# INFERRING MASS LOSS RATES FOR COOL LUMINOUS STARS FROM HIGH-RESOLUTION GHRS SPECTRA

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**Abstract.** We discuss GHRS spectra of single and binary late-type stars and describe in detail the spectra of $\alpha$ TrA and of $\zeta$ Aurigae obtained at ten orbital phases. The wind properties of $\alpha$ TrA are derived using a complete redistribution radiative transfer code, and we describe the properties of a new code, PRISMA, that we are building to fit line profiles using partial redistribution in a spherically-symmetric geometry. The $\zeta$ Aur spectra show that the mass loss process is variable on the timescale of several months, the wind density structure does not repeat from orbit to orbit, and the wind ionization structure is complex.

## 1. Introduction

The rates at which stars lose matter to the interstellar medium play an important role in stellar and Galactic evolution. Mass loss can change stellar evolution when the mass loss time scale is comparable to the core evolution time scale or when the cumulative loss of mass is significant compared to the initial stellar mass. Both conditions can be important for O–type and Wolf-Rayet stars and for late-type stars near the tip of the asymptotic giant branch, the region of the HR diagram where the carbon star phenomenon begins. Here mass loss peels off the outer hydrogen-rich layers, revealing the carbon-rich inner layers where dredge-up processes have altered the initial chemical composition.

Understanding stellar mass loss is even more important for modeling the chemical evolution of the Galaxy, as the metal enrichment of the interstellar medium, out of which the next generation of stars will emerge, depends on both steady and explosive mass loss processes.

Despite the critical importance of stellar mass loss, empirical measurements of mass loss rates for individual stars are very uncertain and, except for the O–type stars, we lack an accepted theory of mass loss with predictive power. Mass loss rates have been inferred from free-free continuum radio and far-infrared emission, infrared dust emission, emission in CO and other molecular lines, and blue-shifted circumstellar absorption features in ultraviolet and optical resonance lines. For a review of these techniques, see Drake (1986) and Dupree (1986).

Here we summarize what the Hubble Space Telescope spectra are telling us about mass loss rates from late-type stars, and we describe a new code for inferring mass loss rates from the analysis of such high-resolution spectra. Our intention is to compute accurate mass loss rates for representative late-type stars with which one can derive a new mass loss rate prescription based on fundamental stellar parameters ($\dot{M} = f(L, M, R)$; e.g. Nieuwenhuijzen & de Jager 1990). Unfortunately, the emerging picture is that the phenomenology of mass loss is very complex and no simple mass loss formula may be realistic.

## 2. Representative GHRS Spectra

Since 1978, IUE has obtained spectra of the Mg II h and k lines in a large number of late-type stars of all luminosity classes with a spectral resolution $R = \lambda/\Delta\lambda \approx 10,000$. The IUE archive now contains high-resolution spectra of more than 400 G–M giants and supergiants. Robinson & Carpenter (1995) show representative examples of such spectra. IUE spectra of Fe II and O I lines are also useful for studying stellar winds.

Since 1990, the GHRS has obtained echelle spectra with the higher resolution ($R \approx 90,000$) needed to distinguish interstellar from wind absorption features and with the higher signal/noise needed to study the nearly black wind absorption features far to the blue of line center. Examples of GHRS spectra of such late-type stars as $\alpha$ Ori, $\gamma$ Cru, $\gamma$ Dra, and $\alpha$ Tau may be found in Robinson & Carpenter (1995) and Carpenter et al. (1995). The N–type carbon star UU Aur was also studied with the GHRS echelle (Johnson et al. 1995). The high spectral resolution of the GHRS data is especially useful in identifying circumstellar absorption by Mn I and Fe I that distort the Mg II profiles of cool supergiants like $\alpha$ Ori. Carpenter et al. (1995) find evidence for wind acceleration in $\gamma$ Cru from the increasing blueshift of absorption lines formed with increasing height.

