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Mass loss from stars

Stars return mass to the interstellar medium throughout their lives. A low-luminosity star such as the Sun is losing mass by a stellar wind at a rate of 10^{-14} solar masses per year ($M_\odot\,\mathrm{yr}^{-1}$). Very luminous stars, whether they are early-type hot stars or cool giants, lose mass at a rate of up to about $10^{-5} M_\odot\,\mathrm{yr}^{-1}$, and such rates have major consequences. The evolutionary track of the star on the Hertzsprung–Russell diagram is modified, the terminal state can be changed, and the winds affect the surrounding interstellar medium by depositing momentum, energy, and chemically enriched material.

This chapter reviews selected highlights of the origin and development of our understanding of stellar winds and mass loss. Much of what we currently know about stellar winds and the effects of mass loss comes from space observations. The space era in this field started with the rocket UV research by Donald Morton and his colleagues at Princeton in the mid-1960s (Morton 1967, Morton *et al*. 1968). The results were unexpected and led to a strong increase in activity regarding the subject of mass loss from hot stars. Figure 1 (top) shows the spectrum of one of the belt stars of Orion. On it were discovered strong and broad features at several UV resonance lines. Some of the line profiles were found to have longward shifted emission and shortward shifted absorption, and these lines are called P-Cygni profiles after the B supergiant which shows many such lines in the visible part of the spectrum. An early study of P-Cygni profiles and their significance as indicators of outflows was carried out in the 1930s by Beals (1929, 1931). He compiled catalogs showing spectra of Wolf-Rayet (WR) stars and η Carinae, and some of the novae and central stars of planetary nebulae which show the profiles. Chandrasekhar (1934a,b) introduced the now often used iso-velocity contour diagnostic for finding outflow properties from line profiles. He also introduced ways for interpreting the flattened continua of WR stars in terms of an extended atmosphere. Kosirev (1934) used these diagnostics to derive a rate of mass loss and outflow velocity ($10^{-5} M_\odot\,\mathrm{yr}^{-1}$ and $1000\,\mathrm{km\,s^{-1}}$) of a WR star, and his values are within a factor of three of current estimates. Most of the initial work on profiles had assumed that the outflow was transparent to line radiation. Sobolev (1947) developed an escape probability method for treating optically thick lines, and his method served as the basis for essentially all of the subsequent work on line profile analysis. Underhill (1949) computed continuum model atmospheres for hot stars and arrived at the important conclusion that luminous stars with $T_{\mathrm{eff}} > 20{,}000$ cannot have stable hydrostatic atmospheres. In spite of this early activity, the understanding of mass loss from hot stars progressed very slowly in the several decades before Morton's rocket observations.

During that interval, the attention of stellar astronomers was on mass loss from cool stars. This began with the discovery by Adams and McCormack (1935) of spectral evidence for slow ($\sim 5\,\mathrm{km\,s^{-1}}$), outward, mass motion. Lyman Spitzer (1939), who would later lead the development of space astronomy, carried out a PhD thesis on a study of the supergiants α^1 Her (M5 II) and α Ori (M2 Iab). In his thesis he developed the idea of "fountains" to explain the fact that the optical spectra of cool stars show evidence for expansion, but only at a speed well below the escape speed. He postulated that there would occur a change in the ionization to an unobservable stage, followed by a fountain-like infall. Many decades later this concept of fountain flow was found useful for modeling the infalling gas trajectories in our Galaxy. The first strong evidence that cool giants involve matter actually leaving the stars was developed by Deutsch (1956) from his observations of α Her (M5 II + G0 III). His analysis showed that the expansion of the primary star's

