OBSERVATION OF WINDS IN COOL STARS

A. K. Dupree
Harvard-Smithsonian Center for Astrophysics
Cambridge, MA 02138

ABSTRACT

Sufficient observational material - ultraviolet spectroscopic measures, quantitative optical spectroscopy, and X-ray photometry - has accumulated to enable us to discern the presence and character of mass loss in cool stars and to establish meaningful constraints on theoretical models. Two determinants of atmospheric wind structure - temperature and gravity - may suffice in a most superficial way to define the wind and atmospheric structure in a star, however more extensive observations demonstrate the importance of magnetic surface activity and its particular geometrical configuration. Successive observations of an active binary system and a supergiant star have revealed that magnetic activity and perhaps mass loss occur on restricted regions of a stellar surface and that long lived structures are present in a wind.

Introduction

It was in 1935 that Adams and MacCormack detected the Doppler shift of neutral and lowly ionized species towards a cool supergiant star - α Her. The outflow velocity was only a few kilometers per second, substantially less than the escape velocity from the stellar surface, and led Spitzer (1939) to conjecture that the outflowing material became ionized and then returned to the star. Almost twenty years passed before Deutsch (1956) discovered stationary lines in the spectroscopic binary that is a companion to the supergiant star. These ground state lines from species of low ionization, defined the extended nature of the wind from the supergiant (1000 a.u.); and their velocities confirmed that the material was actually escaping from the supergiant star. Since then, optical, infrared, and ultraviolet studies have generally confirmed the existence of mass loss in a great variety of cool stars. However, to date the Sun is still the only dwarf star in which there is direct evidence for mass loss.

Recent spectroscopic measurements with the International Ultraviolet Explorer satellite have enabled us to develop a comprehensive view of the mass loss phenomenon for stars more luminous and cooler than the Sun. Complementary X-ray measurements and ground-based spectroscopy allow the character of a stellar chromosphere and corona to be defined and its role in the presence of a stellar wind to be explored. Placing the Sun in the stellar context - with the extended domain of physical conditions - can confront and enhance our theoretical understanding of the mass loss process.

Signatures of Stellar Winds

There are several means to infer the presence of mass outflow and eventual loss in a stellar atmosphere. These include the detection of circumstellar lines of metals and low species of ionization, the measurement of molecular and continuum emission at infrared or radio frequencies from circumstellar material, the observation of asymmetric line profiles, and the direct measure of an outward Doppler shift in the position of a line. It is through optical and ultraviolet spectroscopy that a large number of stars have been surveyed, and from which most recently it has been possible to draw a comprehensive picture of the mass loss process.

Frequently used spectroscopic signatures of mass loss are the asymmetry of an optically thick chromospheric emission line and/or the presence of narrow circumstellar absorption features. Transitions such as the resonance lines of Ca II and Mg II are formed in the chromosphere of a star, and can indicate mass motions in luminous stars. Figure 1 shows three spectra typical of cool stars.