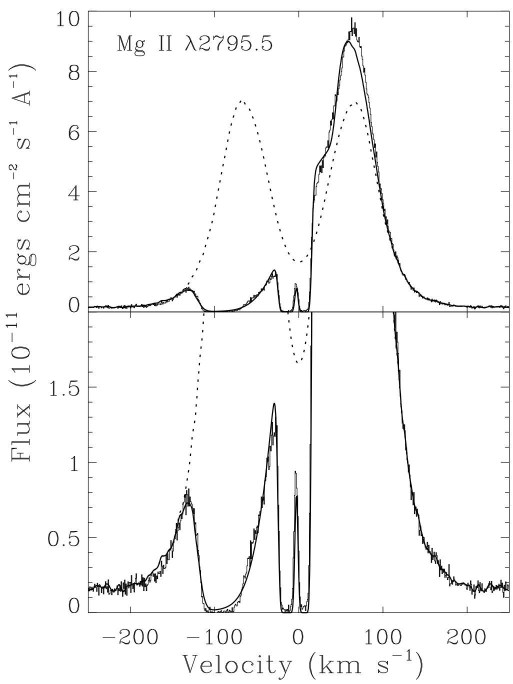


*Figure 1.* *Upper panel*: The observed $\alpha$ TrA echelle spectrum of the Mg II k line (noisy line), the assumed intensity profile at the base of the chromosphere (dashed line), and the best model fit (thick solid line). *Lower panel*: An enlargement of the lower portion of the line profile. From Harper et al. (1995).

## 3. Analysis of the GHRS Spectrum of $\alpha$ TrA

We cite here the analysis of an excellent GHRS echelle spectrum of the Mg II resonance lines that demonstrates what can be learned empirically about the wind properties of late-type stars. Harper et al. (1995) obtained very high quality spectra of the hybrid-chromosphere star $\alpha$ TrA (K4 II) (see Figure 1) that show the blue-shifted absorption and red-shifted emission (the so-called P Cygni line profile) characteristic of scattering in an optically thick, geometrically extended wind. The profile shows total extinction by the wind near $-100$ km s$^{-1}$ and absorption by the interstellar medium (two components near 0 km s$^{-1}$).

Harper et al. (1995) assumed the specific intensity at the base of the spherically-symmetric chromosphere (before the acceleration begins) and complete redistribution (CRD) of the scattered photons. They then solved the transfer equation for a two-level atom using an accelerated lambda interation scheme and the velocity law $V(R) = V_\infty(1 - R_\star/R)^\beta$, where $V_\infty$ is the wind terminal velocity and $\beta$ is an unknown parameter characterizing the scale length over which the wind acceleration occurs. Despite the physical and computational limitations of the analysis methodology, they obtained an excellent fit to the line profile with $\dot{M} \geq 1.8 \times 10^{-10}\ M_{\odot}\ \mathrm{yr}^{-1}$, $V_{\infty} = 100\ \mathrm{km\ s}^{-1}$, $V_{\mathrm{turb}} = 24\ \mathrm{km\ s}^{-1}$, and $\beta \sim 1$. These results indicate a much lower mass loss rate than some previous estimates (e.g. Hartmann et al. 1981) and a large nonthermal pressure gradient near the base of the wind where it is needed, although future analyses of P Cygni–like profiles will require computer codes based on more physically realistic assumptions. In particular, the spectrum at the base of the chromosphere must be determined self-consistently.

## 4. A New Radiative Transfer Code: PRISMA

The interesting wind parameters that emerged from our rather simplistic analysis of the $\alpha$ TrA Mg II resonance lines stimulated us to develop a new radiative transfer code to infer mass loss rates from GHRS and IUE spectra. Our review of existing codes identified a number of desirable characteristics that a code to study the winds of late-type stars should include:

($a$) *A physically accurate treatment of scattering.* For optically thick resonance lines like those of Mg II, most interactions between line photons and ions result in scatterings that are coherent in the atomic rest frame rather than collisional de-excitation or elastic scattering by collisions. Partial redistribution (PRD) codes include the physics of coherent scattering in the atomic frame, Doppler redistribution of the emitted photon due to the atom's motion, elastic scattering when collisions perturb the upper state of the transition, and photon destruction during the rare events when collisions lead to de-excitation before the atom can re-emit a line photon. PRD codes are especially important for analyzing the spectra of late-type stars since the wind velocities are usually only a few times the Doppler width. The Sobolev approximation, which is useful when there are large velocity gradients in the wind, is not usually valid for late-type stars.

