CORONAE OF NONDEGENERATE SINGLE AND BINARY STARS: A SURVEY OF OUR PRESENT UNDERSTANDING AND PROBLEMS RIPE FOR SOLUTION

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ABSTRACT

Einstein has discovered X-ray emission from stars located in nearly every portion of the HR diagram, and, as a consequence, has completely changed our understanding of stellar coronae. Despite this great accomplishment or perhaps because of it, we now recognize that there are many important unanswered questions that require the capabilities of the next generation of X-ray instrumentation. In this survey I review what Einstein has told us about the coronae of stars in different portions of the HR diagram, and how the characteristics of such coronae compare with what we now know about the solar corona. For each type of star, I then list some important unanswered questions and the generic type of X-ray instrument required to answer these questions. This survey clearly points out the critical need for a sensitive X-ray instrument with both moderate spectral resolution ($E/\Delta E$ = 100-300) and imaging ($E/\Delta E \sim 3$) capability that can monitor selected targets for long periods of time. There is also a need for high spectral resolution ($E/\Delta E = 10^3$-10^4), provided sensitivities can be improved greatly over Einstein, and near simultaneous ultraviolet spectroscopy.

I. SOME INTRODUCTORY COMMENTS

While looking through the literature in preparation for this talk, I was struck by how little we knew about stellar coronae as late as 1979. Prior to the launch of Einstein, the literature on this topic consisted of theoretical papers, most of which are now recognized to be based on false premises, X-ray flux upper limits that were not very interesting, and a few tantalizing observations by rockets and the ANS, SAS-3, and HEAO-1 satellites of nearby stars that did not adequately sample the HR diagram. Reviews of this topic prior to Einstein (e.g. Linsky 1977; Vaiana and Rosner 1978; Ulmschneider 1979; Mewe 1979) have thus become very dated with the rapid onslaught of Einstein observations.

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Prior to *Einstein* the few detected X-ray sources among normal stars consisted of RS CVn-type binary systems (e.g. Walter *et al.* 1980), several nearby late-type dwarf stars like α Cen (G2V + K1V), η Boo (G0 IV), and ξ Boo A (G8 V), several M dwarf stars detected during large flares, and the puzzling detections of Vega (A0 V) and Sirius (A1V + WD). Clearly, we needed an instrument that could observe sources several orders of magnitude fainter than the HEAO-1 sky survey. To achieve this gain in sensitivity in soft X-rays, such an instrument would require a pointed telescope with imaging optics and two-dimensional detectors. The launch of *Einstein* (cf. Giaconni *et al.* 1979) in 1978 filled this need.

Among its many accomplishments, *Einstein* has likely had its greatest impact on stellar astronomy because it replaced a picture of stellar coronae based on a handful of detections, which were biased by the high sensitivity limit of previous surveys, with a picture based on detections of X-rays from nearly every type of star (cf. Vaiana *et al.* 1981). In particular, *Einstein* detected X-rays from stars of spectral classes O, B, and A, contrary to most previous predictions, and from stars of all ages and stages of evolution. The only region of the HR diagram from which no stellar X-rays have yet been detected is the upper right hand corner including the K-M supergiants and giants (Ayres *et al.* 1981). Another salient feature of the Vaiana *et al.* (1981) survey is that there is a factor of three hundred spread in the X-ray luminosities of late-type stars of the same spectral type and luminosity class, implying that effective temperature and gravity are not the main parameters determining the properties of stellar coronae. As we shall see, magnetic fields and stellar rotation play important roles.

While *Einstein* has told us a great deal about the types of stars that have hot coronae and the range in L_x for each spectral-luminosity class, it has told us very little about the important physical properties of these coronae. For example, the IPC data have so far permitted only a few crude measurements of coronal temperatures, for example, the M5.5e V flare star Proxima Centauri (Haisch *et al.* 1980), and temperature estimates using SSS data are available only for π^1 UMa (G0 V) (Swank 1981) and a few RS CVn-type systems and Algol (Swank *et al.* 1981). To my knowledge the OGS data have been used to estimate a coronal temperature for Capella (G6III + F9III) (Mewe *et al.* 1980), but no other nondegenerate stars or systems. *Einstein* lacked the sensitivity at high spectral resolution to measure coronal densities. flow velocities, and total energy output for any nondegenerate stars. Thus we can only speculate concerning the geometry, heating rates, wind acceleration mechanisms, and the mechanisms responsible for coronal variability and dynamic phenomena such as flares.

II. CRITICAL X-RAY MEASUREMENTS NEEDED TO UNDERSTAND STELLAR CORONAE

Since the purpose of this Workshop is to plan for future X-ray astronomy missions, I would like to outline what types of measurements are needed to answer the important problems of stellar coronae that *Einstein* could not answer. In Table 1 I list the specific measurements desired and the minimum spectral resolution (E/ΔE) needed to make these measurements. I do not specify the signal-to-noise needed, but clearly spectra with insufficient

Table I

Critical X-Ray Measurements Needed to Understand Stellar Coronae

	Generic Type of X-Ray Instrument[a]					
	Imaging Instrument	Energy Distribution Photometry	Low Resolution Spectra	Moderate Resolution Spectra	High Resolution Spectra	Ultraviolet Spectra
$\Delta E/E$	---	3	10-30	100-300	10^3-10^4	$>10^4$
Measurements						
Target Identification	✓					
Timing + Monitoring	✓					
Temperature (T)		Begin	✓			
Range of T			Begin	✓		
Emission Measure (EM)		Begin	✓			
EM(T)			Begin	✓		
Abundances			Begin	✓	✓	✓
Electron Densities (n_e)				✓	✓	✓
Flow Velocities (v)					✓	✓
Questions						
Geometry	Begin			✓	✓	
Energy Balance		Radiative loss rate			Wind loss rate	Conduction loss rate
Heating Mechanism		Begin			✓	✓
Wind Acceleration Mechanism					✓	✓

[a] The entry marked "Begin" indicates the instrument that can begin to measure the quantity of interest. A check mark indicates the instrument with lowest spectral resolution that can make the required measurement.

signal-to-noise cannot be used to derive information requiring the full spectral resolution. The instruments listed are generic, but by energy distribution photometry I have in mind an instrument with the spectral resolution of an IPC, and by low resolution spectroscopy I have in mind an instrument with the resolution of the SSS at the high energy portion of its bandpass. Moderate resolution spectrometers could have transmission or reflection gratings, either mounted before or after the objective. In general, one would use an instrument with the lowest possible spectral resolution capable of making the necessary measurement as the throughput generally decreases with increasing spectral resolution.

The types of measurements each instrument is capable of performing are the following:

(1) Broadband *imaging* instruments are best suited for identification of targets, timing experiments, and monitoring of coronae for variability due to rotation of active regions on and off the visible disk, intrinsic changes in the active regions, and flares.

(2) *Energy distribution photometry* can give crude estimates of coronal temperatures and emission measures from hardness ratios or the distribution of flux measured in each energy bin, provided the detector is well calibrated, theoretical estimates of the continuum and line flux emitted by an optically thin plasma in steady-state equilibrium are accurate, and these assumptions are realistic.

