HST/GHRS Observations of Cool, Low-gravity Stars. VI. Mass-loss Rates and Wind Parameters for M Giants

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Abstract

The photon-scattering winds of M giants absorb parts of the chromospheric emission lines and produce self-reversed spectral features in high-resolution Hubble Space Telescope (HST)/GHRS spectra. These spectra provide an opportunity to assess fundamental parameters of the wind, including flow and turbulent velocities, the optical depth of the wind above the region of photon creation, and the star’s mass-loss rate. This paper is the last paper in the series “GHRS Observations of Cool, Low-Gravity Stars”; the last several have compared empirical measurements of spectral emission lines with models of the winds and mass loss of K giants and supergiants. We have used the Sobolev with Exact Integration radiative transfer code, along with simple models of the outer atmosphere and wind, to determine and compare the wind characteristics of the two M-giant stars, γ Cru (M3.5III) and μ Gem (M3IIIab), with previously derived values for low-gravity K-stars. The analysis specifies the wind parameters and calculates line profiles for the Mg II resonance lines, in addition to a range of unblended Fe II lines. Our line sample covers a large range of wind opacities and, therefore, probes a range of heights in the atmosphere. Our results show that μ Gem has a slower and more turbulent wind than γ Cru. Also, μ Gem has a weaker chromosphere, in terms of surface flux, with respect to γ Cru. This suggests that μ Gem is more evolved than γ Cru. Comparing the two M giants in this work with previously studied K-giant and supergiant stars (α Tau, γ Dra, and λ Vel) reveals that the M giants have slower winds than the earlier giants, but exhibit higher mass-loss rates. Our results are interpreted in the context of the winds being driven by Alfvén waves.

Key words: instrumentation: high angular resolution – stars: chromospheres – stars: individual (mu Gem, gamma Cru) – stars: late-type – stars: mass-loss – techniques: imaging spectroscopy

1. Introduction

The mass-loss from evolved stars such as red giant, red supergiant, and asymptotic giant branch (AGB) stars, contributes substantially to the chemical enrichment of the universe (Habing & Olofsson 2003). In the cooler, more evolved stars such as AGB stars, the mass loss is driven by an interplay of pulsation that extends the atmosphere, dust formation, and radiation pressure acting upon the dust grains that eventually leads to a stellar wind (for a comprehensive discussion on the topic, see, e.g., Höfner et al. 2003 for the theoretical modeling or Lopez et al. 1993; Danchi et al. 1994; Rau et al. 2015, 2017; Rau 2016; Wittkowski et al. 2018) for the comparison to, e.g., interferometric data for objects of various chemistry). In comparison, the chromosphere plays a more critical role in the mass-loss process in warmer stars, such as red giants and supergiants (Linsky 2017).

Chromospheres and winds are the signature of all cool stars with spectral types later than F5. Evolved stars, unlike main-sequence stars, have chromospheres that are more bloated, with slower and more massive stellar winds. Chromospheres are affected by the mechanical energy flux imparted from the photosphere, and the winds of giant stars are driven by acoustic and magnetic waves generating in those environments (Charbonneau & MacGregor 1995; Verdini & Velli 2007; Airapetian et al. 2015). Earlier studies (e.g., Linsky & Ayres 1978) on the radiative cooling from emission lines, including H I Lyα, Mg II, and Ca II lines enhanced our knowledge of the mechanism that drives the mass loss of giant stars, and enabled further studies of the physical phenomena in the chromospheres. This study includes measurements of the surface fluxes of Mg II and Fe II lines (see Section 4.2).

This paper is the last one of a series “GHRS Observations of Cool, Low-Gravity Stars.” Two of the previous papers (e.g., Robinson et al. 1998; Carpenter et al. 1999) compared empirical measurements of high-resolution UV spectral emission lines recorded with Hubble Space Telescope (HST)/GHRS with theoretical models to examine the winds and mass loss of K-giant and supergiant stars (α Tau, γ Dra, and λ Vel) reveals that the M giants have slower winds than the earlier giants, but exhibit higher mass-loss rates. Our results are interpreted in the context of the winds being driven by Alfvén waves.