($b$) *A realistic geometry.* The presence of P Cygni–type features (blue-shifted absorption and red-shifted emission) in the resonance line profiles of luminous late-type stars provides unmistakable evidence that the winds are geometrically extended compared to the stellar photosphere. Thus useful codes must be able to solve the transfer equation in spherical geometry. As we shall see, wind geometries for binaries are almost certainly more complex than axisymmetric.

($c$) *A multi-level atom.* Codes should solve the statistical equilibrium equations for multi-level atoms to properly include non-LTE ionization, recombination, and transitions between bound levels. The ionization equilibrium of important species should not be assumed constant, but computed in a self-consistent manner.

(*d*) *A self-consistent atmospheric model.* Rather than specifying a temperature/density structure, a code should derive semi-empirical thermodynamic parameters of the wind that best fit the line profiles.

(*e*) *Time-variability.* Since the time scales for ionization and recombination can be comparable to that of advection, codes should eventually include time-varying properties in the wind.

No existing radiative transfer code includes all of these desirable properties. For example, Drake & Linsky (1983) developed a PRD code that solves the transfer equation in the co-moving frame of the wind in a spherically symmetric extended atmosphere, but they used a pre-specified thermal structure, ionization, and velocity law for a two-level Mg II ion. They were able to show schematically the changes in a line profile when the wind velocity and atmospheric extension are varied. Using this code, Drake (1985) showed that the wind of Arcturus (K2 III) observed in the Mg II line is very extended and estimated a mass loss rate of $2 \times 10^{-10}$ $M_\odot$ yr$^{-1}$. Hartmann & Avrett (1984) developed a code using an approximate escape probability formalism that led to an estimated mass loss rate of $1.4 \times 10^{-6}$ $M_\odot$ yr$^{-1}$ for $\alpha$ Ori (M2 Iab), but they could not fit the shape of the Mg II lines well. Luttermoser et al. (1994) analyzed IUE spectra of the M6 III star g Her using the PANDORA code with the partial coherent scattering approximation to PRD, but they considered the atmosphere to be static and plane-parallel with an expanding circumstellar envelope.

We have therefore developed a new radiative transfer code PRISMA (Partial Redistribution In Spherical Moving Atmospheres) that rests on the heritage of the MULTI code written by Carlsson (1986). MULTI handles departures from LTE in multi-level atoms well, but it is written for a plane-parallel geometry and does not include PRD. MULTI has already been modified to include PRD (Uitenbroek 1989) and spherical geometry (Harper 1994) separately, but the new code will include both. We are now testing a preliminary version of PRISMA that solves the transfer equation in the observer's frame using the PRD technique developed by Uitenbroek (1989) and a global Scharmer operator (Scharmer & Carlsson 1985). This version of the code will be revised later to the co-moving frame with a different PRD technique (e.g. Hubeny & Lites 1995).

## 5. The Ugly Truth about Mass Loss from Real Stars: $\zeta$ Aur

The true complexity of stellar mass loss begins to emerge when one dissects a wind using an empirical probe. We are now analyzing GHRS spectra of the $\zeta$ Aur eclipsing binary system (K4 Ib + B5 V) observed at ten orbital