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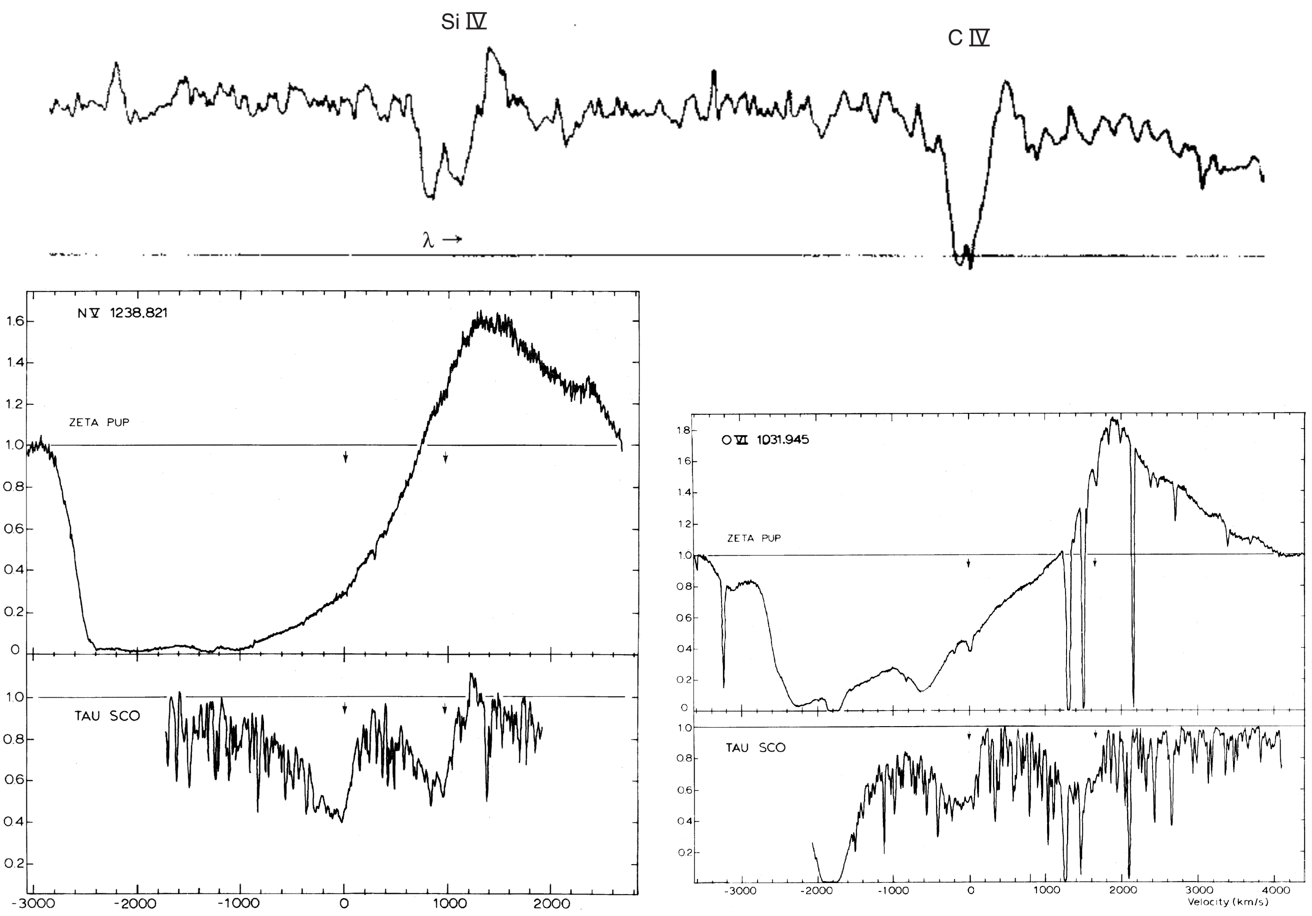

Figure 1 The upper panel shows Morton's (1967) rocket observation of the ultraviolet spectrum of ζ Ori (O 9.5 Ia). The wavelength increases to the right from 1140 to 1630 Å. Note the P-Cygni profiles at C IV and Si IV, and the shortward displaced absorption lines of C III, N V, and Si III. The lower panels show the Copernicus satellite spectra of the doublets of N V and O VI in the O4 f star ζ Pup and the B0 V star τ Sco. The arrows indicate the location of the rest wavelength of the lines. The sharp lines in the O VI spectrum are interstellar lines and the strong line at $-1900\,\mathrm{km\,s^{-1}}$ is Ly-β. (Adapted from Lamers and Cassinelli 1999.)

outer atmosphere extended beyond the orbit of its distant ($360\,R_*$) G0 companion. At such a large distance the flow had reached local escape speed leading Deutsch to infer that there is an outflow with a mass loss rate of $\sim 10^{-7} M_\odot\,\mathrm{yr}^{-1}$.

