk.

Because of these discrepancies, one must postulate that energy and momentum are deposited in the outer atmospheres of B, O, and Wolf-Rayet stars in excess of the amounts which are compatible with the constraints of hydrostatic and radiative equilibrium. In addition, one can argue that bipolar magnetic spots with their associated lines of force are present on the disks of hot stars.

Since it is inconceivable that more radiation would be generated in the outer layers of stars by nuclear processes, one must conclude that the source of the extra energy being seen is nonradiative. Likewise one suspects that the source for the extra momentum is nonradiative because there are good reasons to believe that the constraint of hydrostatic equilibrium permits one to make reasonable models of the interiors of massive stars. Introducing the ad hoc postulate that model stars lose mass according to some arbitrary function of the mass, luminosity and radius of the star as the model star evolves, adds nothing to our understanding of the physics of stars. It merely provides a computing algorithm which has not been linked to the action of the known forces of physics. The forces considered when one is modeling massive stars are the long range forces due to gravitation, to the actions of magnetic fields on charged particles, and to the actions of radiation.

I have suggested that the inner part of the atmosphere where the continuous spectrum is formed and where weak lines from not very abundant ions are formed be called the photosphere and that the outer part be called the mantle of the star. Traditional methods of modeling are adequate for modeling photospheres, but not for modeling mantles. One has to change some of the basic postulates if one is to model a mantle correctly.

I have used spectroscopic observations of hot stars to make the point that in order to model the mantles of stars, one must modify the basic assumptions in the theory used for making models. Some details of the spectra of the Sun and of cool stars also agree badly with the predictions made with traditional theory. Cool stars, like hot stars, have mantles outside their photospheres. The chromosphere and corona of the Sun are particular examples of a mantle that has been observed in great detail.

#### WHAT THE OBSERVATIONS TELL US

We have heard from Cassinelli about the evidence for nonradiative activity in stars with effective temperatures greater than 10000 K, and from Linsky for stars with effective temperatures less than 10000 K. Their remarks confirm the statements which I have just made about the occurrence in the spectra of single stars of many spectral types of features which are not predicted by traditional theory. The spectra of binary stars show enhanced discrepancies in some cases, but I shall not concern myself with this problem.

In the first review paper Cassinelli emphasised that something more than radiation is responsible for the winds and outer atmospheric phenomena of hot stars. He pointed out that no strong correlations are found between the observed phenomena indicating the presence of winds and superheating and the basic stellar parameters such as mass, radius, and effective temperature. In addition Cassinelli argued persuasively that many observations, including polarisation measurements, indicate that the outflow occurs in plumes, at least in part. This requires that the outflow and heating be generated by some process which can be defined to occur locally. The actions of magnetic fields spring to mind.

In the second review paper Linsky surveyed the observations of cool stars and he noted that cool stars present atmospheric and wind-related phenomena which are similar in many respects to those observed for hot stars. Linsky stressed the point that what can be detected depends on the contrast at the wavelength of interest between the energy in the photospheric spectrum and the energy added or subtracted by a line formed in the mantle of the star. It is true that the amount of heating and outflow observed in the mantles of cool stars is different from that observed in the mantles of hot stars, and it is true that one observes somewhat different spectroscopic details to confirm the presence of heating and outflow than one does for hot stars. However, analysis suggests that the same physical processes are acting in both hot and cool stars. The balance between the actions generated by the radiation field, the magnetic field, and the supply of mechanical energy present appears to be different in cool stars from what it is in hot stars, but it is the interactions between the same three factors (the radiation field, the magnetic field, and the supply of mechanical energy) which must be considered if one is to understand what the spectroscopic observations mean.

The contributed paper by Abbott emphasised that there is reason to suspect that some of the radio emission from OB stars may have a nonthermal origin, a point of view which I have expressed in connection with the Wolf-Rayet stars. The contributed papers by Myron Smith, and by Caroline Grady, emphasised that modern observations show that transient changes occur in the line profiles of many O and B stars. Not only are sharp components visible in the ultraviolet resonance lines, (for long intervals of time in the case of supergiants but for relatively short, erratic intervals of time in the case of mainsequence stars), but there are also disturbances to be seen in the profiles of some of the subordinate lines observed from the surface of the earth. The discrete components of the resonance lines are surely formed in the mantle. However, I think we can debate whether or not the disturbances seen in the subordinate lines are formed in the photosphere or in the mantle. In the case of lines from abundant species, I think there is a reasonable probability that the disturbances are formed in a cool part of the mantle. It is not clear to me whether that cool part is close to the photosphere or at some distance, say  $5 R_*$ , from the photosphere. This is because the Eddington-Barbier Principle is not valid in a moving atmosphere.