The present work completes the series of HST/GHRS studies. We extend the analysis to include two M-giant stars: γ Cru (M3.5III) and the slightly more luminous μ Gem (M3IIIab). This allows us to study the dependence of the wind and mass loss on spectral type and surface temperature by comparison with the previously studied stars, in addition to surface gravity and luminosity by mutual comparison of the objects analyzed in this paper. Gamma Cru and μ Gem are substantially cooler than the K5 stars in the previous studies, but both have sufficiently high effective temperature and low luminosity to allow us to use the SEI (Lamers et al. 1987) methodology. This paper aims to finalize the analysis of the HST/GHRS data; provide an initial analysis of the last remaining data set from that program, utilizing similar techniques for a fair comparison with the preceding studies; present a summary for all of the objects in the series. We would like to stress that sophisticated magnetohydrodynamic (MHD) modeling is the next logical step to enhance our knowledge of these objects, but this purpose is beyond the objectives of this paper.
Mu Gem is a long-period variable star of M3IIIab spectral type. It has a V-band magnitude of 2.87 (Ducati 2002), at a distance of 71.02 ± 0.05 pc (van Leeuwen 2007). Gamma Cru is a M3.5III type star, with a V-band magnitude of V = 1.64 (Ducati 2002) at 27.15 ± 0.55 pc (van Leeuwen 2007). The location of the two analyzed M-stars in the Hertzsprung–Russell diagram is shown in Figure 1, which includes evolutionary tracks from Marigo et al. (2013) for various stellar masses, as well as the K-stars previously studied in this program. The error in luminosity in Figure 1 is assumed to be ∼40% based on the distance uncertainty, while the temperature errors are estimated through the standard propagation of error.

For each star the observations taken with the HST and the data reduction techniques are shown in Section 2. Section 3 describes the modeling techniques, and Section 4 presents the results and the stellar parameters derived from our modeling. These results are discussed and used to provide constraints on theoretical models of wind acceleration and mass loss in Section 5; lastly, Section 6 presents our conclusions.

2. Observations and Data Reduction

We have analyzed UV spectra of two late-type M-giant stars, γ Cru and μ Gem, obtained with the GHRS on board the HST in GTO Programs 1195 and 4685. The observed spectra are summarized in Table 1. They cover selected regions in the 2300–2850 Å wavelength range that contain a wide variety of chromospheric emission lines of, e.g., Mg II and Fe II, which show overlying wind absorption features.

We have in hand, for comparison, GHRS spectra and analytic results from our previous studies of the warmer noncoronal giant α Tau (K5III), the hybrid K giant γ Dra (K5III), and the K4Ib supergiant λ Vel. The observations of the two K-giant stars are described in Robinson et al. (1998) and the K-supergiant in Carpenter et al. (1999).

For the two targets of the present study, we use a similar approach. To summarize, we used the Small Science Aperture for these observations to optimize the fidelity of the UV line profiles and the precision of the measured radial velocities. Dedicated wavelength calibration exposures of the onboard platinum lamps (WAVECALS) were obtained close in time to each of the stellar observations to allow us to determine the dispersion coefficients and absolute wavelengths of each of the stellar observations to an accuracy of better than 0.3 diode widths, corresponding to about 3 km s⁻¹ in the medium resolution (R = λ/Δλ = 25,000) observations and about 0.5 km s⁻¹ in the high-resolution (R = λ/Δλ = 80,000) observations. We divided long exposures into a series of subexposures, each with an integration time of 10 minutes or less to further reduce the effects of thermal drifts and geomagnetic interactions within the spectrograph (see Soderblom et al. 1993). These exposures were used during the data reduction process to measure and correct for any such drifts within the spectrograph.

The CALHRS routine developed by the GHRS Investigation Definition Team was used to reduce and calibrate the observations. This program merges the individual samples into a single spectrum, subtracts background counts, and corrects for...
nonlinearities in detector sensitivity. It then corrects for vignetting and the echelle blaze function and applies an absolute flux calibration (Soderblom et al. 1993). The program used the WAVECAL exposures associated with each science observation and obtained at the same grating carousel position, to produce the optimal wavelength calibration. The separate subexposures at a given wavelength were then cross-correlated and coadded to produce the optimal wavelength calibration. The separate subexposures at a given wavelength were then cross-correlated and coadded to produce the final spectra. We compared these calibrated spectra to the most recent calibrated spectra in the MAST archive and did not find any differences significant enough to impact the measurements and conclusions reported in this paper.

3. Modeling UV Emission Lines as Wind Diagnostics

This paper utilizes two techniques to derive wind parameters, both using Mg II λ 2796, 2803 and a large number of Fe II transitions formed at different heights in the stellar atmosphere. First, we use a parameterized fitting procedure of the lines to obtain flow velocities for the emission and the superimposed absorption components. This technique is explained in Section 3.1 and the results are discussed in Section 4.1. Second, we use an SEI model (Lamers et al. 1987) to derive wind parameters such as v∞, v turb, and mass-loss rates. The SEI model is explained in Section 3.2 and its results in Section 4.2.