(3) With somewhat higher spectral resolution ($E/\Delta E = 10-30$), a capability I refer to as *low resolution spectroscopy*, one can more reliably estimate coronal temperatures and emission measures, provided the plasma is isothermal, or begin to determine a two-temperature fit to the temperature distribution as Swank *et al.* (1981) have done for the RS CVn binary systems using the *Einstein* SSS. Holt *et al.* (1979) have also shown that it is possible to estimate abundances of some elements like Mg, Si, S, and Fe using such data.

(4) *Moderate resolution spectroscopy* ($E/\Delta E = 100-300$) has the capability of measuring fluxes of individual spectral lines or close blends formed over a wide range of temperatures. The power of such data has long been recognized by solar astronomers, because selected pairs of lines are often accurate temperature and electron density diagnostics. Jordan and Brown (1981) and Dere and Mason (1981) have recently reviewed the literature concerning such diagnostics.

(5) Finally, *high resolution spectroscopy* ($E/\Delta E = 10^3-10^4$) permits the measurement of line widths, shapes, and Doppler shifts, as well as the separation of individual lines in close blends. Such data permit the measurement of flow velocities, for example winds, in stellar coronae in the way that ultraviolet spectra from *Copernicus* and *IUE* have permitted measurements of outflow velocities in cooler plasmas.

These measurements are the necessary prerequisites for answering specific questions concerning stellar coronae such as:

(1) What is the *geometry* of the emitting plasma? Imaging experiments with high angular precision can begin to answer this question by identifying the X-ray source with a specific star, and by monitoring the X-ray flux variability for periodic changes due to stellar rotation and to intrinsic source changes. Such data contain crude information on the inhomogeneity of the emitting structures in a corona and their dimensions. Estimates of the volume of the emitting structures require measurements of the emission measure and the electron density, and thus require moderate or high resolution spectroscopy.

(2) What is the *energy balance* in a stellar corona? The radiative component of the total coronal losses can be determined directly from broadband instruments that measure the total soft X-ray flux, provided one knows the stellar distance. However, when the coronal temperature is less than about 2×10^6 K, it is necessary to estimate the extreme ultraviolet emission from the emission measure and temperature. For many stars the coronal energy losses may not be primarily in the form of X-radiation. Measurement of wind expansion losses requires a determination of the mass loss rate and coronal temperature. Since the mass loss rate is

$$\dot{M} = 4\pi r^2 \rho v$$

one requires high resolution spectroscopy to measure the expansion velocity (v) and mass density (ρ), but the radial position (r) corresponding to these quantities must be estimated theoretically. I am skeptical that X-ray instruments with resolutions of 10^3-10^4 and sufficient sensitivity to study many stars will be feasible soon, so that for the foreseeable future estimates of coronal wind expansion losses may have to be made on the basis of ultraviolet P Cygni-type profiles and microwave fluxes (cf. reviews by Cassinelli 1979, and Conti 1981). Such data may be adequate for O stars, but X-ray spectra are needed to measure the wind properties of late-type stars with hot coronae. The third important coronal loss mechanism is often thermal conduction to the transition region, which appears as ultraviolet emission line flux. Thus ultraviolet spectra are needed in addition to X-ray data to assess the total coronal energy budget of many stars.

(3) What are the important coronal *heating mechanisms* in different types of stars? This difficult question has not yet been answered even for the Sun (cf. reviews by Kuperus, Ionson, and Spicer 1981; Hollweg 1981; and Ulmschneider 1981). Necessary prerequisites for answering this question are estimates of the total input flux and its dissipation length together with information on whether the emitting volume is spherically symmetric or primarily in closed magnetic loops. As described below, coronal heating in the Sun is enhanced in closed magnetic loops; consequently, estimates of coronal field strengths and filling factors either from extrapolations of photospheric fields or from microwave flux measurements would be useful. These types of data, as necessary as they are, are not sufficient. To clearly identify the dominant heating mechanism in specific types of stars, we need reliable theoretical calculations that point out the unique signatures of the different possible mechanisms in X-ray and other data.

(4) What are the important wind acceleration mechanisms in different types of stars with hot coronae? This is also a difficult question because different mechanisms have been proposed (radiation pressure, momentum deposition by acoustic waves and by magnetohydrodynamic waves), and the unique signatures of these different mechanisms have not yet been worked out. Cassinelli (1979), Hearn (1981), Castor (1981), and Linsky (1981) have recently reviewed these mechanisms and the types of stars for which each may be important. Clearly it is necessary to determine empirically mass loss rates, terminal velocities, and temperatures for different types of stars, and especially how these quantities depend on stellar luminosity, gravity, effective temperature, and age. As previously noted, this is difficult because one generally needs high resolution X-ray spectra; however, for the O stars ultraviolet spectra and microwave fluxes may provide much of the necessary data to discriminate among different mechanisms.

III. WHAT WE KNOW ABOUT THE SOLAR CORONA THAT WILL LIKELY BE OF RELEVANCE TO OTHER STARS

Before proceeding to a discussion of the stellar data and the unanswered questions they raise, it is important to summarize what has been learned recently about the one stellar corona that can be studied with the necessary spatial resolution. I do not wish to imply that all stellar coronae are similar to the Sun or even that the solar corona exhibits all the physical processes that occur in stellar coronae. However, the Sun probably does provide useful prototypes of phenomena and mechanisms that we should search for on stars, but there are some types of stars like the O stars that have coronae that may be qualitatively different from the solar example. Recent reviews of phenomena and structures seen in X-ray observations of the Sun include Withbroe and Noyes (1977), Vaiana and Rosner (1978), and Webb (1981).

a) Geometry of the Solar Corona

(1) Perhaps the most basic statement that can be made about the solar corona as imaged in soft X-rays is that it is not in any way homogeneous or spherically symmetric. On the contrary, it is highly structured. Thus any theoretical model of a stellar corona that assumes spherical symmetry lacks essential physics.

(2) The basic structure in the solar corona is the closed magnetic flux tube. There are three lines of evidence that support this statement. First, soft X-ray images of the corona clearly show structures that appear to be individual loops or arcades of loops. Second, potential (i.e. force-free) extrapolations of the observed photospheric magnetic fields into the corona are nearly coincident with the observed X-ray loops (cf. Poletto et al. 1975), but the match is not precise, implying that there are electric currents in the corona. Thus the soft X-ray emission outlines the three-dimensional magnetic field structure of the corona. Third, the solar corona is a low β plasma (i.e. the thermal energy is much less than the magnetic energy), so that the plasma should be confined by closed loop structures.

(3) The solar corona has three types of regions. Active regions consist of bright loops that generally have at least one footpoint in a spot penumbra or umbra. These loops have strong magnetic fields and connect areas of opposite magnetic polarity. Quiet regions also contain closed loop structures, but the fields are weak and there are no sunspots. Finally, coronal holes are regions of very weak X-ray emission and have field lines that are open to space.

(4) In active and quiet regions essentially all of the observed X-ray emission is from the closed loops. Thus the closed loops are the solar corona, and meaningful coronal models must include a loop geometry and incorporate magnetic forces.

(5) Empirical models of coronal structures clearly show that differences in physical conditions (temperatures, densities, mass and energy flux) from point to point across the Sun appear to be intimately related to the configuration and strength of the magnetic fields, in particular whether the fields are open or closed.