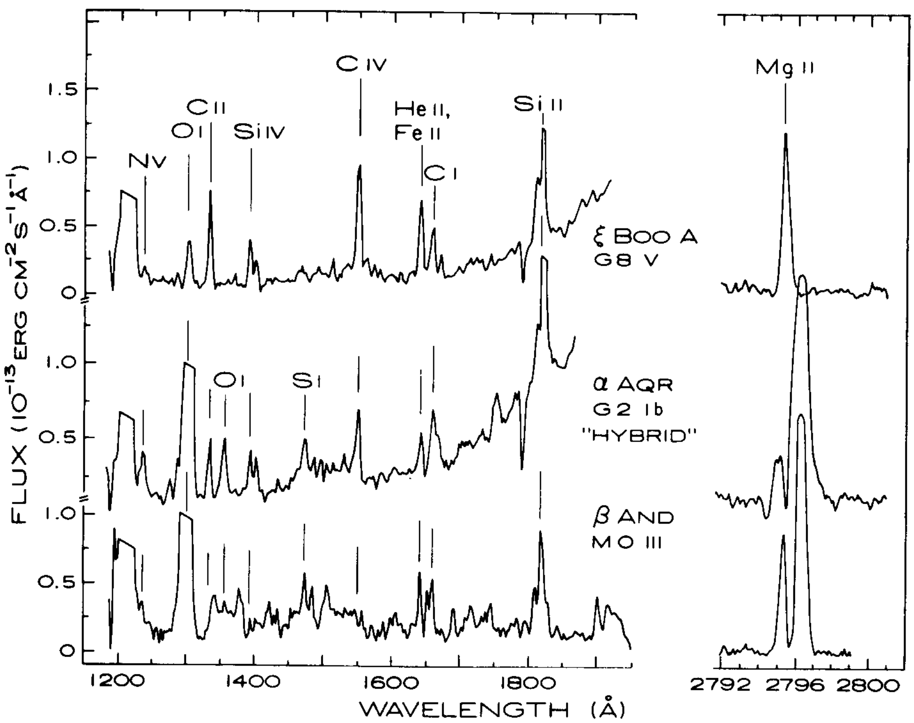

Figure 1. Ultraviolet spectra of cool stars from IUE showing three types of stellar atmospheres: a dwarf similar to the Sun (ξ Boo A); a hybrid supergiant star, α Aqr with both a hot (10^5 K) atmosphere and the asymmetric Mg II profile typical of an expanding atmosphere; a cool luminous supergiant β And showing predominantly species of low excitation and a massive wind. Data from Hartmann, Dupree, and Raymond (1982).

The Mg II emission line is narrow in the dwarf star (ξ Boo A) and at the spectral resolution now available, shows no sign of any absorption or asymmetry. Contrast this with the profiles of the more luminous stars α Aqr and β And where an asymmetry is found in the emission peaks. This asymmetry in the sense, long wavelength peak > short wavelength peak or red > violet - and the accompanying blue-shifted line core (here somewhat distorted by narrow interstellar absorption features) signal the presence of a massive stellar wind. It was the original suggestion of Hummer and Rybicki (1968) that a differentially expanding atmosphere could produce such a profile; this has been confirmed in simultaneous measurements of profiles and direct Doppler shifts in regions of the Sun (Brueckner, Bartoe, and van Hoosier, 1977) and by theoretical calculations for the Sun (see Dupree 1981).

Observations of the Mg II and the Ca II profiles are used to identify stars undergoing mass outflow - which is assumed to eventually lead to mass loss - and to measure the radial velocity of circumstellar absorption features. The highest outflow velocity corresponding to the maximum short wavelength extension of the circumstellar absorption is commonly identified as the terminal velocity of the wind (V_∞) and is taken as a constraint on wind theories. It is believed that such blue-shifted features result from recombination to Mg II and Ca II ions far out in the wind as it cools and flows into the interstellar medium. Corresponding features in both the Mg II and Ca II profiles support this empirical interpretation; and current calculations offer confirmation.

Emission from cool stars at shorter wavelengths in the ultraviolet spectral region can indicate the presence of plasma with temperatures from 10^4 - 2×10^5 K. The strong C IV and N V emission lines found the dwarf ξ Boo A and the supergiant star α Aqr in Figure 1 testify to the existence of hot (2×10^5 K) gas in the atmospheres of these objects. For the dwarf star, as is the Sun, it is no surprise to find the signature of hot plasma; in the supergiant, the spectra clearly demonstrate that hot gas can coexist with a massive stellar wind. The coolest and most luminous stars of all, exemplified by β And in Figure 1 give no indication of high temperature species, suggesting a cool atmosphere and a massive wind.

The appearance of profile asymmetries in stars of various temperatures and luminosities is summarized in Figure 2. As a star becomes cooler and more luminous, there is a progression of the mass outflow signature from lines in the high chromosphere and wind (Mg II) to the lower levels (Ca II). When sufficient material has accumulated, circumstellar absorption features become detectable. Moreover, the terminal velocity of the wind as inferred from the presence of narrow absorption features decreases too. Hybrid supergiants, such as α Aqr, have a terminal velocity ~ 60 km s^{-1}; the cooler more luminous giants and supergiants exhibit absorption features indicating outflow of ~ 10 km s^{-1} (Reimers 1977).