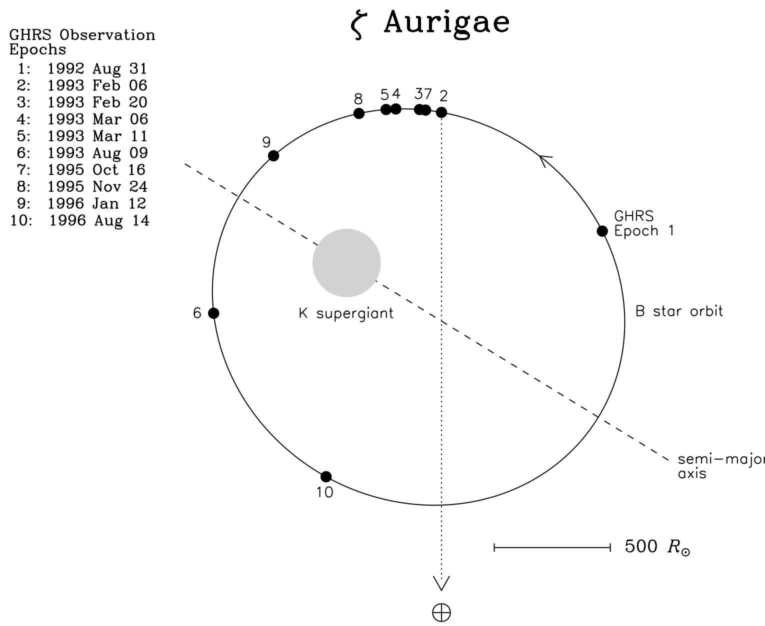


*Figure 2.* The orbit of $\zeta$ Aurigae drawn to scale. The positions of the secondary at the GHRS observation epochs are indicated, and the semi-major axis and the direction of the line of sight from the Earth are also shown. The size of the K supergiant primary is shown to scale, but the actual size of the B star secondary is much smaller than indicated in this diagram.

phases. We initiated this intense observing campaign to exploit the slow passage of the small B star behind the K supergiant, which provides an excellent UV–bright searchlight with which to probe the physical properties of the K star wind. Figure 2 shows the circumstances of these observations that extend over two orbits ($P_{\rm orb} = 972^{\rm d}$).

Analysis of the UV spectrum of the B star, optical spectra of the K star, Mark III optical long-baseline interferometry, and eclipse photometry led Bennett et al. (1996) to derive very precise values for the stellar and orbital parameters of the system. Comparison of these parameters with stellar evolution models indicates an age of $(80 \pm 15) \times 10^6$ yr if the initial abundances are solar. Thus the K star ($M = 5.8 \pm 0.2\, M_\odot$, $R = 148 \pm 3\, R_\odot$) probably lies near the tip of the red giant branch.

The GHRS spectra include lines of Fe II, Ni II, S II, Si II, and Al II. Typically one sees absorption from ions in the K star wind superimposed on the B star continuum and broad emission from B star photons scattered in the wind (Baade et al. 1996). Figure 3 shows the spectrum at epoch 1. Analysis of each spectrum leads to the column density for each ion as a function of velocity and then to the inferred hydrogen column density $N_{\rm H}(v)$ through