3.1. Empirical Measures of Wind Parameters

Photon-scattering winds of cool, low-gravity stars produce absorption features in the strong chromospheric emission lines. The strength and shape of these wind absorptions are sensitive to the wind opacity, turbulence, and flow velocity. Complementing this, the wings of the emission features, which are not affected by wind absorption, can be used to measure the velocity of the line photon creation region. Self-absorptions extend further to the blue of line center in lines of higher opacity, because the last photon scatterings in the more opaque lines occur at higher altitudes, where the accelerating wind is flowing faster than in the weaker lines. Thus, by examining a set of Fe II and Mg II self-reversed lines of different strength, with a set of transitions representing a range of optical depths, we can map the acceleration of the stellar wind.

The shifting wavelengths of the wind absorptions relative to the emission peaks, and the changes in relative strengths of the emission peaks, reflect the acceleration of the wind above the chromosphere. Figure 2 shows examples of such Fe II lines in the spectra of the two M giants.

The emission line measurements for μ Gem and γ Cru are presented in Table 2, including the calculated relative optical depth, which is proportional to the line center optical depth. Following Judge (1986) and Carpenter et al. (1995, 1999), the optical depth τ rel is calculated at T = 6000 K. In this way, we can compute a relative optical depth scale, which allows us to order lines according to the actual optical depth of the Fe II lines in the wind (see Carpenter et al. 1999). The Gaussian fits are used, rather than integrating the line profile, to characterize the chromospheric flux, and of the amount of wind absorption. The wind is assumed to be a pure-scattering medium to estimate the emission and absorption fluxes. The properties of the unreversed emission lines were determined by fitting a single Gaussian to the observed line profile.

The parameters of the fit provide estimates of the integrated flux, width, and radial velocity of the line; for the self-reversed lines, we adopted an empirical model to parameterize the line. In this model the lines wings are represented by a Gaussian profile that is validated by the quality of the fits. The transition core reversal is assumed to be formed in an overlying reversing layer. The parameterized line modeling has an advantage over a simple multiple Gaussian fit in that it allows fitting optically thick lines where the wind absorption dominates the line profile. This is necessary to parameterize the stronger emission lines in which the central intensity approaches zero. The derived accuracy of the measured radial velocities is 0.5–3 km s−1, where the spread reflects the degree of line blending.

As is the case for other noncoronal stars, the stronger self-reversed lines are better fit using two absorption components: one strong component with a significant blueshift, and a second, weaker, redshifted component. We have used the fits to measure the radial velocity of the emission and absorption components of the chromospheric lines. The uncertainty in a typical measurement of the absolute radial velocity of an individual line in a medium-resolution GHRS data frame is about 4 km s−1, including fitting uncertainties (∼2 km s−1) and uncertainty in the absolute wavelength calibration of a single GHRS data frame (∼3 km s−1). When more lines and/or more than a single GHRS...
spectrum are used, the uncertainties are reduced according to:

\[ \sigma_v = \sqrt{\left(\frac{3.0}{\sqrt{N_1}}\right)^2 + \left(\frac{2.0}{\sqrt{N_2}}\right)^2} \text{ km s}^{-1}, \]

where \( N_1 \) and \( N_2 \) are the number of used spectra and measured transitions, respectively. Thus, if the lines are within a single data frame, and thus subject to the same uncertainty in zero-point of the wavelength scale, the minimum uncertainty, even with many lines is \( \sim 3 \text{ km s}^{-1} \). If the lines are spread over multiple data frames with different zero-point errors, the uncertainty is significantly reduced. The errors in the relative velocities of lines within a single spectrum are in the order of 0.5 km s\(^{-1}\). We measured the surface flux, by fitting emission and absorption Gaussian profiles to the lines. Results are discussed in Section 4.1.

### 3.2. Semi-empirical Modeling of the Wind Using the SEI Formalism

Semi-empirical models of chromospheres (for example, in α Tau) were developed by McMurry (1999). To more precisely characterize the wind we model the UV line profiles using the 1D SEI code Lamers et al. (1987) to solve the radiative transfer in a homogeneous, spherically expanding atmosphere using the Sobolev approximation and explicitly including large-scale turbulence.

The code requires the input of the turbulent velocity in the envelope \( (v_{\text{turb}}) \) assumed constant with height, the wind velocity relation \( v/v_\infty = (1 - R_e/R)^3 \) characterized by the acceleration parameter \( \beta \), the optical depth of the modeled line as a function of the velocity, \( \tau_\nu \), the opacity of the wind in each line, the collisional term (if any) in the source function, the underlying photospheric spectrum, and a lower boundary condition, i.e., a chromospheric profile input to the base of the wind.