(6) The structuring of the solar atmosphere into loops dominates the whole atmosphere from the chromosphere, through the transition region, and out some distance into the corona.

(7) Coronal holes are the origins of high speed wind streams (with velocities up to 800 km s^{-1}) and perhaps most of the mass loss from the Sun. The latter point is difficult to verify as coronal holes typically lie at high latitudes and wind measurements are made mostly in the ecliptic. Zirker (1981) has recently reviewed the properties of coronal holes.

(8) There is strong evidence that magnetic fields control the energy balance in loops by channeling the flow of mass and energy as well as presumably playing a major role in the heating rate (see Holweg 1981 for a recent review of this topic). Withbroe and Noyes (1977) have estimated the coronal energy budget for active regions (representative of loops with strong fields), quiet regions (representative of loops with weak fields), and coronal holes (open field regions). It is interesting that although the total coronal loss rates (presumably equal to the heating rates) are 30 times larger in active than in quiet regions, both regions are cooled primarily by conduction down to the transition region and X-radiation. For both regions the wind losses are very small, presumably because closed field lines in loops prevent the escape of plasma to space. The total loss rates for coronal holes and quiet regions are similar, but holes are cooled primarily by the solar wind flux instead of conduction down to the transition region and X-radiation. Also holes have lower temperatures, pressures, and temperature gradients than quiet and active regions.

(9) Thus the solar corona in reality consists of many loops with different physical properties that coexist due to the thermal isolation provided by closed magnetic field lines.

b) Properties of Solar Coronal Loops

(1) Individual X-ray images of the solar corona deceptively suggest that the loops are static; but on the contrary, the solar corona is always changing. The brightness of individual loops changes with time due to the filling and draining of flux tubes with changes in the heating rate and restructuring of magnetic field lines on a time scale of hours. Many loop structures, called empherical regions, appear and fade within a day. The so-called bright points are compact, high density loop structures that represent newly emerging magnetic flux. These typically survive less than a day, but even the large active region loops live for only a few days. Thus theoretical loop models that assume steady-state conditions and hydrostatic equilibrium are gross oversimplifications.

(2) When first seen in X-rays, loops are generally small, hot, dense, and bright. As they evolve, the loops generally expand, decrease in plasma temperature and density, and thus in X-ray brightness. Golub et al. (1980) presented evidence that the energy density of loops ($U_T = nkT$) is inversely proportional to the loop length (L) and age (t). They also argued that $U_T \sim \phi_T^{1.7}$, where ϕ_T is the magnetic flux, and that the gas pressure $P \sim B^{1.6}$, where B is the average longitudinal field.

(3) Observed loop lengths, $L = 10^8$-10^{10} cm, are much smaller than the solar radius, ($R_\odot = 7 \times 10^{10}$ cm) and the coronal pressure scale height ($\approx 0.23\ R_\odot$ for $T = 2.5 \times 10^6$ K). Although loop sizes form a continuous distribution, there are many more small than large loops. Loop temperatures generally lie in the small range, $T = 2$-3×10^6 K, and densities lie in the much larger range, $n_e = 10^8$-10^{10} cm^{-3}. Thus loop pressures lie in the range, $P = 0.03 - 3$ dynes cm^{-2}. There is considerable evidence that individual flux tubes are isothermal, both in the longitudinal and radial directions, and that they are isobaric, consistent with their heights being smaller than a pressure scale height. There is no obvious reason why loops cannot be larger than a stellar radius or coronal pressure scale height in stars with different gravities and magnetic field configurations, but the solar data suggest that at least dwarf stars with bright X-ray emission probably have small, dense loop structures.

(4) There are several empirical scaling laws for the properties of solar coronal loops (cf. Withbroe 1981). One widely quoted law is $T_{max} = 1.4 \times 10^3\ (PL)^{1/3}$, where T_{max} is the maximum loop temperature, proposed by Rosner, Tucker and Vaiana (1978). Since solar loops have only a small range in temperature, this law implies that $P \sim L^{-1}$. Webb (1981) has pointed out that the empirical scatter about this scaling law is very large, and the assumptions of hydrostatic equilibrium, absence of flows along the loop or conductive heat flow at the bottom, and constant loop cross section made by Rosner et al. may not be valid. Recently, Serio et al. (1981) have generalized the Rosner et al. scaling law to include loops larger than a pressure scale height, and Priest (1981) has reviewed the theory of loop flows and instabilities.

(5) At present we should view recent loop models as moderately successful as they can interrelate plasma parameters within a loop in a manner consistent with observations. Such models should also be thermally stable provided that the maximum temperature occurs at the top of the loop. However, the major problem with these models is that the loop properties, in particular L_x, appear to depend only on the heating rate and not on the heating mechanism or even where in the loop the heating occurs. Thus there are no unique signatures of the heating process. Perhaps stellar observations can help. For a recent overview of heating mechanisms see Hollweg (1981) and Kuperus et al. (1981).

(6) Finally, we should ask why the range in solar loop temperatures is so small. I believe that this small range indicates that loops can easily respond to changes in the heating rate by evaporation or condensation of material at transition region temperatures ($\sim 10^5$ K) at the loop footpoints. For example, increased heating anywhere in the loop leads to enhanced conductive heating at the footpoints that evaporates transition region gas into coronal (i.e. $T > 10^6$ K) gas. This process is stable because radiative losses from the loop ($\sim n_e^2$) can then balance the increased heating with little change in temperature. Conversely, decreased heating leads to condensation of coronal gas at the footpoints, decreased radiative losses, and energy balance with little change in loop temperature. Thus stellar coronal temperatures much in excess of 3×10^6 K may indicate a very different energy balance or geometry in such coronae.

IV. DWARF STARS OF SPECTRAL TYPES F, G, K AND M

Given as background what we now know about the solar corona, I would like to survey the HR diagram and ask two questions. First, what have we learned in general about the coronae of each group of stars from Einstein and other experiments? Second, what are the important unanswered questions that could be answered by the next generation of X-ray experiments? Since I would like to compare and contrast the solar and stellar data, I will begin with the stars that are most solar-like and gradually move on to stars that have very different coronae or perhaps outer atmospheres that should not even be called coronae.

a) What We Have Learned from Einstein

(1) Einstein has detected X-rays from almost every type of star with the exception of the cool supergiants, as will be discussed below. In the first comprehensive survey of Einstein stellar observations, Vaiana et al. (1981) detected essentially all nearby F-M dwarf stars that were observed for sufficiently long times. For many of these stars the IPC count rates exceeded 0.1 counts s^{-1}, corresponding to 2×10^{-12} ergs cm^{-2} s^{-1} for the 0.25-4 keV band, and typical limiting sensitivies were 10^{-13} ergs cm^{-2} s^{-1} in 2000 second exposures. The HEAO-1 A2 experiment all sky survey was unable to detect many F-M dwarfs because its sensitivity was only $\sim 6 \times 10^{-12}$ ergs cm^{-2} s^{-1}.