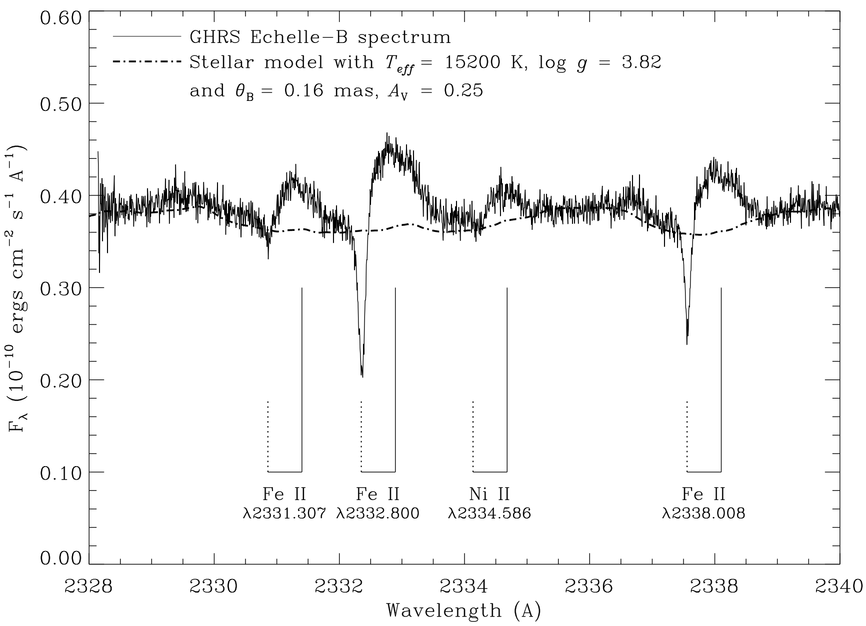


*Figure 3.* The spectrum of $\zeta$ Aurigae B observed with the GHRS Ech-B at epoch 1. A synthetic spectrum of the photosphere of the B star has been superimposed to illustrate the extent of the emission in the wind lines of Fe II and Ni II. This spectrum was computed using the TLUSTY and SYNSPEC codes of Hubeny (1988). The synthetic spectrum has been shifted by the radial velocity of the B star at epoch 1 (+30.6 km s$^{-1}$). The lines of Fe II and Ni II are shown at the systemic velocity of the $\zeta$ Aur system (+12.2 km s$^{-1}$, Griffin 1995) as a solid line, and at the terminal wind velocity of –70 km s$^{-1}$ relative to systemic as a dotted line.

the K star wind for each line of sight. The shapes of these columns differ from one phase to another, leading to the following conclusions:

(*a*) *The ionization structure in the wind is complex.* Some lines of sight show little or no Fe II at certain velocities. A schematic model in which the second ionization of Fe occurs in two regions — an ionized spherical volume around the B star, and an ionized spherical shell around the K star — can qualitatively account for the observed column density structure. At epoch 1, the Fe II ionization shell about the K star is very large, extending out to 45 K–star radii. At closer lines of sight, the outer boundary of the Fe II ionization shell moves in to about 8–10 K–star radii. Sulfur and silicon remain mostly singly ionized throughout the wind.

(*b*) *The properties of the wind are time-dependent.* This is shown by the different column densities at epochs 3 and 7, which are at the same orbital phase but are one orbit apart. At epoch 3 the column density peaks near 0 km s$^{-1}$ (near the radial velocities of both stars) with a smaller peak near $-70$ km s$^{-1}$, whereas at epoch 7 the column density peaks near $-65$ km s$^{-1}$ with no absorption near 0 km s$^{-1}$. The $N_{\rm H}(v)$ column density at epoch 1, which samples a line of sight where the wind is near terminal velocity, is fit by a mass loss rate of $8.0\times10^{-9}$ $M_\odot$ yr$^{-1}$ and a terminal velocity of 70 km s$^{-1}$. However, the column densities observed at epochs 2 and 3, which sample the wind much closer to the stellar surface, are consistent with a mass loss rate reduced by factors of 3–5 from that of epoch 1. We conclude that while the shape of the observed column density structure $N_{\rm H}(v)$ is consistent with a spherical wind with $\dot{M} = 8.0 \times 10^{-9}$ $M_\odot$ yr$^{-1}$ and $v_\infty = 70$ km s$^{-1}$, variations in the mass loss rate by up to a factor of 5 occur on a timescale of months. The column density structure does *not* repeat from orbit to orbit, suggesting that intrinsic mass loss variability is an important effect. Observations during the next orbit are needed to further quantify the extent and timescale of the wind variability.

Thus the commonly used assumptions of time-independent, homogeneous ionization winds are inconsistent with the $\zeta$ Aur data. Future studies of stellar winds should be guided by this ugly truth.