We use the SEI approximation to compute line profiles for the wind absorptions seen over bright chromospheric emission lines and adjusted the input parameters to get the best fit to the observed line profiles. In addition to the very strong Mg II resonance lines, we have a carefully selected a set of Fe II lines to sample a wide range of opacities and, hence, heights in the wind. The advantage of the SEI code is that it allows investigations of a broad range of parameters. It is difficult to simultaneously fit all of the lines...
presented with the same set of parameter values, and one converges to a relatively narrow range of wind parameters; $\beta$, $v_{\text{turb}}$, and $v_{\infty}$ are accurately derived in each case. When comparing the predicted lines with the observed line profiles, the physical parameters are derived from the line fitting. Our results are presented in Section 4.2. The SEI program does not solve the statistical equilibrium equations in the wind and, therefore, the optical-depth relation needs to be specified as input. For examples of applications of the SEI method on winds of O-stars and of planetary nebulae, see, e.g., Perinotto et al. (1989); Groenewegen & Lamers (1989).

Assumptions regarding wind temperatures, ionization ratios, and elemental abundances and, the mass-loss rates can be estimated from the inferred wind optical depths, adopting Equation (29b) from Olson (1982):

$$M = 8.70 \times 10^{-19} \mu \tau (v_{\infty} = 0.5) 
\times \left( \frac{x}{\omega} \right) \frac{dU}{dx} \frac{v_{\text{turb}}^2 R_e}{f \lambda_{\text{if}} A_{\beta} g e^{-q}}$$

where $x = R/R_e$, $\omega = v(r)/v_{\infty}$, and $q = E_l/kT$. While $I$ is the ionization fraction, $A_{\beta}$ is the elemental abundance relative to hydrogen, $g$ is the statistical weight, $f$ the oscillator strength, $E_l$ is the lower energy level of the transition, $U$ is the partition function, and $\lambda_{\text{if}}$ is the central wavelength of the spectral line (in Å); for further details, see Carpenter et al. (1999).

4. Results

4.1. Wind Parameters via Empirical Measurements

Figure 3 shows the measured velocities of the chromospheric emission and of the self-absorption as a function of line opacity for the two M-stars in this study. The opacity is used as a proxy for the atmospheric height. The measured first and second absorption components are listed in Table 2 (see also Carpenter et al. 1995). The monotonic increase (with relative optical depth) of the blueshift of the dominant absorption component reflects the acceleration of the outflowing wind. The weaker, redshifted, absorption component shows a redshift that increases with optical depth. The interpretation of this feature is ambiguous and depends on the geometry of the atmosphere. In the geometrically thin (i.e., plane-parallel) case, it represents an inflow of material; but if the formation region is very spherically extended, the feature could be caused by a simple monotonically increasing outflow, because the fluxes at these wavelengths would then be formed in regions preferentially behind the plane through the center of the star in the sky. Questions thence arise concerning the redward absorption components, as to the effects of occultation of photons by the