Ludwig Biermann (1951) recognized from the directions of the ion tails of comets that there must be a fast and continuous "corpuscular radiation" from the Sun. Eugene Parker (1958) developed an explanation of this mass outflow, which he called solar wind theory. This theory formed the basis for all the subsequent work on stellar winds and stellar mass loss (Chapters 9 and 47). The high speed or "wind" outflow that he predicted was verified by the *Mariner II* interplanetary space mission (Neugebauer and Snyder 1962). Weymann (1960, 1963) pioneered the application of wind theory to other cool stars, initially using extensions of coronal or thermally driven wind theory, and then considering other forces such as radiation pressure on resonance line and dust grain opacities.

The following reviews the development of the subject of mass loss by stellar winds in the space age. As a unifying theme, we give special attention to the various dividing lines and boundaries on the Hertzsprung–Russell (HR) diagram that mark sharp changes in outflow properties associated with slight changes in stellar parameters. These boundaries were discovered mostly through space satellite surveys. Their locations on the HR diagram led to insight regarding the driving mechanisms, and the dependence of the winds on basic stellar properties such as effective temperature, surface gravity, and stellar rotation.

MASS LOSS FROM EARLY-TYPE STARS

In the late 1960s research was being carried out on stellar atmospheres theory regarding stars with a high luminosity-to-mass ratio, and hence near the stars' Eddington limit (Böhm and Deinzer 1965, Cassinelli 1970). Proximity to the Eddington limit was seen as a requirement for producing stars with extended density distributions which have scale heights comparable to the stellar radius. The rocket observations had begun to make it clear that the outer atmospheres of hot luminous stars are not hydrostatic, but are expanding at high velocities.

Lucy and Solomon (1970) wrote a ground-breaking paper that explained the high speed of the winds from hot stars. They showed that the same P-Cygni lines that had been used to recognize the outflow could be responsible for accelerating the winds to speeds of $v_\infty \sim 3000\,\mathrm{km\,s^{-1}}$, and that each strong line could drive a mass loss rate of $\dot{M} = L/c^2$, which corresponds to a total mass-loss rate of OB supergiants of about $\dot{M} \sim 10^{-8} M_\odot\,\mathrm{yr}^{-1}$. Furthermore, they showed that coronal wind theory could not explain both the high speeds and the low-ion stages observed through P-Cygni profiles. The basic theory of outflows driven by *selective absorption* of the continuum radiation in the shortward wing of the line opacity in an expanding atmosphere was originally developed in a sequence of papers by Saha (1919), Milne (1924, 1926), and Johnson (1925). This early interest in the acceleration of atoms was in part to find a mechanism to explain the heating of the solar chromosphere and corona.

Castor, Abbott, and Klein (CAK) (Castor *et al*. 1975, 1976) developed a powerful method to treat the effects of driving of an outflow by very large numbers of lines, which have a statistical distribution in line strengths. CAK theory led to predictions of mass-loss rates and terminal velocities as a function of stellar properties and the line statistics parameters. With the modifications by Friend and Abbott (1986), Pauldrach *et al*. (1986), and Kudritzki *et al*. (1989), CAK multi-line theory gives good agreement with observationally derived values of $\dot{M}$ and v_∞. In particular, strong winds could be driven by radiation alone, with no extra driving associated with mechanical energy deposition. Thus it was the expectation of the CAK theory that the wind temperatures would be cool, that is, about 80 to 90% of the star's effective temperature, as would be the case for an extended atmosphere that is in radiative equilibrium with the photospheric radiation field. Space observations showed evidence for a quite different temperature structure.