It was shown by other contributed papers that conclusions like those which are specific to massive hot stars are reached in other parts of the HR diagram. Nonthermal radio emission, nonradiative heating, and irregular changes in the line profiles and line strengths seem to be phenomena which occur for all kinds of stars. Stars of all spectral types radiate X rays at a detectable level, some more strongly than others.

#### THEORIES OF THE ORIGIN AND DISTRIBUTION OF NONRADIATIVE HEATING AND MOMENTUM IN STARS

On the second morning of the conference Chiuderi reviewed the theories which attempt to explain the observations of heating and outflow in the solar chromosphere and corona. The Sun is an exceptionally well observed object, and it is a useful testing ground for many types of theory. However, the

plethora of observational details has led to an abundance of theoretical studies, many directed at understanding specific observations. The review by Chiuderi provided us with a road map through the complex theory which tells how a moving, ionized gas may interact with magnetic fields in plasmas where the gas pressure is smaller than the magnetic pressure. It is fortunate that the complex magnetohydrodynamic theory which is needed can be checked to some extent by means of solar observations.

We heard from Golub about what parts of the theories may be checked by observations of cool stars. Golub emphasized the value of X-ray observations as a diagnostic tool. His analysis suggested that the generation of magnetic flux in the subsurface convective zones of stars and the expulsion of magnetic flux through the photosphere are important physical processes which control much of what we observe in the way of superheating and outflow. The onset of convection in the envelopes of different types of star and the ability of a model star to contain subsurface magnetic fields and to regulate the expulsion of magnetic flux are subjects which must be mastered if we are to understand the origin of heating and momentum in stellar mantles.

In the afternoon of the second day we heard the results of calculations designed to model the coronal layers of stars and the outer reaches of the wind. Considerable effort has gone into finding out the effect of the presence of mechanical energy in the form of turbulence or convective motions and how the presence of magnetic fields moderates the heating and driving of winds and loops. Mullan noted that if fast and slow wind streams are released from adjacent areas on the stellar surface, corotating interaction regions (CIR's) may be formed. These regions may cause some of the phenomena which are observed. If CIR's exist and behave as Mullan has deduced they may, then one must conclude that all areas on the surface of a star are not identical so far as acting as a source region for a wind. One then needs a factor for causing the adjacent regions to differ. Magnetic fields are attractive for this purpose. What goes on in the interior of the star affects what happens on the surface of the star. Some aspects of this topic were put before us by Sreenivasan in the case of rotating massive stars.

#### THE PARTICULAR PROBLEMS OF THE HOT STARS

On the morning of the third day Hearn summarized for us results which have been obtained on the physical state of a radiatively driven wind. An important point made by Hearn is that the deposition of heat and momentum in the subsonic region of the mantle determines the properties of the flow of the wind. In particular, it is this which determines the rate of mass loss. The properties of the supersonic part of the wind are what control the character of most of the spectroscopic features which we observe in order to infer the presence of a wind and superheating.

Hearn reviewed the theory of radiatively driven instabilities and showed how radiatively driven instabilities can act as source agents for at least some of the heating and momentum seen in the mantles of hot stars. The effects of radiatively driven instabilities will vary through a modest

range. Radiatively driven instabilities are, perhaps, a source for some of the changes observed in the X-ray fluxes and for some properties of the profiles of the resonance lines from some hot stars.

We concluded our morning session by hearing from Uchida about what happens when the model mantle is postulated to contain magnetic fields and a source of turbulent or unstable motion as well as radiation. Uchida emphasised the importance of X rays as a diagnostic tool, and he presented some intriguing studies of bipolar flows from young stellar objects. Recognizing that superheated, moving plasma and magnetic fields are present may change the way in which we analyse stellar spectra because it forces us to consider non-traditional physics in a range of temperature and pressure different from what is expected according to traditional analyses.