(2) It is clear that the soft X-ray emission is from analogues of the solar corona rather than accretion as in the classical X-ray binary systems because both single and binary stars are soft X-ray sources, and as will be

described later, the X-ray emission from the tidally synchronous binary systems (like the RS CVn systems) is similar to that of single stars with the same rotational velocities.

(3) Perhaps the most far reaching result is that the standard stellar parameters of mass, effective temperature, and gravity, which determine where a star is located in the HR diagram, are not the most important parameters determining the soft X-ray luminosities of F-M dwarf stars and most other types of stars. There are two main reasons for this conclusion. First, the Vaiana *et al.* (1981) survey shows that for stars of the same effective temperature and luminosity class there is a factor of 300 spread in L_X, which could be even larger because of the sensitivity threshold of *Einstein*. Second, the mean value of L_X for the F, G, K, and M dwarfs is roughly $10^{28.5}$ ergs s^{-1}, independent of spectral type even though L_{bol} decreases rapidly toward the cooler stars. With appropriate hindsight we should have expected this result because the solar X-ray brightness varies greatly from point to point across the solar surface, and it is apparently controlled by the local magnetic field strength and geometry.

(4) The range in L_X observed for G-type dwarf stars is entirely consistent with the range in L_X seen in the Sun. For example, the mean value of L_X for the quiet Sun is roughly $10^{26.8}$ ergs s^{-1}, which lies close to the bottom of the distribution for early G dwarfs, whereas the value of L_X for the whole solar surface if covered with active regions ($L_X = 10^{29.3}$ ergs s^{-1}) would lie near the top of this distribution. This latter coincidence could be interpreted either that the brightest solar-type stars are covered entirely by coronal structures similar in brightness to solar plages (active regions) or that they are partially covered with superplages (regions with X-ray brightness much larger than is seen in solar active regions). The Hyades data strongly support the existence of superplages.

(5) There is convincing evidence that stellar rotation plays a critical role in determining the relative X-ray luminosity of stars with similar spectral type and luminosity class, although the functional form of this relation has not yet been decided conclusively. The importance of rotation can be seen at once by comparing three early G dwarf stars — π^1 UMa (G0 V), α Cen A (G2 V), and the quiet Sun (G2 V). π^1 UMa is the most luminous G dwarf observed by Vaiana *et al.* ($L_X = 10^{29.1}$), and it is a rapid rotator for its spectral type ($v \sin i = 9$ km s^{-1}). By comparison α Cen A and the quiet Sun have low X-ray luminosities ($L_X = 10^{27.1}$ and $10^{26.8}$ ergs s^{-1}, respectively) and small rotational velocities ($v \sin i \approx 2$ km s^{-1}).

However, there is disagreement as to the dependence of L_X on rotational parameters for F-M dwarfs. Using HEAO-1 observations of a few single stars and RS CVn systems, Ayres and Linsky (1980) suggested that L_X/L_{bol} increases rapidly with $v \sin i$. Pallavicini *et al.* (1981) used the existing *Einstein* observations of single F7-M5 stars to show that $L_X \sim (v \sin i)^{1.9\pm0.5}$, independent of L_{bol} and luminosity class. This result is consistent with the X-ray surface flux being proportional to Ω^2, where Ω is the angular rotational velocity. On the other hand, Walter and Bowyer (1981) and Walter (1981) found that $L_X/L_{bol} \sim \Omega$ fairly well represents the *Einstein* and HEAO-1 data for 47 RS CVn systems and 13 rapidly rotating F8-G5 dwarfs stars. Subsequently, Walter (1982) proposed that no single power law can fit the *Einstein* observations of single F8-G2 dwarfs including the Sun and Hyades stars, but instead two power laws are needed of the form $L_x/L_{bol} \sim \Omega^{\alpha}$ with a break near a rotational period of 12 days. It is interesting that Vaughan and Preston (1980) and Vaughan (1980) find evidence that the character of stellar dynamos changes when dwarf stars slow down to a rotational period of 12 days, which occurs at an age of about 1×10^9 yr.

(6) The age of late-type stars on the main sequence is also an important parameter, perhaps in a more fundamental sense than rotation. In the 1960s there were a number of important studies of the rotation of F and G dwarf stars by Wilson, Kraft, Skumanich, and others, who concluded that stellar rotational velocities decrease with age on the main sequence, presumably as a consequence of angular momentum loss in stellar winds. On the basis of these data, Skumanich (1972) proposed that the stellar equatorial velocity, $v \sim t^{1/2}$, where t is the age on the main sequence. Recently, rotational velocity measurements have become more precise as a result of increased throughput for high resolution spectroscopy, Fourier techniques for analyzing line profiles (cf. Gray 1976), and programs to monitor the rotational modulation of stellar active regions by observing the Ca II flux (e.g. Vaughan *et al.* 1981). Duncan (1981) and Soderblom (1981) showed that these new data confirm the Skumanich (1972) rotation-age correlation.

As yet there is no thorough survey of the relation of stellar X-ray luminosity or surface flux with age. However, the Stern *et al.* (1981) study of the Hyades cluster ($t = 10^{8.6}$) stars with *Einstein* clearly indicates a definite correlation of bright X-ray emission with youth. Despite their sensitivity threshold, which corresponds to a factor of 10 higher than the quiet Sun value of L_x, they detected 80% of the F and G dwarfs in the cluster. Their brightest source is 71 Tau, an F0 V star with v sin i = 200 km s^{-1} and $L_x \gtrsim 10^{30}$ ergs s^{-1}, and their brightest G star is HD 27836 (G1 V) for which $L_x = 10^{30}$ ergs s^{-1}. Since this star is about five times as bright in X-rays as the Sun would be if covered entirely by plages, it must contain flux tubes which are beyond the range of brightness, and thus presumably also of density, typically seen in the solar corona. Stern *et al.* (1981) have proposed, on the basis of scaling laws, that this star contains superactive regions covering about 10% of the stellar surface.

(7) By analogy with the solar corona, the F-M dwarf stars, especially the young stars with bright X-ray emission, should have strong closed magnetic field structures in their coronae. This argument is no longer speculation, but has now been confirmed by two separate lines of evidence. First, Robinson, Worden, and Harvey (1980) have measured photospheric magnetic fields in two young dwarfs, ξ Boo A (G8 V) and 70 Oph A (K0 V) by measuring line splitting in unpolarized light. For ξ Boo A, they found the field to be 2,600 ± 400 Gauss covering 30% of the surface. Marcy (1980) has detected magnetic fields in additional stars and is now studying variability and rotational modulation of stellar active regions with large magnetic fields. It is interesting that the major difference noted so far between the photospheric magnetic fields of these young stars compared to the Sun is that the strong fields cover a much larger fraction of the stellar surface.

The second type of direct evidence is observations of microwave emission from stellar coronae. Gary and Linsky (1981) detected steady 6 cm emission from χ^1 Ori (G0 V) and UV Cet (dM5.5e) with the VLA, which they interpreted as gyroresonant emission from electrons spiralling along coronal magnetic field lines. This emission is consistent with coronal fields of roughly 300 Gauss, slightly larger than the field strengths in solar coronal loops. Both stars are bright X-ray sources for their spectral types.