| Table 2 | Fe II Measurements for $\gamma$ Cru and $\mu$ Gem |
|---------|-----------------------------------------------|
| $\lambda_{\text{if}}$ (Å) | Multiplet | $\tau_{\text{rel}}$ | $RV_{\text{em}}$ (km s$^{-1}$) | $RV_{\text{abs1}}$ (km s$^{-1}$) | $RV_{\text{abs2}}$ (km s$^{-1}$) | $F_{\text{abs1}}$ (erg cm$^{-2}$ s$^{-1}$) | $RV_{\text{em}}$ (km s$^{-1}$) | $RV_{\text{abs1}}$ (km s$^{-1}$) | $RV_{\text{abs2}}$ (km s$^{-1}$) | $F_{\text{abs2}}$ (erg cm$^{-2}$ s$^{-1}$) |
|---------|-----------------|------------------|------------------|------------------|------------------|------------------|----------------|------------------|------------------|------------------|
| $\gamma$ Cru | | | | | | | | | | | |
| 2231.307 | 35 | 614.4 | 0.0 | −13.5 | 6.8 | 523.8 | −5.0 | −11.0 | 9.6 | 303.2 |
| 2332.800 | 3 | 2733.0 | 0.6 | −13.4 | 9.7 | 590.4 | −5.1 | −12.8 | 4.9 | 266.1 |
| 2338.008 | 3 | 1562.7 | −1.0 | −13.3 | 8.4 | 868.7 | −6.5 | −11.0 | 8.3 | 358.5 |
| 2354.889 | 35 | 214.0 | −1.7 | −8.9 | ... | 352.2 | −5.9 | −9.7 | 10.5 | 141.9 |
| 2362.020 | 35 | 477.7 | −0.6 | −8.3 | ... | 553.4 | ... | ... | ... | ... |
| 2364.825 | 3 | 1948.1 | 1.4 | −11.9 | 11.8 | 355.9 | ... | ... | ... | ... |
| 2366.593 | 35 | 273.9 | 2.6 | −7.6 | ... | 326.4 | ... | ... | ... | ... |
| 2485.076 | 34 | 4.52 | 2.9 | ... | ... | 85.7 | ... | ... | ... | ... |
| 2508.338 | ... | 0.0 | 1.4 | ... | ... | 84.6 | ... | ... | ... | ... |
| 2585.876 | 1 | 3952.0 | 0.2 | −13.2 | 12.0 | 753.5 | ... | ... | ... | ... |
| 2591.542 | 64 | 228.3 | 2.6 | −6.8 | 9.7 | 299.1 | −0.9 | −5.3 | 10.2 | 118.0 |
| 2598.369 | 1 | 4425.1 | 3.7 | −10.7 | 13.1 | 529.2 | −1.0 | −11.4 | 7.7 | 258.0 |
| 2599.395 | 1 | 13534.0 | 3.3 | −14.3 | 11.4 | 1038.9 | −1.2 | −11.5 | 9.9 | 302.1 |
| 2607.086 | 1 | 3557.0 | 1.4 | −11.9 | 10.9 | 478.5 | −2.3 | −10.0 | 12.9 | 194.1 |
| 2613.825 | 1 | 2018.8 | ... | ... | ... | −1.3 | −9.9 | 9.4 | 76.8 |
| 2617.618 | 1 | 1380.3 | −0.1 | −10.8 | 12.0 | 687.6 | −3.8 | −8.1 | 11.7 | 230.2 |
| 2619.075 | 171 | 0.0 | ... | ... | ... | −1.5 | −0.3 | ... | ... | ... |
| 2621.669 | 1 | 488.9 | 3.9 | −10.7 | 8.7 | 188.2 | 1.5 | −9.7 | 7.3 | 84.2 |
| 2625.664 | 1 | 1754.3 | −0.3 | −12.5 | 8.1 | 915.4 | −5.4 | −10.5 | 9.6 | 361.4 |
| 2628.291 | 1 | 1559.9 | 6.1 | −11.9 | 8.4 | 354.9 | ... | ... | ... | ... |
| 2732.441 | 32 | 1.5 | 1.5 | ... | ... | 390.0 | ... | ... | ... | ... |
| 2736.968 | 63 | 194.1 | −0.2 | −8.0 | 9.4 | 824.5 | −2.7 | −4.2 | ... | 293.8 |
| 2739.545 | 63 | 1738.1 | 2.0 | −11.7 | 8.9 | 1779.6 | −4.2 | −9.2 | 9.8 | 601.6 |
| 2741.395 | 260 | 0.0 | 1.9 | ... | ... | 87.3 | −2.2 | ... | ... | 25.4 |
| 2755.733 | 62 | 2172.2 | 1.7 | −12.6 | 8.4 | 2770.2 | ... | ... | ... | ... |
| 2759.336 | 32 | 1.3 | 0.7 | ... | ... | 281.4 | −2.4 | ... | ... | 70.3 |
| 2761.813 | 63 | 83.4 | 0.7 | −6.7 | 5.0 | 765.8 | −2.9 | −10.7 | 0.9 | 177.5 |
| 2772.719 | 63 | 21.6 | 2.7 | ... | ... | 167.9 | −2.6 | ... | ... | 54.7 |
| 2775.339 | 32 | 0.6 | 0.2 | ... | ... | 192.8 | −2.6 | ... | ... | 45.5 |
| 2861.168 | 61 | 0.8 | ... | ... | ... | 0.6 | ... | ... | ... | 91.8 |
| 2868.874 | 61 | 6.2 | ... | ... | ... | 0.2 | ... | ... | ... | 195.3 |

Note.
$^a$ The listed opacities are taken from Carpenter et al. (1995).
stellar disk and whether the feature is really absorption or just a lack of emission. Detailed transfer calculations in spherical geometry are needed to answer these questions. Such transfer calculations are beyond the intent of this paper and raise additional questions in themselves because they will be extremely sensitive to the adopted microturbulence and flow profiles. We intend to pursue such calculations in a later paper. In this paper, we present our interpretation based on the assumption that the geometrical effects are minimal. In this case, the amount of the material involved in the downflow is substantially less than that in the upflow, as indicated by its much weaker absorption line strength. This would suggest that there may be a circulation pattern superposed on the dominant outflow and that some of the material initially accelerated in the lower regions of the wind does not reach escape velocity and later returns toward the surface.

As for the previously studied K-stars the mean velocity of the emission is approximately at rest with respect to the photosphere, while the mean outflow velocity of the wind absorptions increases with opacity. This indicates that the line photons are created in a region at rest with respect to the star, below the region of the wind acceleration.