Superionization of hot star winds

The Copernicus satellite, launched by NASA in 1973, provided the first extensive set of data regarding winds from bright, hot stars. The spectra covered the far-UV region in the 1000 to 1450 Å band with very high resolution ($\lambda/\Delta\lambda = 10^4$). Among the most surprising discoveries was the presence of anomalously high ionization stages with broad, strong P-Cygni profiles. Lamers and Morton (1976) called this "superionization" in the winds, and two superionization lines are shown in Figure 1 (bottom). Doublets of O VI near 1040 Å and N V near 1240 Å were seen in the spectra of stars across the entire O star spectral sequence, and resonance lines of C IV and Si IV extended into the B spectral range (Snow and Jenkins 1977). The extent of these superionization zones with their well defined *dividing lines* on the HR diagram are shown in Figure 2. These ions are anomalous because they were not expected to be present in a gas photoionized by the stellar radiation field. Their presence indicated that that there was a problem regarding the temperature structure assumed in line-driven wind theory, and that an extra source of heating was present and a source for that was needed.

In the Copernicus observation of ζ Pup (O4 f) shown in Figure 1 (bottom), the profiles of the superionization stages are fully developed as saturated P-Cygni profiles. The nature of the profiles could be taken as good evidence that the ions O^{5+} and N^{4+} are present at all levels in the wind, not just near the base nor just far from the star where high speeds are reached. Initially the superionization was interpreted by Lamers and Morton (1976) by the "warm wind model." In this model superionization would be produced collisionally in a gas with a temperature above 10^5 K. Collisional ionization required that stars with O VI should have winds with temperatures of about 200,000 K. Lamers and Snow (1978) extended the warm wind idea to B supergiants which showed a lower stage of superionization (N V and C IV and Si IV), by using progressively lower wind temperatures such that $T_{\mathrm{wind}} \sim 80{,}000$ K for the later B supergiants.

Producing the warm wind temperatures required some sort of mechanical heating or wave-energy deposition. The amount needed was troubling, however. In the case of ζ Pup, the required mechanical luminosity was estimated to be about 10% of the radiative luminosity of the star. Such a large proportion of the luminosity is required because gases with temperatures near 2×10^5 K are near maximal efficiency for radiating away thermal energy. The mechanical flux required for ζ Pup was considered to be unacceptably large given that hot stars have no obvious source of wave energy such as an outer convection zone, so alternative solutions were sought.

At a workshop at JILA, Cassinelli, Castor and Lamers (1978) critically analyzed three models for explaining the superionization: Lamers' warm wind model, Cassinelli's "corona plus cool wind" model, and Castor's non-LTE model with a wind temperature of $\sim$60,000 K, which was dubbed the "tepid wind" model. In the corona plus cool wind idea, a geometrically thin corona with a temperature of a few million kelvins, at the base of the wind was postulated. The idea that a hot star could have a thin corona had been proposed by Hearn (1975). Some mechanical flux

