Empirical Constraints on Wind Flows and Turbulence from HST Observations of Cool Giants and Supergiants

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Abstract.
Observations of UV emission lines from the chromosphere and wind of cool giant and supergiant stars taken with the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST) are used to obtain empirical constraints on the macroturbulence and plasma flow velocities in their outer atmospheres and to directly measure the acceleration of their stellar winds. The disk-averaged chromospheric macroturbulence is on the order of 25 km s\(^{-1}\) in the giant stars and about 35 km s\(^{-1}\) in the supergiant and carbon stars. In the giants the mean outflow averages 4-10 km s\(^{-1}\) but a weak return flow (circulation pattern) may also be occurring. In the supergiant, the mean outflow is about 5 km s\(^{-1}\). The winds are seen accelerating from initial velocities of 3-9 km s\(^{-1}\) to upper velocities of 15-25 km s\(^{-1}\) in the noncoronal stars and up to 70 km s\(^{-1}\) in the hybrid star \(\gamma\) Dra. Examples of the line profiles used in this analysis are shown and the results to date for each star in our sample are presented.

1. Introduction

UV spectra of K-M giant and supergiant stars have been acquired with the GHRS on the HST to measure chromospheric flow and macroturbulence velocities, study the acceleration of their stellar winds, acquire constraints on the outer atmospheric structure of such stars, and provide data needed to understand the radiative line transfer in these atmospheres. In this paper, we present the results to date from our observations and analysis of the velocity fields in the outer atmospheres of the giant stars \(\alpha\) Tau, \(\gamma\) Dra, \(\gamma\) Cru, and \(\mu\) Gem, the supergiants \(\alpha\) Ori and \(\lambda\) Vel, and the carbon star TX Psc. The differences seen, especially between the giants and the supergiant, are highlighted. This work has been done in collaboration with R. Robinson (all programs), H. Johnson et al. (carbon stars \& \(\mu\) Gem), and A. Brown et al. (\(\gamma\) Dra).

2. Observations

The data for this analysis consists of medium (G270M) or high resolution (Ech-B) GHRS spectra of 1) the C II (UV 0.01) intercombination lines near 2325 Å (all targets), 2) a set of mid-UV Fe II lines with a range of intrinsic strengths...
(α Tau, γ Cru, μ Gem, λ Vel, and α Ori), and 3) the O I (UV 2) lines near 1304 Å (γ Dra and α Tau). The names and types of all the stars in our sample are given later in Table 1, together with a summary of the results.

3. Chromospheric Macro turbulence

We estimate the disk-averaged chromospheric macro turbulence from the width of the C II] lines, which suffer negligible opacity broadening but are much broader than the expected thermal doppler width of about 6 km s⁻¹. We characterize these line profiles by fitting a single Gaussian to them and using the FWHM of that Gaussian as a measure of the macro turbulence. A sample of the C II] data is shown in Figure 1a, which presents two of the five emission lines from the UV 0.01 multiplet as seen in the K giant α Tau, the M supergiant α Ori, and the carbon star TX Psc. The lines are considerably narrower in the giant star than in the other two. This is true for the rest of the sample as well, with the giants exhibiting a macro turbulence of about 25 km s⁻¹ and the supergiants and carbon star a value near 35 km s⁻¹. Although the line ratios within the multiplet differ from star to star due to differences in electron density, the profiles are very similar, except in the case of TX Psc, where the 2325.4 Å lines is severely mutilated by overlying absorption due to Fe I UV 13 at 2325.32 Å on the blue side of line center and another unknown absorption on the red side of the profile. The former absorption line leads to fluorescent emission in the Fe I UV 45 line near 2807 Å—a feature seen only in the carbon stars (Johnson et al. 1995). The macro turbulence measured for each star in our sample is given in Table 1. When G270M data are used the measured widths are corrected for the line-spread-function of the grating (FWHM ≈ 13 km s⁻¹).

4. Chromospheric Flows and Wind Acceleration

We have measured mean chromospheric flow velocities for both the C II] data discussed above and for a sample of Fe II lines. For the C II] lines, we simply use the shift of the central wavelength of the fitted Gaussian relative to the stellar radial velocity as a measure of that flow. The Fe II lines are more complex, with most of them suffering substantial opacity broadening and self-absorption. We have therefore characterized the Fe II profiles by fitting them with a combination of a single emission Gaussian on which is superposed one or more absorption Gaussians to represent the self-absorptions and/or interstellar absorptions (where relevant). For the Fe II lines we therefore obtain mean flow velocities for both emission and absorption components.

