The Giant Star Ca II Ionization Problem: Mass Loss Revisited

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Abstract. Pioneering studies of winds from non-coronal evolved late-type stars were plagued by uncertainties in the Ca ionization balance which severely limited the accuracy of derived mass-loss rates. Here we re-examine the Ca II ionization balance in these stellar winds using FUSE spectra which reveal, for the first time, the flux from the photoionizing radiation field shortward of 1045Å. We present a FUSE 912-1185Å spectroscopic survey of evolved late-K and M stars; including the M giants α Cet (M1.5 III), γ Cru (M3.5 III), β Gru (M4.5 III), and R Dor (M8e III). Using FUSE spectra of α Tau (K5 III), supplemented with partial redistribution calculations of H Ly-α and Ly-β, together with UV and radio data, we present a study of α Tau's wind ionization balance and derive new constraints which place the mass-loss rate significantly below that suggested by the Reimers formula.

1. Introduction

Mass loss from cool giants and supergiants is important for understanding the chemical evolution of the Galaxy. Stellar winds return nuclear-processed material from the dredge-up phases back into the ISM where it becomes available for the next generation of stars. Mass loss is also important for the stellar evolution of intermediate and massive stars; in particular, it controls the frequency of supernovae, and the amount of iron-peak and r-processed elements returned to the ISM. Mass-loss rates for late-type stars are, however, very difficult to determine, and the mechanisms that drive mass loss are poorly understood.

Early optical studies of mass loss from cool stars relied heavily on the Ca II H & K wind absorption features as diagnostics. It was soon realized, however, that calcium exists as Ca III in the inner wind. Also at that time the UV ($1200 < \lambda(\text{Å}) < 3200$) and FUV ($912 < \lambda(\text{Å}) < 1200$) photoionizing radiation fields were essentially unknown, and this led to an inherent uncertainty in derived mass-loss rates. Since 1978, IUE and HST have provided UV spectra for cool stars, but the photoionizing flux for the Ca II $4s\,^2S$ ground state $\lambda < 1044$Å remained unknown until the *Far Ultraviolet Spectroscopic Explorer* (FUSE) provided a window into the FUV.

2. FUSE Observations

Surprisingly few FUSE observations of non-coronal evolved late-type stars have been made, and most of these are from FUSE programs by the authors. The spectra presented here (Table 1) were retrieved from the Multimission Archive at Space Telescope, re-calibrated with CalFUSE v2.1.6, and custom extracted. Figure 1 shows the LiF 1000-1185Å spectra where the stellar signal and FUSE sensitivity are highest, for the sample of K and M giants - R Dor shows no significant signal. These spectra were obtained during orbital night when the airglow and geocoronal emission is weak. Surface fluxes are computed using the angular diameters adopted in Table 1. (Bedding, Robertson, & Marson 1994; Bedding et al., 1997; Mozurkewich et al., 1991.)

Table 1.   FUSE Sample of Non-Coronal Evolved Late-Type Stars.
UD-uniform, LD-limb darkened disk. †More observations scheduled.

Star	Spec. Type	Angular Diam. (mas)	Exposure (ksec)	FUSE ID
α Tau	K5 III	21 LD	12	P1040901
α Cet	M1 III	13 LD	10†	C0230303
γ Cru	M3 III	23 UD	23	B0680101
β Gru	M5 III	27 UD	21	C0230101
R Dor	M8 III	57 UD	38†	C0230203

A prominent feature in the SiC channels is the C III 977Å resonance line, which is observed as late as M3 III (γ Cru). The most prominent emission features in the LiF channels are the forest of narrow lines between 1106-1150Å, first observed in ORFEUS SPAS-II spectra by Dupree & Brickhouse (1998). Most lines were identified from high S/N and R~ 18,000 FUSE spectra by Harper et al. (2001) as fluorescent Fe II pumped by H Lyα from the excited $(a\,^4D)$ term. The rise in the chromospheric continuum shortward of 1100Å marks the C I ^3P ground state edge. The photoionization of the Ca II ground state is controlled by the C I continuum and H Lyβ (λ1026Å). An early discovery with FUSE was the detection of collisionally excited O VI (λ1032, λ1038Å), a proxy for coronal emission, in α Tau (K5 III). There are features close to these wavelengths in γ Cru (M3 III), however, there are other unidentified features in the structured continuum and identification is ambiguous.