We do not see the acceleration in its early stages because the wind absorptions in the weak lines, which could sample those low altitudes (velocities), have insufficient total opacity. Table 2 shows the results of those fits.

Fitting emission and two absorption Gaussian profiles to the lines, and calculating velocities for the center of the Gaussian profiles, we derived net integrated surface flux values by subtracting the two absorption components from the emission integrated flux. We calculated extinction factors following Cardelli et al. (1989) and using values of $A_v$ and $R_v$ from Gontcharov & Mosenkov (2018). For $\mu$ Gem those are $A_v = 0.22$, $R_v = 2.99$; while for $\gamma$ Cru they are $A_v = 0.16$, $R_v = 3.09$. To calculate the surface fluxes we adopt angular diameter values of: 24.7 mas for $\gamma$ Cru (Glindehmann et al. 2001), while for $\mu$ Gem we used an average of the limb-darkened values from the CHARM2 catalog: $\theta_{LD} = 13.45$ mas (Richichi et al. 2005). Results of the surface fluxes calculations are presented in Table 2 for the two investigated stars.

Table 3 lists the basic parameters of the program and compare stars along with two empirical measurements of the wind speed, the maximum velocity from line center at which wind absorption is seen in any line in the spectrum, and the

| Star       | Type     | $T(\text{K})$ | $L(L_\odot)$ | log $g$ | $R (R_\odot)$ | Max $V_{\text{abs}}$ (km s$^{-1}$) | Mean $V_{\text{abs}}$ (km s$^{-1}$) |
|------------|----------|---------------|--------------|---------|---------------|----------------------------------|----------------------------------|
| $\alpha$ Tau | K5 III   | 3898 ± 30     | 394 ± 15     | 1.25    | 44            | 40                               | 1–25                             |
| $\gamma$ Dra | K5 III   | 3985 ± 45     | 535 ± 25     | 1.50    | 49            | 80                               | 5–50                             |
| $\lambda$ Vel | K5 Ib   | 3820         | 7943         | 0.64    | 210           | 60                               | 10–25                            |
| $\mu$ Gem  | M3 IIIab | 3675         | 2754         | 1.5     | 230.4         | 25                               | 6–14                             |
| $\gamma$ Cru | M3.4 III | 3689         | 758          | 2.00    | 120           | 25                               | 13–60                            |

Notes.

* The $V_{\text{abs}}$ is a measure of the $V_{\text{esc}} + V_{\text{surf}}$ in the wind if lines of sufficient opacity.
* The $V_{\text{abs}}$ is the centroid of the wind absorption features—the range reflects that observed for lines of different opacity.
* Robinson et al. (1998).
* Primary (low-velocity) wind component.
* Secondary (high-velocity) wind component.
* Carpenter et al. (1999).
* Wood et al. (2016).
* Mallik (1999).
* Massarotti et al. (2008).
* Calculated with the Stefan–Boltzmann law.
* McDonald et al. (2017).
* During the majority of observational epochs (normal wind).
* During strong/high-opacity wind epoch (April 1978).

The increase in the mean velocity of the wind absorption with increasing line opacity reinforces that observed for lines of different opacity.

![Figure 3](image-url)
range of mean velocities seen in lines of different strength throughout the spectrum. The radius of \( \mu \) Gem is given by applying the Stefan–Boltzmann law \((L = 4\pi R^2\sigma T^4)\) to the ratio of luminosities of \( \mu \) Gem/\( \gamma \) Cru, consequently \( R_{\mu \text{Gem}} = 230.4 \ M_\odot \) and \( R_{\gamma \text{Cru}} = 120.0 \ M_\odot \).

4.2. SEI Fits to HST/GHRS Spectra

The method of the SEI fit described in Section 3.2 was applied to the HST/GHRS data of \( \mu \) Gem and \( \gamma \) Cru. Figures 4 and 5 show a sample of SEI fits to emission lines in \( \mu \) Gem and \( \gamma \) Cru, respectively.

The dependence of the wind velocity versus height and the opacity versus velocity for various values of the wind acceleration parameter \( \beta \) are shown in Figure 6. The parameters of the fit to each emission line are given in Table 4 for \( \mu \) Gem and \( \gamma \) Cru.

From the fits, we are able to estimate the wind parameters, listed in Table 5, inferred from our SEI modeling of the complete set of lines, for both the program and comparison stars (see modeling description in Section 3.2).

SEI models of the outflowing winds indicate that \( \mu \) Gem has, in general, a weaker wind, in terms of turbulent and terminal velocity, than \( \gamma \) Cru. This is consistent with expectations, given the higher surface gravity and lower luminosity class of \( \mu \) Gem (see Rau 2018).