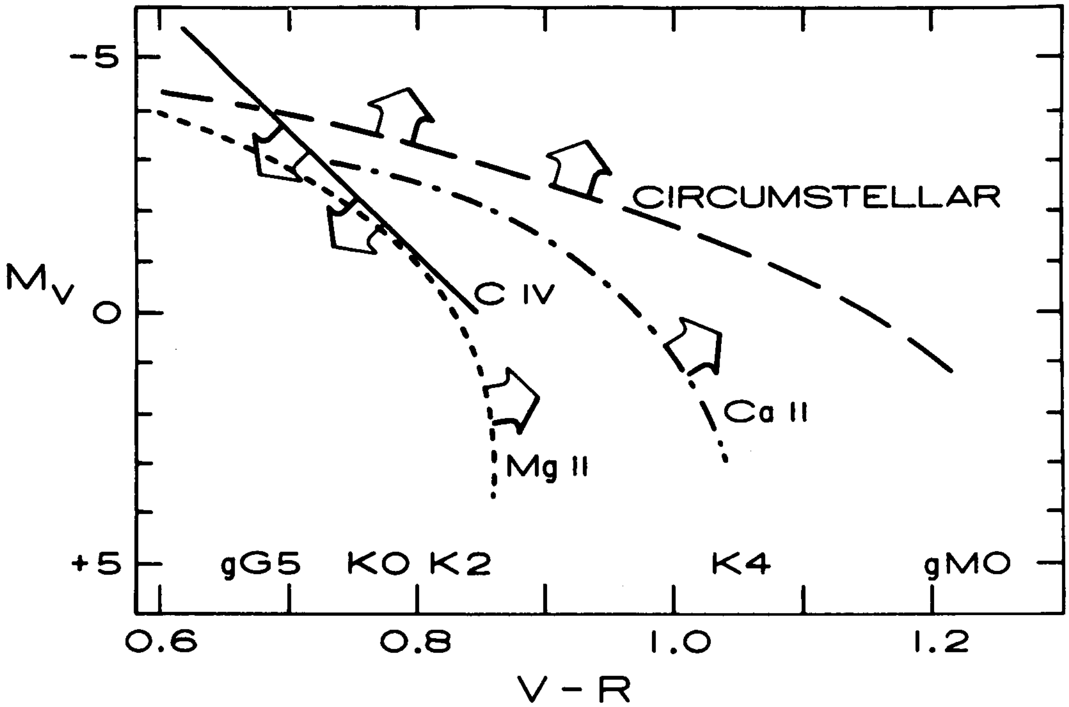

Figure 2. The appearance of various spectral features as a function of color (V-R index) and absolute magnitude (M_v) for the most luminous stars. C IV emission is prominent to the left of the solid line; the ratio of red:blue emission peaks for Mg II and Ca II is greater than 1 to the right of the appropriate broken lines (Stencel 1978; Stencel and Mullan 1980). Circumstellar Ca II features are found above the long broken line (Reimers 1977). For the Sun, the values are M_v = +4.79 and V-R = +0.52.

Atmospheric Conditions

The domain of hot atmospheric plasma can be related to the presence of mass outflow. In Figure 3 is summarized the presence of various spectral features in cool stars. Spectra of dwarf stars (luminosity class V) generally contain detectable C IV emission, whereas most cool luminous stars (spectra type M0-M5, luminosity class I-III) show no indication of C IV. If C IV is undetected in a sufficiently long exposure, upper limits result that are 10^{-1} to 10^{-2} of the surface flux of the quiet Sun (Hartmann, Dupree and Raymond 1982). In the latter case, these luminous stars possess strong winds as can be inferred from Figure 2. Moreover, there is a substantial intermediate region of stars showing both the presence of C IV emission and of low excitation features - the "hybrid" stars (Hartmann, Dupree, and Raymond 1980). X-ray surveys (Vaiana et al. 1981;

Helfand and Caillault 1982) from the HEAO-2 ("Einstein") satellite confirm the C IV results in the extremes. X-rays are generally found in dwarf (main-sequence) stars, but there is an absence of detectable X-ray emission in the luminous giant and supergiant stars - except for active binary systems.