(8) There are as yet very few measurements of coronal temperatures for late-type dwarfs. In principle, the *Einstein* IPC pulse height spectra can provide crude temperature estimates, but meaningful temperatures await the reprocessing of these data. The *Einstein* SSS instrument has proved to be useful in estimating coronal temperatures for RS CVn systems, but so far the only coronal temperature for late-type dwarf stars obtained with the SSS is for the young G0 V star π^1 UMa, for which Swank (1981) estimated $T = 3\text{–}5 \times 10^6$ K. Haisch *et al.* (1980) have also estimated $T = 4 \times 10^6$ K for Proxima Centauri (dM5e) at quiescent times using IPC pulse height spectra.

b) Some Important Unanswered Questions

1. What is the range of coronal temperatures that occurs in magnetic loop structures? In particular, does the temperature increase with stellar X-ray luminosity or surface flux, and does it depend at all on spectral type among the cool dwarfs? This question can be answered with energy distribution photometry, perhaps with reprocessed *Einstein* IPC data, and low resolution spectroscopy (see Table 1).

2. What fraction of the coronal volume is filled with bright X-ray emitting loops for stars of different ages, spectral types, and L_x? Since the volume of the emitting region can be derived from the emission measure and electron density, this question requires moderate resolution spectra.

3. What are the evolutionary time scales of coronal loops and active regions, and what are the properties of stellar magnetic cycles and dynamos? Monitoring of stars with imaging experiments is important for studying these time scales, but such observations should be accompanied by simultaneous measurement of the stellar transition regions with ultraviolet spectroscopy, photospheric magnetic fields with optical spectroscopy, and microwave observations with the VLA.

4. What are the densities of coronal loops in different types of stars? Of specific interest is the question of whether loops in stars with large L_x are dense and small, or tenuous and large, or both. Moderate or high resolution spectroscopy is needed to measure density-sensitive line ratios in order to answer this question.

5. What mechanism or mechanisms heat coronae in late-type dwarf stars? The observational data needed to answer this difficult question cannot be predicted easily due to our lack of knowledge as to how even the solar corona is heated. My guess is that we need to know more about how the energy balance in dwarf star coronae changes with effective temperature, age, and L_x, and whether the geometry of these coronae are solar-like as we presently

believe. An understanding of the energy balance will require energy distribution photometry, high resolution spectroscopy, and ultraviolet spectroscopy (see Table 1). Also, the study of eclipsing systems with imaging experiments will provide information on where the coronal cooling occurs for comparison with theoretical models.

6. Do active dwarf stars ($L_X >> L_X(\odot)$) have hot winds and low mass loss rates like the Sun? This question might be unanswerable with foreseeable instrumental developments, but it is important to try to answer this question by searching for Doppler-shifted X-ray lines with a high throughput high resolution spectroscopic experiment.

7. What are the fundamental differences between the coronae of young and old dwarf stars. Are the differences primarily in the fraction of the coronal volume filled with loops, the loop lengths, densities, temperatures, or total coronal heating rates? Since the measurement of coronal densities is critical to answering this question, we need moderate or high resolution spectra.

8. What are the hottest dwarf stars with solar-like corona? A high throughput imaging experiment should be able to answer this question.

V. PRE-MAIN SEQUENCE STARS

Pre-main sequence (preMS) stars, including the T Tauri stars, the young stars in clusters such as Orion, and the recently identified post-T Tauri stars, probably have coronae that are qualitatively similar to the young F-M dwarfs that recently became main sequence (MS) stars. However, as we shall see, the X-ray emission from the preMS stars can be absorbed by overlying circumstellar gas.

a) What We Have Learned from Einstein

1. When detected as X-ray sources, the T Tauri and other preMS stars are the most luminous among the late-type stars that are not known to be close binaries. Since these stars are distant, the detection thresholds are large; for example, $L_X \approx 10^{30}$ ergs s^{-1} for the Taurus-Aurigae cloud and $L_X = 2 \times 10^{31}$ ergs s^{-1} for the Orion cloud. Nevertheless, 10 out of the 14 known T Tauri stars in the Taurus-Aurigae cloud brighter than $m_V = 13$ have now been detected as X-ray sources by Walter and Kuhi (1981), and the fainter T Tauri stars were likely not detected due to the sensitivity limit of Einstein. Feigelson and de Campli (1981) detected DG Tauri at $L_X = 8 \times 10^{30}$ ergs s^{-1}, and Gahm (1980) detected Th 12 at $L_X = 6 \times 10^{30}$ ergs s^{-1} in the Taurus-Aurigae cloud. These stars are 10^4 times more luminous than the quiet Sun. The most luminous preMS star detected so far is GW Ori ($L_X = 5 \times 10^{31}$ ergs s^{-1}) observed by Feigelson and de Campli (1981).

2. Given that the detected preMS stars are so luminous in X-rays, an important question is why many of these stars in the Taurus-Auriga and Orion clouds, primarily those with strong Hα emission and blue excess emission, are not detected as X-ray sources. Gahm (1980) argued that interstellar absorption is not the reason for the many nondetections on the basis that

RW Aurigae is a T Tauri star with extremely bright optical and ultraviolet emission lines, yet it is not a detected X-ray source despite its lying outside the dark obscuring regions of the Taurus-Aurigae cloud, and the small interstellar gas column density in its line of sight. Instead he argued that the preMS stars have hot coronae that are surrounded by extensive cool circumstellar gas envelopes that can totally absorb the X-ray emission in some cases. For example, he estimated optical depths for the RW Aurigae envelope of $\tau(0.6 \text{ keV}) \approx 72$ and $\tau(2 \text{ keV}) \approx 2$. Thus the soft X-ray emission would be totally absorbed, but this star might be a hard X-ray source. Walter and Kuhi (1981) supported Gahm's (1980) model by finding an inverse correlation among the T Tauri stars of Hα equivalent widths and X-ray fluxes. They concluded that the T Tauri stars have small solar-like coronae surrounded by extensive cool envelopes that produce the Hα emission and X-ray absorption.

3. Feigelson and de Campli (1981) observed rapid variability in the X-ray flux of the T Tauri star DG Tau. They detected no flux during the first 35 minutes of observation and then a rapid increase in flux on a time scale of 4 minutes. This rapid flare-like variability also suggests emission from a small region of high density close to the star, and like the brightest X-ray features on the Sun (the so-called bright points) could be emission from small dense loops of newly emerging magnetic flux just above the photosphere.

4. In T Tauri stars for which X-ray emission is detected, $L_X/L_{bol} \approx 10^{-4}$, which is similar to the ratio for the youngest F and G main sequence stars. By comparison $L_{H\alpha}/L_{bol} \approx 10^{-3}$, $L_{Mg\ II}/L_{bol} \approx 2 \times 10^{-3}$, $L_{Ca\ II}/L_{bol} \approx 5 \times 10^{-4}$, and $L_{Wind}/L_{bol} \approx 5 \times 10^{-3}$ for the same stars. Thus the emission from the corona is much less than from the chromosphere and/or envelope, and the radiative losses are comparable to the wind losses in T Tauri stars.

5. The coronal temperatures for T Tauri stars are poorly known, but Feigelson and de Campli (1981) estimated $T \gtrsim 5 \times 10^6$ K for DG Tau during its flare, and Walter and Kuhi (1981) estimated $T \gtrsim 14 \times 10^6$ K for AA Tau on the basis of IPC pulse height spectra. Estimated T Tauri coronal temperatures are likely affected by circumstellar gas absorption.