Our results show that for \( \mu \) Gem the wind opacity in each self-reversed emission line is significantly smaller than in \( \gamma \) Cru. Also, the turbulent velocity in the wind is smaller in \( \mu \) Gem (9 km s\(^{-1}\)) versus \( \gamma \) Cru (14 km s\(^{-1}\)). The same is true for the terminal velocity: 11 km s\(^{-1}\) in \( \mu \) Gem versus 19 km s\(^{-1}\) in \( \gamma \) Cru; and for the corresponding mass-loss rate: \( 7 \times 10^{-11} M_\odot \) yr\(^{-1}\) for \( \mu \) Gem versus \( 45 \times 10^{-11} M_\odot \) yr\(^{-1}\) for \( \gamma \) Cru (see Table 5).

Table 6 compares the mass-loss rate calculations resulting from the present work, and from other techniques, with the findings of earlier spectral-type K giants \( \alpha \) Tau, \( \gamma \) Dra, and \( \lambda \) Vel. This comparison shows that the winds from K giants are much faster and terminal wind velocities of K giants are greater by a factor of two. However, the rate of wind acceleration is comparable (\( \beta = 0.6 \) versus 0.7) in the two stars. The measurements suggest that M giants have slower but more massive winds.

5. Discussion

5.1. Winds and Stellar Parameters

Several observational studies have demonstrated the important role of Alfvén waves propagating in the lower solar
atmosphere to deliver the energy to the corona, as observed by Jess et al. (2009).

Verdini et al. (2010), Vasheghani Farahani et al. (2012), and Suzuki (2007, 2013) demonstrated the importance of propagation and dissipation of waves in the solar coronal heating through turbulent cascade of Alfvén waves; however, this mechanism is not at work in cool, evolved stars, as the surface gravity of the Sun is much higher than for M-giant stars. These papers indeed predominantly describe the wind acceleration features due to turbulent heating caused by counter-propagating Alfvén waves in solar coronal loops and do not address the wave dissipation and chromospheric heating. Airapetian et al. (2000, 2010, 2015) have shown that winds from late-type giant stars can be successfully modeled via Alfvén waves driving acceleration, due to the propagation of waves in partially ionized atmosphere, and their reflection in the gravitationally stratified atmospheres.

Therefore, to understand the difference in wind dynamics in μ Gem and γ Cru, we need to examine the atmospheric properties of these two stars. As shown in Table 3, effective temperatures $T_{\text{eff}}$ of both observed stars are similar, while
μ Gem is 3–4 times more luminous than γ Cru, suggesting that its surface area is correspondingly larger. Thus, if both stars generate winds at the same efficiency, then the mass-loss of μ Gem should be expected to be 3–4 greater than for γ Cru. However, Table 5 indicates that the wind of μ Gem is a factor of 6 weaker. This suggests that, assuming a spherically symmetric wind, the wind mass-loss rate per unit surface area of μ Gem is a factor of 20 smaller than for γ Cru.

The chromospheric thickness of μ Gem, determined from its pressure scale height $H$, given by $H \propto T_\text{eff}/g$, is a factor of 3 larger than in γ Cru. Thus, the characteristic frequency of acoustic waves generated at the atmosphere, which scales as $\nu_\text{sc}/H$, is correspondingly 3 times lower.

A possible mechanism of Alfvén wave excitation at the wind base is acoustic shocks that dissipate and heat the stellar chromosphere (see, e.g., Judge & Coutz 1993). As the Alfvén waves propagate upward in the atmosphere, μ Gem experiences reflections at much lower heights in the atmosphere, and drive slower winds at lower speeds, compared to γ Cru. Since the amplitudes of upward propagating waves increase as $\rho^{-4}$, they are expected to be correspondingly smaller, as lower frequency waves get reflected from lower heights. This is consistent with the measurements of nonthermal broadening of Fe II intercombination chromospheric lines (see Table 5).

While detailed MHD modeling is required to reproduce the mass-loss rates, turbulent, and terminal wind velocities implied from observations (G. Rau et al. 2018, in preparation), our HST/GHRS observations can be interpreted within the framework of the Alfvén wave driven winds, as shown in Figure 7 (see Airapetian et al. 2010). Alfvén waves that drive stellar winds are generated at the top of the chromosphere by acoustic shocks. The latter are formed due to photospheric convection and/or pulsation mechanisms in evolved K- or M-giant stars. Alfvén waves are efficiently dissipated well below the top of the stellar chromosphere where the wind acceleration is initiated. From our measurements of the surface fluxes, the chromosphere is stronger in γ Cru than in μ Gem.