3. Ca II/Ca III Ionization Balance

To re-evaluate the mass-loss rates derived from optical studies of Ca II wind absorption features, we first quantify the Ca II/Ca III ratio. Two routes for photoionization of Ca II are H Lyβ and the C I continuum from the ground state,
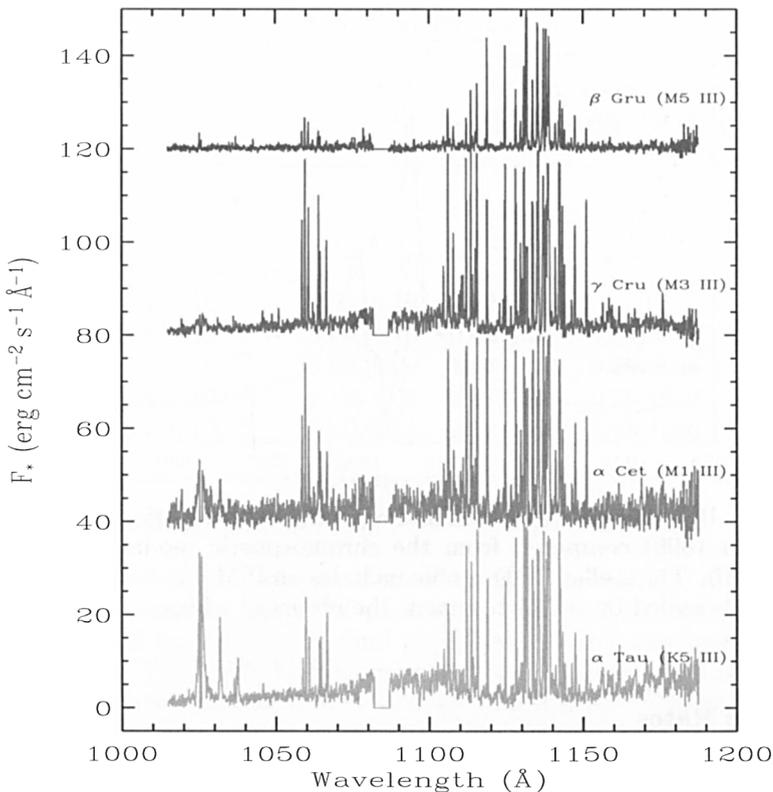
Figure 1.   FUSE orbital night LiF spectra for the K and M giants, plotted as surface fluxes (each offset by 40). The break in data near 1080Å is from the space between the detector segments. The strongest fluorescent Fe II emission lines between 1106-1150Å have been clipped for clarity. These lines and the Cr II lines near 1060Å are pumped by H Lyα from excited levels, and hence appear shortward of 1215Å. The rise shortward of C I continuum edge at 1100Å is clearly seen.

and H Lyα from the metastable $3d^2D$ term - both Lyman lines lie just shortward of the bound-free edges. To obtain photoionization rates the H Lyman profiles must be reconstructed to remove the effects of the ISM and geocoronal emission. Figure 2 shows α Tau's H Lyβ profile and a scaled PRD line profile computed (Sim 1999) from the detailed chromospheric model of McMurry (1999).

The photoionization cross-section edge for the metastable term is $6.1 \times 10^{-18} \, cm^2$ at 1218Å which is a factor of 30 greater than for the ground state at 1044Å (Norcross, in Shine & Linsky, 1974). For α Tau the photoionization rate from the metastable level is ∼7000 times that of the ground state. In the cool low density giant winds, the metastable level is populated by the scattering of chromospheric Ca II H & K photons into the infrared triplet, and by direct photospheric pumping by the forbidden lines at 7291 & 7324 Å. H Lyα is extremely effective in ionizing Ca II to Ca III even in the cool winds of M giants.
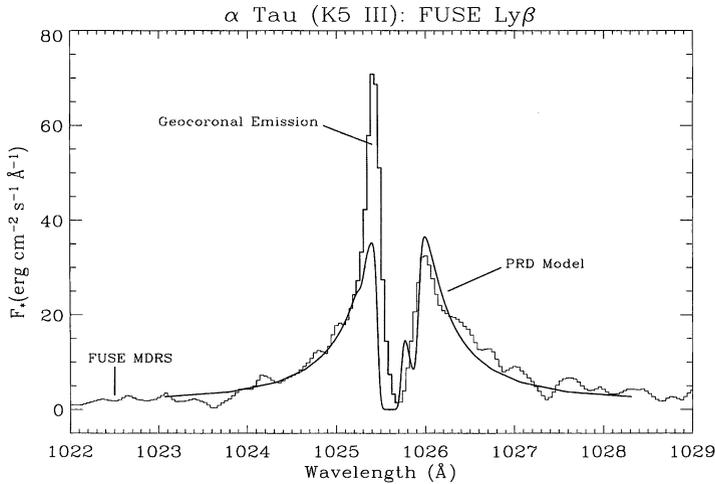
Figure 2. H Lyβ profile of α Tau and a partial redistribution (PRD) profile (Sim 1999) computed from the chromospheric model of Mc-Murry (1999). The stellar PRD profile includes an ISM and wind+ISM model and is scaled by $\times 1.15$ to match the observed wings.