The appearance of one of the stronger Fe II lines, the UV 1 line near 2586 Å, in three stars is shown in Figure 1b. In the M giant γ Cru, there are two distinct absorption components (one on each side of the emission line center) superposed on the emission component. These are displaced by roughly the same velocity from line center, but the blue-shifted component is much stronger. We assume the blueshifted component is due to absorption by the outflowing stellar wind. The redshifted component could be due to an inflow (return flow) of some material which is not fully accelerated to escape velocity, or it could be a radiative transfer feature created by a variation in turbulence with height (Ensman and
Figure 1. C II] and Fe II profiles in cool, low gravity stars.

Figure 2. Fe II profiles vs. line center optical depth.
Johnson (1995). In the M-supergiant, only one (blue-shifted) absorption is seen and the emission is much stronger and broader than in the giant. In the K-supergiant λ Vel, the profile is even more complex. We have fit it here with four superposed absorption components, but the profile suggests a nearly continuous blur of absorptions indicating much stronger velocity gradients in the regions where the self-reversals are formed than are present in any of the other stars in our sample. The center of the various absorption components are indicated on the plot by thick vertical lines.

Table 1. Measured Macroturbulence, Mean Flow Velocities and Wind Acceleration for Cool Giants and Supergiants (in km s\(^{-1}\)).

<table>
<thead>
<tr>
<th>Star</th>
<th>Type</th>
<th>Mean C II Turb.</th>
<th>Mean C II Flow</th>
<th>Mean Fe II Emiss. Flow</th>
<th>mean Fe II blue-shifted abs. flow</th>
<th>mean Fe II red-shifted abs. flow</th>
<th>wind accel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ Dra</td>
<td>K5 III hyb</td>
<td>24</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0-70</td>
</tr>
<tr>
<td>α Tau</td>
<td>K5 III</td>
<td>24</td>
<td>4</td>
<td>2</td>
<td>-4</td>
<td>14</td>
<td>2-25</td>
</tr>
<tr>
<td>μ Gem</td>
<td>M3 IIa</td>
<td>23</td>
<td>-3</td>
<td>-3</td>
<td>-10</td>
<td>8</td>
<td>9-13</td>
</tr>
<tr>
<td>γ Cru</td>
<td>M3-4 III</td>
<td>27</td>
<td>2</td>
<td>2</td>
<td>-10</td>
<td>10</td>
<td>7-14</td>
</tr>
<tr>
<td>30 Her</td>
<td>M5 III</td>
<td>26</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>λ Vel</td>
<td>K4 Ib-II</td>
<td>34</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>α Ori</td>
<td>M2 Iab</td>
<td>35</td>
<td>-2</td>
<td>-3</td>
<td>-7</td>
<td>-</td>
<td>0-9</td>
</tr>
<tr>
<td>TX Psc</td>
<td>N0; C6,2</td>
<td>37</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Since the Fe II lines have a wide variety of optical depths, they allow us to probe changes in the velocity field with height, with the stronger lines sampling higher regions in the atmosphere and the weaker lines lower regions. The weakest lines appear similar to the C II] lines, i.e. narrow and without self-reversals, while the strongest lines are very broad and have substantial self-absorptions. The change in the profiles with intrinsic line strength in an M giant and M supergiant are illustrated in Figure 2. The blue-shift of the strong absorption component is seen to increase with increasing line center opacity (labelled “Tau” on the figure), and is a direct measurement of the acceleration of the stellar wind. The wind is clearly more opaque in the supergiant atmosphere, with both broader emission and more substantial absorption. The acceleration is still seen in the supergiant, although the absolute velocity is lower in this more massive wind.

The mean chromospheric flow and the acceleration of the stellar wind in the M giant γ Cru, as indicated by the Fe II lines, are seen in Figure 3. The velocity of the emission components (shown as asterisks) scatter about a mean value of 1-2 km s\(^{-1}\) suggesting a low-velocity inflow in the region of photon creation. The velocity of the stronger, blue-shifted absorption components on the other hand show a very clear dependence on relative line center opacity (τ) and allow us to observe the wind accelerating from about 7 km s\(^{-1}\) up to about 14 km s\(^{-1}\). We cannot sample lower velocities (lower altitudes) with the absorption features since none of the lines formed at those altitudes are self-reversed. There are no Fe II lines of sufficient opacity to sample higher regions, although the acceleration of the wind continues. However, there is a way to look higher into the atmospheres of these stars, and that is to observe lines from
Figure 3. \( V_{flow} \) of Fe II emission & absorption components vs. \( \tau \)

Figure 4. Fe II and O I line profiles in GHRS spectra of \( \alpha \) Tau
other ions with even higher opacity. Figure 4 shows a comparison for the K-giant α Tau, of the strongest observed Fe II line (near 2756 Å) with the three lines of O I UV 2 near 1304 Å. Using these O I lines, we can follow the wind acceleration up to about 25 km s\(^{-1}\). We have also observed these line in the hybrid star γ Dra, where the wind can be seen reaching speeds of ≈70 km s\(^{-1}\).

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References

Ensman, L. and Johnson, H. R. 1995, BAAS, 27, 839