5.2. Robustness of SEI Modeling

Examples of our line fits in the HST/GHRS spectra of μ Gem and γ Cru are shown in Figures 4 and 5 and discussed in Section 4.2. The figures show that we are able to obtain good fits to lines with different opacity with a self-consistent set of wind parameters. The fits constrain $\beta$ to ±0.2, the $\nu_\text{sc}$ to ±2 km s$^{-1}$, the turbulence to ±5 km s$^{-1}$, and the mass-loss rates to about ±30 %. However, the line opacity is difficult to constrain, in particular, for high-opacity, often saturated, lines.

The validity of the SEI modeling to cool giant and supergiants has been assessed by comparison with comoving frame CRD calculation and is discussed in Carpenter et al. (1999). Their comparison shows that the SEI profiles are a good approximation over the entire line profile up to $\beta \approx 1$. At a higher value of $\beta$ the SEI profiles are still sufficiently accurate compared to observed profiles outside the red wing of the line cores.

The advantage of the SEI code is that it is computationally fast and allows a much more efficient initial exploration of wind parameter space. The primary assumptions/limitations of the SEI technique are a uniform wind temperature; the treatment of the wind as a pure-scattering medium (and thus the assumption that all the emerging photons are created in the chromosphere below the initiation of the wind flow); and a two-level approximation for the transitions. The impact of the latter appears minimal when fitting normalized profiles, especially in the wind absorption region as shown in Carpenter et al. (1999). We assume a $\beta$ power velocity law, no photon creation in wind, and spherical symmetry.

The uniform wind temperature may preclude application to M-supergiants and to the coolest giants (see, e.g., Carpenter et al. 1999). Indeed, the uniform wind temperature and the treatment of the wind as a pure-scattering medium are true for the K-stars and the M giants considered here. But we cannot extend this to higher luminosities in the M supergiants, because their winds appear to begin their acceleration well-within the region of photon creation. Any attempt to push the application
of the SEI technique too far quickly becomes evident, as it is not possible to fit the full variety of Fe II and Mg II lines seen in the 2200–3200 Å spectrum with a consistent set of wind parameters.

The two analysis techniques presented in this paper are complementary, and we do not use them to derive and estimate the same parameters. The empirical measurements do not depend on a model, but are direct measures. The SEI modeling, on the other hand, is needed to estimate the mass-loss rate (which we cannot measure directly) and to derive a more detailed estimate of the detailed shape of the wind flow versus height/opacity. Indeed, the straight line measurements, as done in the empirical modeling, average over a range of opacities/heights for each line/data point and does not permit that.

5.3. Comparison with Previous Works

For the two stars studied in the present work, μ Gem and γ Cru, a comparison of computed and observed UV emission line profiles containing overlying wind absorption indicate that the line photons are created in a region approximately at rest with respect to the photosphere. The winds are rather rapidly accelerating (β ≲ 1), with turbulent velocities of 10–20 km s⁻¹, and terminal velocities of 20–30 km s⁻¹ (for the noncoronal stars) and 67 km s⁻¹ (for the hybrid star). The mass-loss rates are of 10⁻¹⁰ M₀ yr⁻¹ for the K giants α Tau and γ Dra, 4 × 10⁻¹⁰ M₀ yr⁻¹ for the M giants μ Gem and γ Cru, and 3 × 10⁻⁹ M₀ yr⁻¹ for the K supergiant λ Vel. Table 6 shows that the λ Vel mass-loss rate is consistent with the previous optical upper limit, but disagrees with the current radio model for all stars, the derived mass-loss rates are within about an order of magnitude of the Judge & Stencel (1991) semi-empirical relation, but widely discordant with the Kudritzki & Reimers (1978) relation.

6. Conclusions

In this paper we studied the two M-giant stars μ Gem and γ Cru, modeling their chromospheric contribution with two approaches: empirical modeling and SEI modeling. We derived their wind parameters, and note that μ Gem has a higher mass and luminosity, a lower surface gravity, and a weaker wind and chromosphere than γ Cru, suggesting that μ Gem is the more evolved star.

If we consider the surface flux as a measurement of the strength of the chromosphere, we can conclude that the chromosphere of γ Cru appears stronger in comparison to μ Gem.

We compared the results of the present work with previous ones on different type (K-giant and supergiant) stars (see Section 5). We observe that for the two M giants in this study, the terminal velocity of the wind is slower than in the earlier giant stars, but the mass-loss rate is considerably higher.

To understand the full dynamics of those winds, simulations of the chromospheric heating mechanism are necessary. We are thus planning to implement a more sophisticated modeling (G. Rau et al. 2018, in preparation), using parameters derived with the SEI modeling as starting point for MHD calculations, and new HST/STIS data (e.g., Carpenter et al. 2018 for STIS data on μ Gem).

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Software: CALHRS, SEI (Lamers et al. 1987).

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