In the afternoon we heard some details about the character of model rotating winds which contain magnetic fields and about how the presence of radiation can amplify the effects of sound waves. What produces the assumed amount of sound waves low in the mantle is still an open question.

It is true that the presence of radiation and small-scale motion together can lead to the deposit of heat and outward directed momentum in the mantle of a star. In addition, the presence of rather small, locally distributed magnetic fields and "turbulent" motion in the photosphere can also lead to the deposit of heat and momentum in a stellar mantle. An important question which we have not resolved is how significant each of these possibilities is for determining the physical state of the mantles of the different types of B, O, and Wolf-Rayet stars.

In the case of hot stars, observations of the discrete components in the resonance lines, of polarisation changes, and of the small-amplitude, irregular light changes of O and B type supergiants find their most satisfactory explanation when events generated locally on the surface of the star are considered. To understand such phenomena, one needs to consider magnetic fields because the actions of magnetic fields are the only events which can cause something to happen at a particular spot on or above the surface of a star. We have exchanged comments on this point. It is, perhaps, too much to say that we reached a consensus on it.

Finally, we must not forget the growing body of evidence that some of the radio emission from hot stars is nonthermal in origin. I take this to mean that part of the radio flux is gyroresonant radiation. Magnetic fields must be present before you can have gyroresonant radiation.

#### THE PROBLEMS POSED BY THE MANTLES OF HOT STARS

Let me conclude my remarks by adding a few words about the problems which I find most interesting. These modeling problems are all difficult. We may not yet have defined each in an adequate manner, but I think we should think about these problems. Theoretical studies should not be confined only to doing those problems where one sees a large chance of coming to a definitive

answer after a modest amount of analytical and numerical work. One also should go out on a limb and attempt to make new problems tractable using hitherto undeveloped or unexplored methods. That is true adventure. I think that we can afford to put some adventure into the theory of stellar atmospheres and stellar spectra.

When I consider the nine areas of discrepancy between observation and theory in the case of the hot stars, and when I consider the observations and theory for the atmospheres of the cool stars, I am struck by the fact that similar types of discrepancies occur for hot and for cool stars. The amounts of the discrepancies are different for different stars, but the character of the discrepancies is similar. All stars, when observed over their full spectral range at high resolution, present evidence for superheating of at least some of the gas in the mantle, for outflow of material from the star, and for an inhomogeneous, constantly changing mantle. The size of each departure from the predictions made using traditional theory is different in one class of stars from what it is in another class, but similar types of discrepancy occur.

The mantle of the Sun has been observed in great detail for quite a few years now. We should make use of the vast body of information which is at hand. Therefore I suggest that we use the Sun as a model of what motion in and below the photosphere in the presence of weak, locally distributed magnetic fields can do for us. The solar mantle should be used as a model for the reactions to the presence of the magnetic fields which may occur in the mantles of all stars.

It seems reasonable to think of the mantle of a star as being composed of arcades of coronal loops extending, typically, to a distance of  $20 R_*$ , and of coronal-hole-type structures where the magnetic lines of force leave the star and go off into interstellar space. An important point is this. Can one observe any effects of such structures? We have heard that perhaps we do for all types of star, if we look carefully.

Four factors may be expected to differ from star to star: (1) the proportion of areas covered by arcades of loops to areas covered by coronal holes; (2) the linear extent and density of the mantle; (3) the quantity of radiation emerging from each unit of surface on the photosphere and the energy distribution of the photospheric radiation field; and (4) the rate at which the features which are controlled by the local presence of magnetic field lines (that is the arcades of loops, and the coronal-hole-type structures) change in strength and move about on and just above the surface of the star.

An adequate theory for modeling a mantle will embrace the same physics in all cases. The observable features predicted by the theory, however, will be different from star to star. The differences from the predictions of traditional theory, which are what we want to understand, will depend on the relative importance at each location in the mantle of radiation-driven events and of magnetic-field driven events. I would like to see theory developed that can size this problem and do something about it.