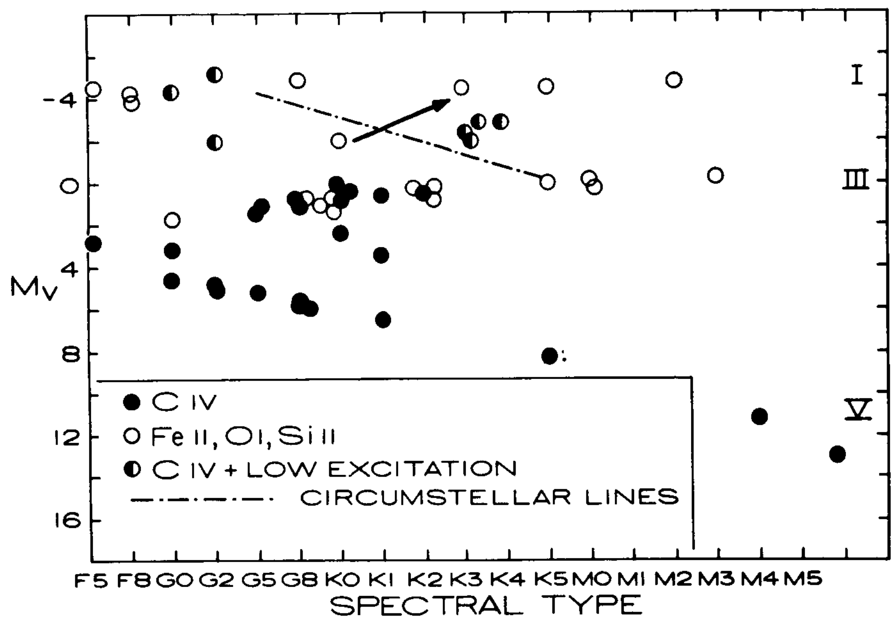

Figure 3. The presence of various spectral features in stars of different spectral types and luminosities. Stars exhibiting low and high (C IV) excitation species are termed "hybrid" - and denoted by the half filled circles (Hartmann, Dupree, and Raymond 1980). The broken line denotes the boundary above which circumstellar lines appear in optical spectra (Reimers 1977). Soft X-rays are generally detected only in stars which show C IV (Vaiana et al. 1981).

More detailed study of the radiative losses from an atmosphere in the luminous lines shows substantial variation in the surface fluxes (see Figure 4). The Mg II lines show a dispersion of 2.5 dex, whereas for the high temperature species, C IV and N V, the difference can amount to more than 4.0 dex. The pattern of enhanced emission with temperature of formation is similar to that found in a solar active region and is exemplified by the emissions in VW Cep and HR4665, two binary systems, and ξ Boo. In the more luminous stars, where signatures of mass outflow are evident, there is a dearth of high temperature material. And for stars which are optically very similar viz: 77 Tau, δ Tau and η Dra, there can be several orders of magnitude difference in their surface fluxes.