6. Recently Feigelson and Kriss (1981) and Walter and Kuhi (1981) discovered five X-ray sources that lie 1-3 magnitudes above the main sequence yet have weak Hα emission, no ultraviolet excess, and show no evidence for optical variability or winds. They therefore believe these stars to be intermediate in age between the T Tauris and main sequence stars. These stars are luminous ($L_X \approx 10^{30}$ ergs s^{-1}), and presumably have coronae similar to but more active than the stars that have recently arrived on the main sequence.

7. Three mechanisms have been proposed to explain high temperature emission from preMS stars. Ulrich (1976,1978) and Mundt (1980) studied accretion shocks, but their models typically predict $T < 3 \times 10^6$ K, which appears to be smaller than observed. Heating by shocks at the wind-interstellar medium interface was proposed by Kuhi (1964) and Ku and Chanan (1979), but the observed anticorrelation of Hα equivalent width and X-ray emission are hard to explain by this model. At present, the most plausible model appears to be that of a small corona surrounded by an extensive cool

circumstellar gas envelope. If this model is valid, as is suggested by the data, then the coronae of preMS stars are probably extreme examples of the solar corona with emission from small dense magnetic loop structures.

b) Some Important Unanswered Questions

1. What are the physical properties of the X-ray emitting regions in preMS stars: their temperatures, densities, and volumes? As previously discussed in §IV, temperature measurements require either energy distribution photometry or low resolution spectroscopy, but the latter is probably needed for these stars because one must measure both the circumstellar absorption and coronal temperature together. While in principle well-calibrated energy distribution photometry could measure both parameters, experience with the Einstein IPC points out the need for higher resolution data. Measurements of density and volume require at least moderate resolution spectroscopy.

2. What is the geometry of the emitting regions in preMS stars? I would estimate that the rotational periods for these stars probably lie in the range 3-8 days. Thus monitoring the X-ray emission from these stars for this time period with an imaging experiment should determine whether the X-rays are emitted from a few active regions or uniformly across the stellar surface, and such observations should also determine time scales for the variability of these active regions. High resolution ultraviolet spectra should also be useful in measuring the Doppler shifts of transition region emission lines from active regions and thus their location on the stellar surface, however, such measurements will be difficult because of the large line widths.

3. Various authors have estimated mass loss rates and flow velocities for the cool circumstellar gas, but there are no measurements of the outflow or infall velocities for the hot coronal gas. It is entirely possible that the X-ray emitting plasma is confined to closed magnetic loops that do not participate in the flow while the wind originates in magnetically open regions (coronal holes). Measurement of the flow velocities for coronal plasma requires high resolution X-ray spectroscopy, which may not be feasible for these stars, but similar measurements for the plasma at transition region temperatures requires high resolution ultraviolet spectroscopy, which will be feasible with Space Telescope. Even with such data, however, the interpretation will be difficult as different authors have interpreted P Cygni-type profiles for T Tauri stars as indicating mass inflow and outflow.

VI. M DWARF FLARE STARS

a) What We Have Learned from Einstein

1. Flares on the Sun have been studied extensively with instruments covering the electromagnetic spectrum, and flares on M dwarf stars have been studied at optical and radio wavelengths since 1949. While it was recognized that X-ray observations would be critical in understanding the properties of the hot plasmas in flares, sensitivity limitations precluded X-ray observations of all but the most energetic events prior to Einstein. For example,

Heise et al. (1975) detected a large flare on YZ CMi (M4.3eV) and UV Cet (M5.6eV) using the ANS satellite, and Kahn et al. (1979) detected two flares each on AD Leo (M3.5eV) and AT Mic (M4.4eV). The X-ray luminosities for the flares observed in AD Leo and AT Mic are very large, $L_X = 1.3-1.6 \times 10^{30}$ ergs s^{-1}, as much as a factor of 4000 larger than very large solar flares.

2. Einstein has now observed flares on Proxima Cen (Haisch et al. 1980, 1981), YZ CMi (Kahler et al. 1982), Wolf 630 AM and BD + 44°2051 (Johnson 1981), and perhaps other M dwarfs. Many of these observations were part of collaborative observing programs involving simultaneous optical, ultraviolet, and radio observations. As a result of the greater sensitivity of Einstein, less luminous flares can be studied in detail. For example, the flare on Proxima Centauri observed by Haisch et al. had a peak luminosity of $L_X = 7.4 \times 10^{27}$ ergs s^{-1}, comparable to a very large solar flare.

The X-ray light curve and temperatures of this flare on Proxima Centauri were in many ways similar to solar flares. For example, the temperature, as crudely estimated from IPC pulse height spectra, reached a peak of 17×10^6 K early in the flare and the X-ray luminosity peaked about 5 minutes after the peak temperature. Both properties are typical of solar flares. From the X-ray decay time they postulated that the flare was cooled by radiation, but simultaneous ultraviolet spectra are needed to determine the importance of conduction and expansion cooling. For the extremely luminous flare on AT Mic, Kahn et al. (1979) were able to derive a single characteristic temperature of $30 \pm 10 \times 10^6$ K, which is somewhat larger than the temperatures typically seen during the cooling phase of solar flares.

b) Some Important Unanswered Questions

1. We need to observe a considerable number of flares to see what ranges of temperature, X-ray luminosity, and emission measure are typical for flare events in M dwarf stars of different effective temperatures and ages. Monitoring by imaging instruments with energy distribution photometry capability is needed.

2. What are the variations of temperature, electron density, X-ray luminosity, and emitting volume as a function of time during flares? To answer this question, we need a high throughput instrument with moderate spectral resolution capability.

3. What are the turbulent and systematic mass motions during flares, and do these motions play an important role in the flare energy balance? Depending on whether the velocities are $\sim 10^2$ or $\sim 10^3$ km s^{-1}, either high or moderate X-ray spectral resolution will be needed to study the hot gas. Velocities of the cooler gas should be easily studied in the ultraviolet by the Space Telescope High Resolution Spectrograph.

4. A critical question is whether flares are cooled primarily by radiation, conduction, or expansion. This question requires simultaneous measurements by different instruments: radiative losses can be measured by X-ray energy distribution photometry, conductive losses by ultraviolet spectroscopy, and expansion losses by moderate or high resolution X-ray spectroscopy

as previously discussed. A determination of the total cooling rate determines the heating rate, and thus provides valuable information on the flare energy source.

5. Do flares occur on warmer stars? The answer must be yes because the Sun flares, but such flares are difficult to see optically because of reduced contrast with respect to the photospheric background and the probable lower frequency of flares. X-ray observations should be able to answer this question as the quiescent coronal background is generally small compared to flares even for the Sun. Monitoring of G and K dwarfs with a simple X-ray imaging experiment for long periods of time is needed to answer this question.