The origin of heating and momentum in the atmospheres of hot stars seems to be due to two major actions of electromagnetic forces in low-density gases. We have (1) events caused by the interactions of photons with ions, and (2) events caused by the interactions of magnetic flux with ions. The new step in the physics of stellar atmosphere which modern observations force us to take is to recognize this duality and take it into the theory. The observations suggest that kinetic energy originating in rotationally driven "turbulence" can be transferred to the particles of the mantle as heat and as momentum by means of processes moderated by the ambient radiation field and by processes moderated by the magnetic flux which is present. Now we should try to find out which moderating factor is most important at each place in the mantle.

#### DISCUSSION

M.A. Smith: Actually, there is a lot of recent observational evidence from Maeder's group and Percy's group for photometric variations of B supergiants. Such variations are ubiquitous. They are far more common than the detection of variations among B main-sequence stars, but they are not so regular as those variations among the B main-sequence stars that are observed. By this I mean that the variations in supergiants show time scales not periods. These time scales are typically  $1/4$  d to 2 d, and they are well within the overlap of observed periods of single nonradial modes in many B stars. This is the kind of behaviour one would expect from the interaction of several or many NR modes. Lucy's paper on Deneb (A2 Ia) is a paradigm of this behaviour for radial velocity variations.

Underhill: The work of observers at ESO in Chile (Sterken, Wolf, and others) suggests chiefly time scales of the order of 6 to 20 days for the irregular light changes. Several studies aimed at detecting changes in hours have had to conclude that such short time-scale changes were not indicated by the available data strings for supergiants.

Linsky: I have one comment and two pleas. My comment is that I have heard many reviews of the status of hot-star research prior to this meeting that generally concentrated on the classical problems of the field. I therefore considered hot stars to be a very different field of research from cool stars and the Sun, because the phenomenology appeared to be very different. As a result of this meeting, however, I am nearly convinced that the two fields of research are very similar in that the essential physics of both fields appears to be the interaction of magnetic fields, hot plasmas, and radiation.

My first plea is that we not reinvent the wheel. By this I mean that the hot-star theorists should read the solar literature to understand and utilize the extensive studies there concerning MHD waves, damping mechanisms; heating mechanisms, etc.

My second plea is that the hot-star and cool-star people collaborate in pushing for future ultraviolet spectroscopy missions like Columbus to discover the new phenomena needed to revolutionize our understanding of the atmospheres of both hot and cool stars.

Mullan: Is there a distinction between hot and cool stars? Some speakers presented results which suggest that there is a distinction (e.g. Golub), whereas others suggested a continuum from hot to cool stars, with no break at any spectral type (e.g. Praderie, Waldron).

Underhill: I would say that the physics is the same for hot and cool stars. The separation into distinctive groups is chiefly determined by observing considerations. For hot stars you want detectors sensitive chiefly shortward of 5000 Å; for cool stars you can detect the light most easily longward of 5000 Å. There is also a difference in time of year when most of the stars of a given type are accessible from any particular ground-based observatory.

Castor: I think that a major barrier to pursuing solar-physics ideas in the hot stars is our total lack of knowledge about the magnetic field morphology. I believe we should work very hard for direct observational information about the field and establish the morphology before carrying over solar/cool star theory.

Underhill: Detection of field morphology by direct observation is an almost hopeless task for hot stars. It is desirable to proceed theoretically on the basis of inferences that irregularly distributed magnetic fields are present. One surely can size the problem by exploring what may be observable from certain distributions of magnetic fields, both spatial and magnitude-of-field distributions. Doing that would be a valuable first step. Magnetic fields are such an indestructible and ubiquitous part of nature that I think we have no reason to neglect their possible actions just because we cannot make a direct detection at this time.

Praderie: Since we agree that we should seek for signs of quantified magnetic "activity" in hot stars, may I suggest that we follow the empirical steps opened by the cool-star people. I have been impressed in recent years by two pieces of work: (1) the direct determination of rotation periods of solar type stars by the Mt. Wilson collaboration, and (2) the simultaneous monitoring, following the rotation period, of emissions formed at different depths in the outer atmosphere (e.g. in II Peg), which effectively detected magnetically controlled active regions on unresolved stellar disks as the aspect changes through rotation. If we admit that magnetic field signatures are somehow related to the rotation rate (or to differential rotation), we should try to monitor such signatures of magnetic activity. If possible we should study indicators formed at various depths in the outflowing envelope, and detect the rotation period or its harmonics. This is a prospect that some people in France would like to see accomplished by a dedicated satellite which would study, at the same time, surface activity and oscillations for stars over the whole HR diagram.