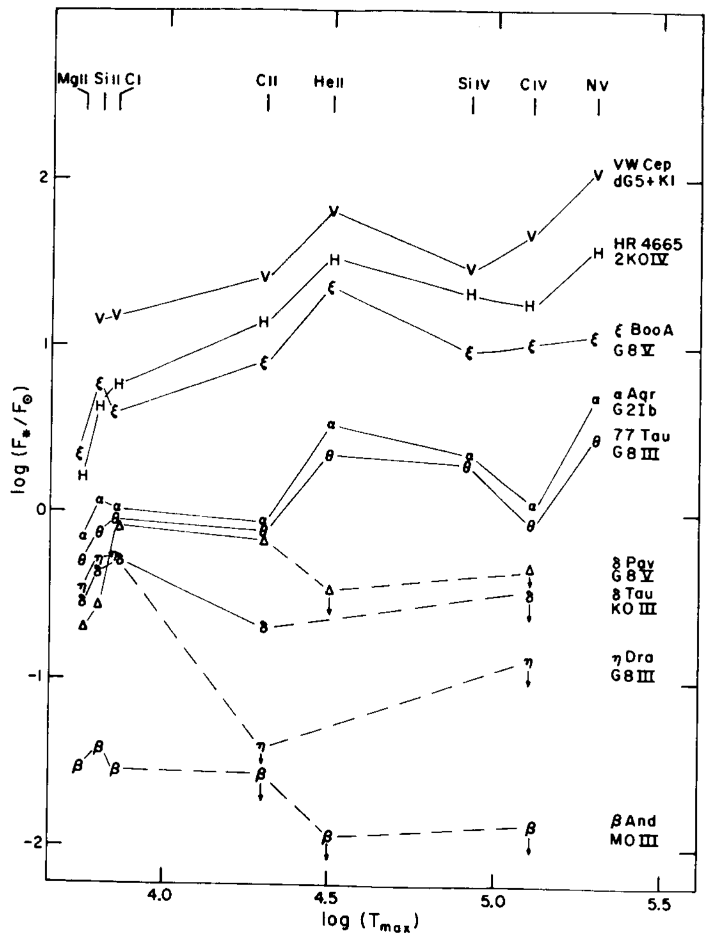

Figure 4. The stellar surface flux (erg cm^{-2} s^{-1}) in various emission lines as compared to solar values. The temperature of formation of these lines can be inferred for collisionally dominated ionization and excitation equilibrium. Stars showing the highest surface fluxes, VW Cep and HR4665, are close binaries having rapid rotation (from Hartmann, Dupree, and Raymond 1982).

It is obvious that a two-dimensional classification of temperature and gravity is insufficient to predict the character of a cool stellar atmosphere.

A comparison of typical stellar and wind parameters is given in Table 1, where we note the vast scale changes in the stellar dimensions and more than eight orders of magnitude in the mass loss rate. Of particular interest is the rapid decay of the terminal velocity as a fraction of the escape velocity from the stellar surface. Reimers (1977) has noted a rough correlation from a survey of many stars that $V_\infty \sim V_{esc}^2$, but the values diverge a great deal at any given value of T_{eff} and g. Table 1 also illustrates that the radiative losses (here underestimated by only 2 lines) are commensurate with the energy losses in the wind. The total losses in both wind and radiation are also a remarkably constant portion of the total stellar luminosity as measured by σT^4.

Table 1: Typical Physical Parameters of Stars and Winds*

Stellar Characteristics	Dwarf (Sun)	Giant (KO III)	Supergiant (M2Ia)
Mass ($M_\odot$)	1	4	20
T_{eff} (K)	5600	4100	2800
Radius ($R_\odot$)	1	15	800
Luminosity ($L_\odot$)	1	100	50000
log g (cm s^{-2})	4.4	2.5	0.0
V_{esc} (surface, km s^{-1})	600	300	100
Coronal Temperature (K)	1(6)	1(5)	1(4)
Radiative Losses			
Mg II (erg s^{-1})	6(28)	1(31)	4(32)
C IV (erg s^{-1})	6(27)	1(30)	<4(31)
Wind Parameters			
V_∞ (km s^{-1})	500	100	20
$\dot{M}$($M_\odot$ yr^{-1})	1(-14)	1(-8)	1(-6)
Time for 1 R_* (hrs)	0.5	30	8760
Kinetic energy (erg s^{-1})	8(26)	3(31)	1(32)
Grav. pot. energy (erg s^{-1})	2(27)	4(32)	4(33)

* The notation 2(6) implies 2 x 10^6.

Criteria for Wind Theory

Figure 5 gives an overview of the constraints placed by stellar observations on a quantitative theory of stellar winds. Our understanding of the behavior of winds from dwarf stars is based on remote measurements of the Sun and direct sampling of its wind in space. To date there is no spectroscopic evidence for mass loss or circumstellar absorption in any other dwarf star. This is perhaps not surprising since the asymmetries associated with mass outflow are only apparent - if at all - over restricted regions of the Sun. Coronal holes in the solar atmosphere are not detectable in the strong chromospheric lines of Ca II and Mg II. This results from the relatively narrow line formation regions in a dwarf star, coupled with the fact that the outward acceleration associated with eventual mass loss does not occur to a significant extent, if even at all, at low chromospheric levels in the Sun.