VII. LUMINOUS COOL STARS

a) What We Have Learned from Einstein

1. Prior to Einstein no nonbinary late-type giant or supergiant was detected as an X-ray source. Einstein detected several nonbinary G giants with L_x between 10^{28} - 10^{30} ergs s^{-1} and two early K giants, ε Sco (K0 III-IV) and α Ser (K2 III), with $L_x \approx 10^{28}$ ergs s^{-1} (Vaiana et al. 1981, Ayres et al. 1981). The latter two stars have $L_x/L_{bol} \approx 3\times10^{-8}$, which is smaller than this ratio for solar coronal holes.

2. Einstein was unable to detect X-rays from single giants cooler than about K2 III and G-M supergiants. For example, α Boo (K2 III) and α Tau (K5 III) were not detected with upper limits $L_x/L_{bol} < 3 \times 10^{-9}$, about a factor of 30 smaller than for solar coronal holes. Also the G supergiants β Aqr (G0 Ib) and α Aqr (G2 Ib) have upper limits $L_x/L_{bol} < 10^{-7}$ and the M supergiants α Ori (M2 Iab) and α Sco (M1 Ib+M) have upper limits $L_x/L_{bol} < 2 \times 10^{-9}$. These nondetections led Ayres et al. (1981) to propose a boundary in the cool portion of the HR diagram separating a region (consisting of K2-M giants and G-M supergiants) in which there is no evidence for hot coronae from a region (consisting of G-K2 giants and F-M dwarfs) in which hot coronae are usually, but not always, detected. The location of this boundary is similar to that separating regions where transition regions are or are not typically seen and where massive cool winds begin to appear.

3. At present we do not know which of several possible explanations for this boundary in the HR diagram is correct. If the nondetection of X-rays from stars cooler and more luminous than this boundary is an instrumental threshold effect, then the coronae have surface brightnesses much smaller than coronal holes. Alternatively, the coronae may be cooler than ~ 1×10^{6} K and the X-ray emission will be too soft for detection by Einstein. Absorption of soft X-ray emission by overlying cool circumstellar gas is a possible explanation for the lack of detected X-rays from the G-M supergiants but not the K2-M giants. Finally, these stars may not have hot coronae, but rather extended cool ($T \approx 10^{4}$ K) envelopes that do not emit X-rays. Ayres et al. (1981) proposed the latter explanation, but more information is needed to confirm or refute this proposal.

b) Some Important Unanswered Questions

1. Do the K2-M giants and G-M supergiants have faint coronae at 10^5 - 10^6 K? This question can be answered with ultraviolet spectra, such as from IUE and Space Telescope, or by an extremely soft X-ray or extreme ultraviolet imaging experiment. Hartmann et al. (1980, 1981) have already found that β Aqr (G0 Ib), α Aqr (G2 Ib), and α TrA (K4 III) show ultraviolet emission lines formed at 10^5 K.

2. What are the coronal temperatures for the G giants that are detected as X-ray sources? Energy distribution photometry can answer this question, and in principle recalibrated Einstein IPC pulse height spectra will provide this information on a few stars.

3. What are the electron densities and emitting volumes (i.e. loop dimensions) for the G giants? Moderate resolution X-ray spectra are needed.

4. What are the geometries of the G giant coronae? Monitoring of these stars over rotational periods with imaging experiments is needed to answer this question.

VIII. RS CVn AND RELATED CLOSE BINARY SYSTEMS

The RS CVn binary systems are detached systems with periods of 1-14 days, generally consisting of a K0 IV primary and a late G dwarf secondary star. Hall (1976, 1981) has reviewed the properties of these systems as well as the related long period systems with giant star components and the contact W UMa systems, and Popper and Ulrich (1977) have discussed their evolutionary status. The most striking peculiarity of the RS CVn systems is a migrating quasi-sinusoidal distortion in their optical light curves (Hall 1981; Rodono 1981) that is generally explained by an uneven distribution of dark, cool photospheric spots (cf. Eaton and Hall 1979). There is evidence that the chromospheric Hα and Ca II H and K emission lines are bright when the visible hemisphere shows maximum coverage by the dark spots (cf. Dupree 1981).

a) What We Have Learned from Einstein

1. Using the HEAO-1 A2 experiment, Walter et al. (1980) detected 15 out of 59 systems observed with luminosities in the range $L_x = 10^{30.5}$-$10^{31.6}$ ergs s^{-1}, and ascribed the nondetections to the sensitivity threshold of HEAO-1. As a consequence of its lower sensitivity threshold, the Einstein IPC has detected at least 47 systems with $L_x = 10^{29.4}$-$10^{31.5}$ ergs s^{-1} and $\log(L_x/L_{Bol})$ in the range -4.9 to -2.4 (cf. Walter and Bowyer 1981). Further, the L_x/L_{Bol} ratio does not depend on the gravity of the cooler star in the system (usually the more active star) over two decades in gravity.

2. Walter and Bowyer (1981) showed that $L_x/L_{Bol} \sim \Omega$, the angular velocity of the star with the most active chromosphere in the system. Since single G-type stars follow the same relationship (Walter 1981), the bright X-ray luminosity of the RS Cvn systems is not a direct consequence of

binarity, but rather a result of rapid rotation which is in turn produced by tidally-enforced synchronism of rotation and orbital motion. Rapid rotation presumably results in strong dynamo-generated magnetic fields in stars with deep convective zones.

3. HEAO-1 observations of Walter et al. (1980) and Garcia et al. (1980) indicated that RS CVn systems have rather hot, variable spectra. Subsequently, Swank et al. (1981) were able to obtain low resolution spectra of 7 RS CVn systems and Algol (a contact eclipsing system) with the Einstein SSS detector. Assuming that the X-ray emission is from an optically thin thermal plasma in collisional ionization equilibrium, they found that the spectra can be fit by two components — a warm component with $T_{warm} = 4-8 \times 10^6$ K, and a hot component with $T_{hot} = 20-100 \times 10^6$ K. The luminosities of the two components lie in the range $L_{warm} = 10^{30}-10^{31}$ ergs s^{-1} and $L_{hot} = 10^{29.3}-10^{31.3}$ ergs s^{-1}. The warm component appears not to vary, while the hot component varies by a factor of 2. The ratio L_{hot}/L_{warm} lies in the range 0.1 (for the 104^d Capella system) to 4 (for the 6.5^d UX Ari system). Since the hot components vary while the warm components do not, the two components probably originate in separate plasmas.

4. In all likelihood the emitting structures are closed magnetic loops. This hypothesis is based on solar analogy, the appearance of large dark starspot groups on the photospheres of these stars, and the inability of these stars to confine the observed hot plasma by gravity alone. Swank et al. (1981) and Walter et al. (1980) assumed the Rosner, Tucker, and Vaiana (1978) scaling law for magnetic flux tubes with the following results. If the gas pressure in the loops is roughly 10 dynes cm^{-2}, similar to the largest pressures seen in solar active region loops, then the loop sizes for the warm plasma are small compared to the stellar radii and the hot loops have sizes comparable to the binary separations. If, on the other hand, the loop pressures are ≥ 100 dynes cm^{-2}, then both the warm and hot loops are smaller than the stellar radii in scale. There is no compelling evidence yet as to which pressure is correct, but the absence of large changes in the X-ray flux from AR Lac during primary and secondary eclipse (Swank et al. 1981) suggests that the emitting regions may be comparable to the binary separation in this system. This raises the possibility of interactions between loops from the two stars, which Simon, Linsky, and Schiffer (1980) proposed as the mechanism responsible for flares in these systems.

b) Some Important Unanswered Questions

1. What are the geometries of the X-ray emitting regions in these systems? Monitoring the X-ray and ultraviolet emission during a full binary orbit with X-ray energy distribution photometry and ultraviolet spectroscopy can determine the location of the hot and warm loops and their relation to the spots. Also moderate resolution X-ray spectroscopy will permit measurements of electron densities and thus pressures and loop sizes using appropriate scaling laws. Such data will also provide information on the fraction of the available volume that is filled by loops.