Linsky: It is important to recognize that solar magnetic fields were discovered about 40 years before people began seriously to take magnetic fields into account in interpreting solar phenomena. We have, over the last few years, observed mass loss and hot coronal plasma in the early-type stars. I hope that the gestation period for incorporating these phenomena into the detailed models of early-type stellar atmospheres will be less than 40 years.

Friend: I think that what is needed in the area of magnetic fields in hot-star atmospheres is a dynamical calculation of closed magnetic loops as well as open field lines in a wind. What we need to find out is whether or not closed magnetic loops are dynamically possible in the presence of a strong radiation force.

Wentzel: We should carefully distinguish momentum from energy. The solar wind needs only a small addition of non-radiative momentum (MHD waves?) to the normal acceleration by pressure gradients. Much of the role of the magnetic fields may be through their energy: static fields provide structure.

The only measure of the solar magnetic field above the chromosphere and prominences is made from microwave emission, including its polarization. It is disconcerting that only one star has been cited with radio polarization.

Castor: Apart from the ambiguous IR/radio discrepancies, the only good indicator of velocity-law variations from one hot star to another is the  $H\alpha$  profile. Olson and Ebbets found substantial variation in the law even among O9 supergiants. This work needs repetition, but the price is that very high-accuracy profiles (well under 1 % error) are needed.

Underhill: The choice of which diagnostic to use in order to differentiate between two theories is difficult. One needs to find something which can be observed sufficiently accurately easily and which depends in a sensitive way on the important differences between the two theories. The selected criteria for identifying model atmospheres with stars are not always sensitive to the details of the model, particularly to those details which define the character of the outermost layers where nonradiative energy and momentum determine the physical state. Does the strength of the  $H\alpha$  emission and the shape of the profile depend chiefly on the details of the velocity law, or are the observable features dependent also on the distribution of heating and cooling in the mantle?

R.L. White: Diagnosing velocity laws using  $H\alpha$  profiles may not be reliable because inhomogeneities in the wind can fool you into thinking the wind velocity is lower than the true velocity.

Abbott: Regarding the previous comments, what I have seen at this conference is many people coming from the study of the Sun and cool stars, who have the conviction that magnetic fields control all observed behaviour in hot stars. This conviction does not seem subject to debate or scientific testing. I assume that the origin of this conviction is that these same researchers were badly "burned" by neglecting magnetic fields in earlier cool-star work. However, the reason they failed to recognize the crucial role of magnetic fields is that they could not observe the mass loss in cool stars until very recently.

In hot stars the situation is very different. Not only is it exceedingly easy to observe the mass loss, but in some classes of stars - such as the Wolf-Rayets - the mass loss is all you can see; the star is obscured by the wind. Now, I am not saying that hot stars are as simple as my models, and I am not denying that hot stars have magnetic fields. I am just asking, if magnetic fields control the structure of the surface and winds of hot stars, why do we not see this in the observational data?

Mullan: Would you say that your own observations of non-thermal radio emission in hot stars indicate the presence of magnetic fields?

Abbott: Yes.

Mullan: If so, then magnetic fields do exist in hot stars, and they may have important dynamical effects. Is there a momentum problem in hot stars in the sense that  $Mv_{\infty} > L/c$  by an amount which is too large to be explained by multiple scattering alone?

Underhill: I have suggested that we do see the effects of magnetic fields in the discrepancies which we find between predicted spectra and observed spectra. In the case of WR stars, if you attribute all of the radio flux to bremsstrahlung, then the deduced values of  $\dot{M}$  and the measured  $v_{\infty}$  are such that the wind requires 50 to 100 times the amount of momentum available in the radiation field, this quantity having been estimated in a generous, but consistent way. Factors of the order of 50 to 100 cannot be explained by multiple scattering.

Cassinelli: Several of us attended a meeting in this room in 1972 on stellar chromospheres. I recall that at the time J.C. Pecker and R.N. Thomas were saying that mass loss definitely means there is a presence of solar-type activity in hot stars. I did not understand this argument, as Castor and I were developing a purely radiative model. Since then I have begun to realize that the radiative picture is too perfect. It is, in fact, useful and important to view hot-star phenomena with a solar picture in mind.



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