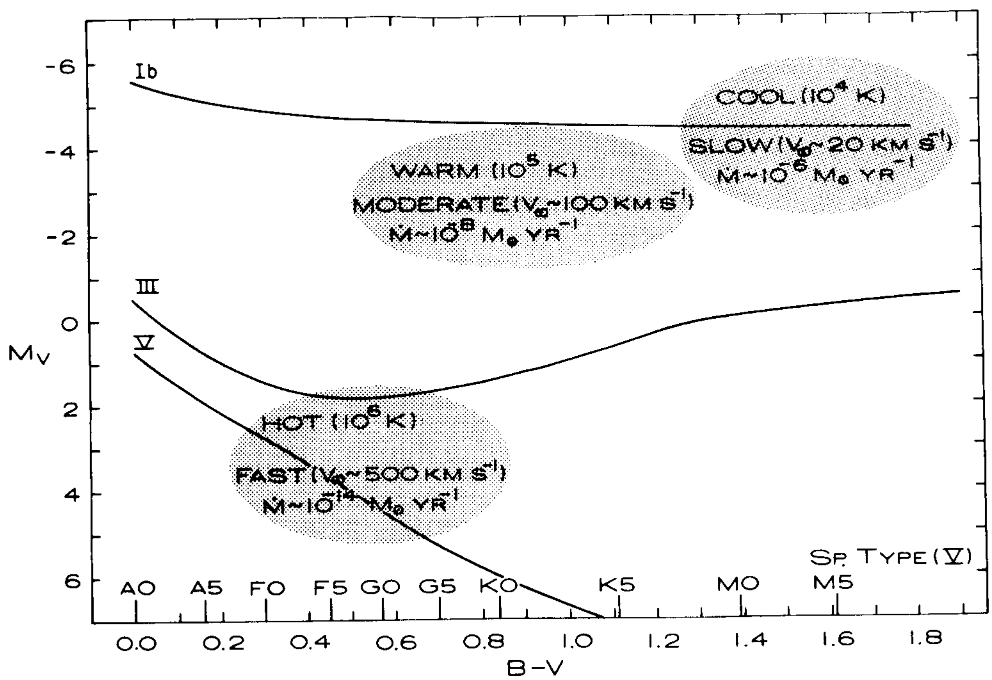

Figure 5. Characteristics of mass loss rates and winds in stars of various luminosities. Luminosity class V indicates dwarf stars; Class III denotes giant stars; the curve for class Ib marks the position of supergiant stars (from Dupree 1981). Details of the physical conditions are in Table 1.

For the cooler, more luminous giant and supergiant stars, the electron temperature in the wind decreases as the effective temperature and/or gravity decrease. This has been inferred from both the presence of ultraviolet emission lines as well as their profiles (Hartmann, Dupree, and Raymond 1981). The terminal velocity of the winds decreases (as deduced from measurement of circumstellar absorption features) concurrently with the decrease in effective temperature and gravity.

Mass loss rates themselves are very uncertain, and have been obtained by a variety of direct radio, infrared, and optical measures combined with modeling of line profiles where available. It appears that mass loss can result from a similar and continuous mechanism for cool stars. For the most luminous stars the acceleration begins in the chromosphere.

Various mass loss mechanisms have been considered. If a purely thermally driven wind is invoked, the high mass loss rates required can only be achieved with a hot atmosphere - for which there is no spectroscopic evidence - and moreover, expansion will not begin in the chromosphere as indicated by the observations. A particularly attractive mechanism relies on Alfven waves to carry the required mechanical flux. Such models developed by Hartmann and MacGregor

(1980) are successful in reproducing the general behavior of cool star winds, but require arbitrary assumptions of characteristic damping length in order to produce the observed (slow) terminal velocities. An extended discussion of various mechanisms is given by MacGregor in this volume.

Wind Variability

The previous discussion tacitly assumes that the outer atmospheres of stars are homogeneous and that a stellar wind has constant density, temperature and velocity. The Sun, of course contradicts this assumption. And as observations accumulate, it is apparent that cool stars show substantial variation as well.

Remarkable behavior has been found in λ Andromedae - a binary system whose primary star is a giant or subgiant of spectral class G8 III-IV. This close, but detached system has a 20.5-day orbital period but a stellar rotation period - 54 days - which is not synchronous with the orbital period. λ And is a member of a class of active binary stars, the RS CVn type stars, and displays surface activity in the form of spots, active regions, and flare activity. The chromospheric and coronal emissions are strong (with surface fluxes enhanced by factors of 10 to 100 times the quiet Sun) and variable. Most recently, a clear dichotomy in the atmosphere was discovered (Baliunas and Dupree 1982). When optically darker spots are on the disk, the brightening of chromospheric and coronal emissions occurs in conjunction with line profiles whose shapes indicate downflow of material. When the spots are at a minimum, the line luminosities decrease and the chromospheric line profiles of Ca II and Mg II indicate outflow. The analogy with solar coronal holes is striking, and these observations suggest that mass loss or mass transfer is probably occurring. The profiles have not been modeled in detail to obtain mass loss rates, but an estimate of 10^{-9}-10^{-11} $M_\odot$ yr^{-1} is generally consistent with profile shapes, the lack of circumstellar absorption, and as Weiler (1978) *et al.* noted, the observed lack of X-ray self-absorption.