2. Is the radiation in the hot component indeed thermal and why is this plasma so hot? The answer to this question will require a hard X-ray

spectroscopy instrument that can monitor these systems to study their variability time scales.

3. What are the mechanisms responsible for flares in these systems? Two kinds of observations are needed. First, we need to monitor these systems during flares with moderate resolution X-ray spectroscopy and ultraviolet spectroscopy to determine variations in the X-ray and ultraviolet fluxes, temperatures, and electron densities with time. Second, we need to determine the plasma flows, perhaps in interacting flux tubes from the two stars or other binary interactions. Such measurements require high resolution X-ray and ultraviolet spectra.

IX. HOT STARS

a) What We Have Learned from Einstein

1. *Einstein* discovered that the O and B stars are the brightest X-ray sources among all nondegenerate stars, despite prior predictions that these stars should not have hot outer atmospheres on the basis that they lack convective zones and thus acoustic wave heating processes should be inoperative. Harnden *et al.* (1979) and Seward *et al.* (1979) reported the initial *Einstein* observations of luminous O stars in the Cyg OB2 association and the region around the η Carinae nebula, finding that L_x is typically $\sim 10^{33.7}$ ergs s^{-1} for these stars. Subsequent observations of hot stars by Long and White (1980), Vaiana *et al.* (1981), Pallavicini *et al.* (1981), and Cassinelli *et al.* (1981) have led to the results that typical luminosities are 10^{31}-10^{33} ergs s^{-1} for the O dwarfs, 10^{27}-$10^{30.7}$ ergs s^{-1} for the B8 V- A1 V stars, $10^{31.9}$-$10^{33.6}$ ergs s^{-1} for the O supergiants and $\lesssim 10^{31}$ ergs s^{-1} for the late B supergiants. The reason that these stars were not observed as X-ray sources prior to *Einstein* is that they are generally more than 100 pc distant, especially the O supergiants, so that the apparent X-ray flux of the brightest source, ζ Pup (O4f), is only 1×10^{-11} ergs cm^{-2} s^{-1}, close to the HEAO-1 threshold.

2. Pallavicini *et al.* (1981) reported that $L_x/L_{bol} = 1.4 \times 10^{-7}$ for most O3-A5 stars in their sample, independent of spectral type and luminosity class. Using a sample of 21 supergiants of spectral type O4-A2, Cassinelli *et al.* (1981) found a similar result, $L_x/L_{bol} \approx 1.6 \times 10^{-7}$, for B1 and hotter supergiants, but this ratio is perhaps a factor of 3 smaller in the later B supergiants. The roughly constant value of L_x/L_{bol} for the hot stars suggests that only one mechanism is responsible.

3. Pallavicini *et al.* (1981) searched without success for any correlations between L_x or L_x/L_{bol} with rotational velocities (v sin i). Thus rotation does not play an important role in determining the X-ray emission from these stars.

4. The O and B stars, especially supergiants, exhibit rapid mass loss with rates up to $\dot{M} \approx 10^{-4.5}$ $M_{\odot}$ yr^{-1} and terminal velocities up to $v_{\infty} \approx 3500$ km s^{-1}. Cassinelli (1979), Conti (1981), Lamers (1981) and others have reviewed the properties of these winds and how they are derived from P Cygni-type line

profiles and VLA observations. Garmany *et al.* (1981) found that $\dot{M} \sim L_{bol}^{1.73}$, and compared this result with the predictions of radiatively driven stellar wind theory. The ratio of X-ray luminosity to the kinetic energy in the wind flow, $L_x/1/2\, Mv_\infty^2 \approx 10^{-4}$. Thus the X-rays do not drive the wind, but rather the wind could be responsible for creating the X-rays.

5. The measurement of considerable soft X-ray flux at energies below 1 keV has played a crucial role in understanding the origin of the X-rays from the hot stars. Long and White (1980) argued that the large column densities of the wind in O supergiants should absorb all the soft X-ray emission from a hot corona lying at the base of the wind as proposed by Cassinelli and Olson (1979). Thus the X-ray emitting region must be distributed throughout the wind, and Long and White (1980) proposed that both hot (~3 × 10^6 K) and cool (~3 × 10^4 K) plasma coexist in the winds of these stars. Cassinelli *et al.* (1981) discussed constraints on the range of hot plasma temperatures and wind column densities, assuming the hot plasma is embedded in the wind.

6. Lucy and White (1980) proposed a phenomenological theory to explain the observed X-ray emission from hot star winds. As a working premise, they accepted earlier calculations that winds driven by radiation pressure in lines are unstable, since density enhancements will feel greater acceleration than the surrounding gas and the increased velocity will result in greater acceleration as the absorption lines are Doppler-shifted into the bright stellar continuum of the star. Lucy and White (1980) proposed that this mechanism will produce density enhancements in the wind that are radiatively driven through the ambient gas and confined by ram pressure. These enhancements (the so-called blobs) will form hot bow shocks that radiate the observed soft X-rays. Cassinelli *et al.* (1981) discussed the validity of this mechanism and competing mechanisms for explaining the *Einstein* data as well as such ionization anomalies such as the O VI/O IV ratio.

b) Some Important Unanswered Questions

1. What heats the hot plasma in these stars and where is it located? In particular, is the Lucy-White mechanism valid, or can such alternative mechanisms as a hot corona near the base of the wind or spatial separation of a hot corona from the expanding cooler gas by magnetic fields (Rosner and Vaiana 1980) better explain the data? To answer this question one needs low resolution spectra to measure both the temperature and attenuation as a function of time (and thereby aspect angle due to stellar rotation) for both dwarf and supergiant O and B stars. Observing stars of different spectral types and luminosities is important because there is evidence that the X-rays are created by only one mechanism in the hot stars but the ionization state of the wind depends critically on spectral type.

2. What are the processes responsible for the ionization equilibria seen in these stellar winds, and, in particular, what is responsible for the ionization anomaly of O VI? To address this question we need to know the range of temperatures and electron densities in these winds from moderate resolution X-ray spectra as well as contemporaneous measurements of ultraviolet line profiles, especially the O IV λ1032, 1037 doublet.

3. What mechanisms are responsible for the acceleration of hot star winds? What we now know about these winds is based only on ultraviolet spectra that tell us only about the flow properties of plasma cooler than 2×10^5 K. Since hot gas may be embedded in the cooler wind and perhaps flows faster, moderate resolution X-ray spectra should be able to measure the flow properties of this component.

4. Similar types of measurements are needed to study the poorly understood winds and coronae in Wolf-Rayet stars.

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