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## References

Baade, R., Kirsch, T., Reimers, D., Toussaint, F., Bennett, P.D., Brown, A. & Harper, G.M. 1996, *ApJ*, 466, 979
Bennett, P.D., Harper, G.M., Brown, A. & Hummel, C.A. 1996, *ApJ*, 471, 454
Carlsson, M. 1986, Uppsala Astron. Obs. Report No. 33
Carpenter, K.G., Robinson, R.D. & Judge, P.G. 1995, *ApJ*, 444, 424
Drake, S.A. 1985, in *Progress in Stellar Spectral Line Formation Theory*, ed. J.E. Beckman and L. Crivellari (Reidel), p. 351
Drake, S.A. 1986, in *Cool Stars, Stellar Systems, and the Sun*, ed. M. Zeilik and D.M. Gibson (Springer-Verlag), p. 369
Drake, S.A. & Linsky, J.L. 1983, *ApJ*, 273, 299
Dupree, A.K. 1986, *Ann. Rev. Astron. Astrophys.*, 24, 377
Griffin, R.F. 1995, private communication
Harper, G.M. 1994, *MNRAS*, 268, 894
Harper, G.M., Wood, B.E., Linsky, J.L., Bennett, P.D., Ayres, T.R. & Brown, A. 1995, *ApJ*, 452, 407
Hartmann, L. & Avrett, E.H. 1984, *ApJ*, 284, 238
Hartmann, L., Dupree, A.K. & Raymond, J.C. 1981, *ApJ*, 246, 193
Hubeny, I. 1988, *Comp. Phys. Comm.*, 52, 103
Hubeny, I. & Lites, B.W. 1995, *ApJ*, 455, 376
Johnson, H.R. et al. 1995, *ApJ*, 443, 281
Luttermoser, D.G., Johnson, H.R. & Eaton, J.A. 1994, *ApJ*, 422, 351
Nieuwenhuijzen, H. & de Jager, C. 1990, *A&A*, 231, 134
Robinson, R.D. & Carpenter, K.G. 1995, *ApJ*, 442, 328

Scharmer, G. B. & Carlsson, M. 1985, *J. Comp. Phys.*, 59, 56
Uitenbroek, H. 1989, *A&A*, 213, 360

## Discussion

**Whitelock**: As you have said, "pulsation is important," and we find, from IR observations, that low-mass, large-amplitude pulsators lose mass at between $10^{-7}$ and $10^{-4}$ $M_\odot\,\mathrm{yr}^{-1}$. These are the mass-loss rates that modify stellar evolution, enrich the interstellar medium, and give us C stars. Is there a possibility of your applying the very impressive techniques you have described to these stars?

**Linsky**: Our objective is to use our new radiative transfer code to derive mass-loss rates for all types of stars for which there will be high quality data, including AGB stars with high mass-loss rates. Unfortunately these high-mass-loss-rate stars will be difficult to analyze as a result of complex circumstellar absorption by other lines superimposed on the resonance lines that we are studying, and the mass loss will likely be asymmetric and time-dependent. It is therefore prudent to start with the simpler cases, such as giants with small mass-loss rates like Arcturus. Once we are confident that the code is debugged and provides reliable results, we will proceed on to the more difficult and interesting cases.

**Little–Marenin**: Given the complexity of the $\zeta$ Aur system, do you think we will be able to make some general statement about winds and mass-loss rates of stars in general?

**Linsky**: We have no alternative but to try to generalize the results that come from our study of $\zeta$ Aur and other binary systems. The ability to observe a K supergiant wind in absorption against a bright point source that moves behind the K star is an extraordinary opportunity that must be exploited. At the same time one must not forget the added complexities introduced by a binary companion — ionization of the K star's wind by the B star, interaction of the two winds that can lead to a shock front, changed gravitational field, and perhaps other effects.

**Luttermoser**: Do you want to speculate on what mechanism drives the winds of these stars?

**Linsky**: What acceleration mechanisms drive winds in different types of stars remains an open question despite many years of theoretical and observational studies. I think that mechanical energy input from pulsations and acoustic or magnetoacoustic waves probably plays a major role for most late-type giants and supergiants, but other mechanisms (e.g. thermally-driven winds, dust, and perhaps radiation pressure on molecules and atoms) probably also contribute to the acceleration somewhere in the flow. It is important to include multiple acceleration processes.

**Feast**: Has anyone attempted to observe wind characteristics spectroscopically from the white dwarf companion to Mira Ceti?

**Linsky**: Not to my knowledge, but this would be an interesting observing program.