Supergiant stars, in particular of the "hybrid" type, show variability of the wind opacity. The Mg II line profiles in α Aquarii were found (Dupree and Baliunas 1979) to undergo a substantial decrease in the blue peak of its Mg II emission over a period of ~ 1 year which corresponds to increased Mg II opacity in the high velocity part of the wind. During this time, the Ca II (K) line varied on a timescale of days. The increased opacity appears to result from a long-lived phenomenon since the line profile has exhibited its new form for about two years.

Young stars such as T Tauri stars are believed to be pre-main sequence objects that will eventually be dwarf stars of spectral type F5 to M5. They have extremely active chromospheres and coronae exhibiting higher fluxes than even the active RS CVn binary systems. It is not clear whether the emission is just a naturally highly active atmosphere (Dumont *et al.* 1973; Imhoff and Giampapa 1980) or results from infall of material that is being accreted in final stages of premain sequence evolution (Ulrich 1976; Ulrich and Knapp 1979). Or perhaps, both phenomena are present. The ultraviolet Mg II profiles (see Figure 6) show the typical asymmetry and circumstellar features found in evolved stars, and the mass loss rate has been estimated at ~ 4×10^{-7} $M_{\odot}$ yr^{-1} with terminal velocities on the order of 200 km s^{-1} (Kuhi 1964). This also leads to an energy flux in the stellar wind that is comparable to the radiative losses in the chromosphere and corona (Giampapa et al. 1981).

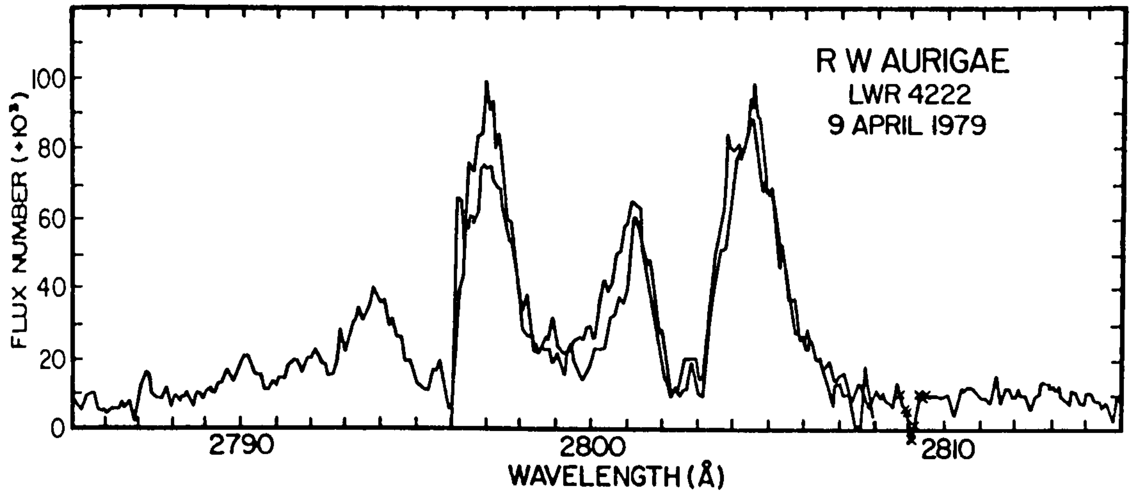

Figure 6. The Mg II lines in the T Tauri star RW Aur as observed with IUE. The line asymmetry coupled with multiple absorption features suggests a strong stellar wind in this pre-main sequence object (from Imhoff and Giampapa 1980).

A particularly active star, RW Aur, showed changes in the emission flux from 10^5 K lines by factors of 2 to 4 during a week's time while the Mg II profiles remained constant to 70 percent (Imhoff and Giampapa 1980). However, high resolution optical observations by Hartmann (1982) have revealed relatively stable blue absorption cores in the Na D lines, accompanied by dramatically variable emission components from night to night. This observation and others suggest (Hartmann 1982) a continuing mass loss process in conjunction with extremely complicated motions (perhaps even infall) in lower atmospheric layers.

The study of variability of such objects and their implications for the theory of stellar winds can now be a major focus of observing programs with the availability of high resolution spectroscopy and photon counting detectors, both in space and on the ground.

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