4. Mass-Loss Rates

K5 III marks the onset of circumstellar (CS) Ca II H & K absorption amongst giant stars, and α Tau provides a test-case to establish the mass-loss rates required for CS Ca II H & K to be detectable. In α Tau the CS features are variable and not always present (Reimers 1977); when present they can have optical depths of $\tau \sim 0.5$. To the simplest approximation the following parameters are required to describe the formation of Ca II H & K CS features:
(1) Ca II photoionization rates; (2) $V(R)$ wind velocity as a function of radius;
(3) $\dot{M}$ mass-loss rate; (4) $T_e = T_e(R_0)(R_0/R)^p$ parameterized wind temperature;
(5) $x = n_{HII}/n_H$ hydrogen ionization at the base of the flow.

For α Tau, FUSE and HST spectra now tightly constrain (1); Robinson, Carpenter & Brown (1998) have derived estimates for (2) and (3) ($1.4 \times 10^{-11}\,M_\odot\mathrm{yr}^{-1}$: P Cygni models), and (4) is weakly constrained by wind absorption features in Fe II line profiles and cm-radio observations. The Ca II/Ca III balance at the wind base is set by (1), (4), and (5).

Using these data, the optical depth for the Ca II K CS line is computed for different initial values of x at $R = 1.2 R_*$. For the low mass-loss rate indicated for α Tau the hydrogen ionization is *frozen-in*, so that the electron density is a function of $\dot{M}$ and x. Adopting an excitation temperature for the metastable term of $T_{exc} = 4000$ K: $y = n_{C\,II}/n_C \ll 0.01$ and $n_{C\,II}/n_{C\,III} \ll 1$. Using analytical solutions for steady advection for the H and Ca ionization balance we compute the maximum optical depth (τ_λ) for the Ca II K CS line, shown in Table 2, for two different values of the wind cooling parameter p. The solutions show that y slowly increases with radius showing no sharp change reminiscent of a distinct shell.

Table 2.   Maximum τ_λ Ca II K CS feature for different initial hydrogen ionization fractions with $T_{exc} = 4000\,\mathrm{K}$. Data pairs for different T_e models: p=1.33/0.50. Note $T_{exc} = 3000\,\mathrm{K}$ gives similar results.

Mass-loss Rate $M_\odot\,\mathrm{yr}^{-1}$	$x(1.2R_*) = n_{HII}/n_H$			
	0.1000	0.0100	0.0010	0.0001
1.4×10^{-11}	0.94/0.32	0.12/0.03	0.01/–	–/–
2.8×10^{-11}	3.06/1.16	0.46/0.14	0.04/0.01	–/–
5.6×10^{-11}	8.62/3.90	1.74/0.54	0.19/0.06	0.02/0.01
1.1×10^{-10}	20.6/11.6	6.32/2.08	0.75/0.22	0.08/0.01
2.2×10^{-10}	44.0/29.5	21.2/7.69	2.95/0.88	0.31/0.09

5.   Discussion

FUSE observations allow us, along with a reconstruction of the H Lyβ profile, to tightly constrain the FUV photoionization radiation field. Along with UV spectra of H Lyα the Ca II wind ionization problem can now be quantitatively addressed. For a CS K feature with $\tau \sim 0.5$ acceptable solutions from our simplified treatment have $\dot{M} \sim (0.1/x)^{1/3} \cdot 1.4 \times 10^{-11}\ M_\odot\mathrm{yr}^{-1}$ (Table 2).

Our findings can be summarized as: (a) In α Tau's steady wind Ca II does not form in a well defined shell. (b) Formation of Ca II CS features with discrete absorption near the terminal velocity requires an outward decrease in temperature. (c) The mass-loss rates required for Ca II CS features may be larger than derived from P-Cygni profiles. However, these values are an order of magnitude lower than those extrapolated from Reimers mass loss formula. New constraints on the hydrogen ionization at the base of the wind are required to further restrict the range of possible $\dot{M}$ solutions.

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