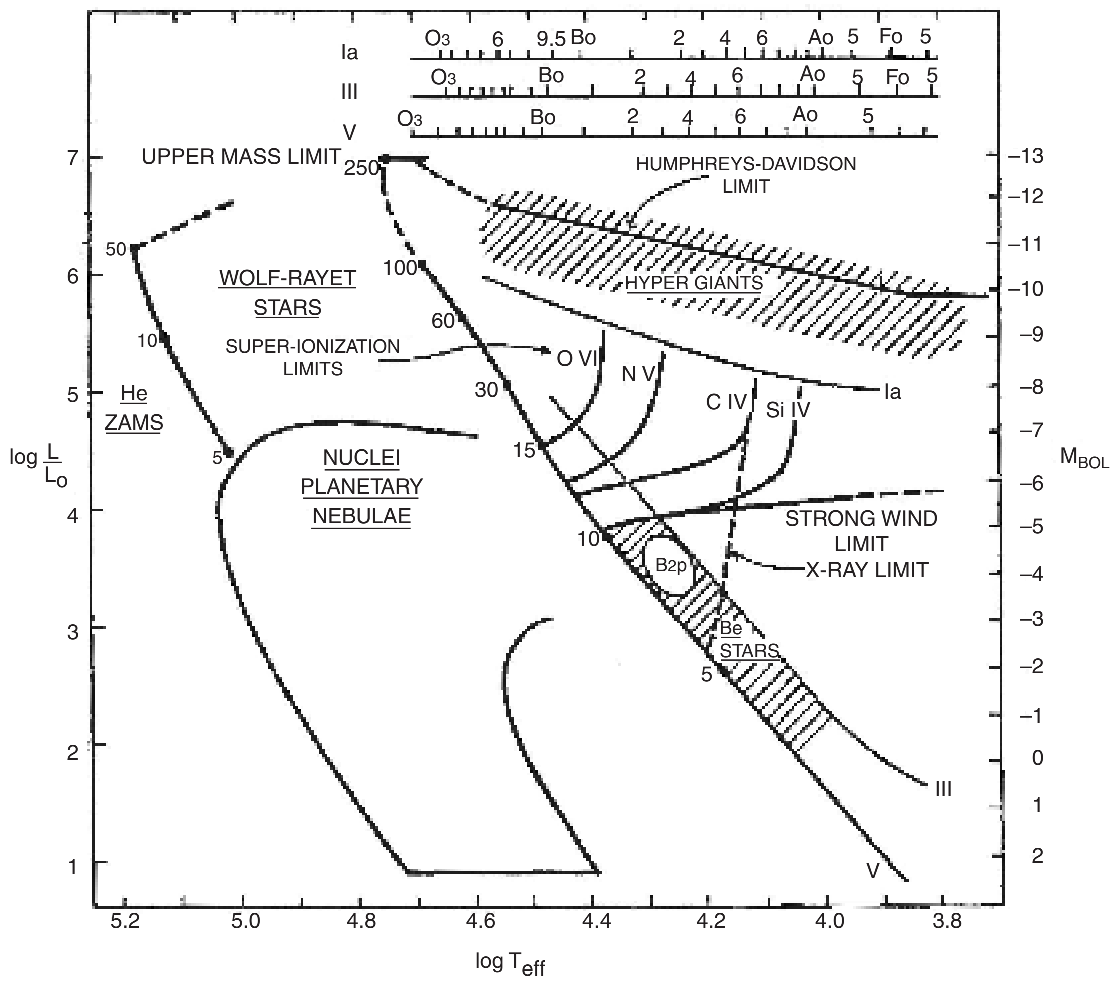

Figure 2 Regions and boundaries for hot stars in the HR diagram. The locations of various classes of stars with interesting mass-loss properties are shown. Of particular interest are the "superionization boundaries" of O VI, N V, C IV, and Si IV, which demarcate the range in effective temperatures of stars that show these high-ion stages. (From Cassinelli and Lamers 1987.)

from the star was invoked to produce the thin coronal region. However, the amount of mechanical flux would be orders of magnitude below that required by the warm wind model, because gas at million-degree coronal temperatures has a much lower emissivity than does warm gas. A corona would produce X-rays at energies beyond the K-shell edges of carbon, nitrogen, and oxygen, and the absorption of these X-rays in the cool wind above the corona could produce superionization. Castor showed that the photospheric radiation field of the O4f star ζ Pup could produce some O VI ions. However, the O VI line persists through the O spectral range to τ Sco at B0.5 V. This star has a much lower luminosity and effective temperature than ζ Pup (30,000 K *v.* 42,000 K). The non-LTE effect could not explain the O VI superionization at this low stellar temperature.

Cassinelli and Olson (1979) made use of the boundaries of the superionization on the HR diagram (Figure 2) to argue that the superionization is produced by the Auger effect, following X-ray photoionization by the star. If an X-ray is absorbed by an ion with fewer than 10 electrons, then *two* electrons are essentially always ejected from the ion (Daltabuit and Cox 1972). The X-ray photon ejects a K-shell electron, and then in the transition of an electron from the L shell to the K shell, a second electron is ejected. As a simple numerical consequence, if a wind has stage "n" as its dominant ion, Auger ionization will lead to an overabundance of the "n + 2" stage. Cassinelli and Olson (1979) argued that the O VI line should be present in winds for which O^{3+} is the dominant ion. The ion O^{3+} persists as the dominant stage for all of the O stars and extending as late as B0.5. Similarly, the UV line of N V should persist out to spectral type B2 I for which N^{2+} is the dominant ion stage, and C IV and Si IV can be produced to B8 I (Odegard and Cassinelli 1982). The mechanism involving X-rays thus

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