THE OUTER ATMOSPHERES OF COOL, LOW GRAVITY STARS AS REVEALED BY HST

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ABSTRACT. We have used the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST) to measure the macroturbulent and flow velocities, the acceleration of winds, and the amount of hot (transition-region) plasma in the outer atmospheres of Carbon and K - M Giant/Supergiant stars. We see the acceleration of the stellar winds in the chromospheres of several of these stars from initial velocities of 3 - 9 km/s to upper velocities of 15 - 25 km/s and measured chromospheric macroturbulences ranging from approximately 25 to 35 km/s. We have found in the non-coronal giant α Tau weak C IV emission indicative of hot transition-region plasma, many new fluorescent lines of Fe II, and fluorescent molecular hydrogen emission and Ca II recombination lines seen for the first time in a giant star.

Key Words: stars: atmospheres, chromospheres, late type giants, supergiants, carbon

I. INTRODUCTION

We have obtained UV spectra of K - M giant and supergiant stars and of carbon stars with the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST). These spectra have been used to measure chromospheric flow and turbulence 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. Stars included in our sample are the normal, oxygen-rich giants γ Dra (K5 III hybrid), α Tau (K5 III), γ Cru (M3.4 III), μ Gem (M3 IIIab) and
30 Her (M6 III) and the supergiant α Ori (M2 Iab), as well as the carbon stars TX Psc (N0; C6,2) and TW Hor (N0; C7,2). We take advantage of the high resolution and wavelength accuracy of these data to make direct measurements of the macroturbulence in the chromospheres of these stars and the acceleration of their stellar winds. The high signal-to-noise and large dynamic range of these spectra also allow us to detect and identify numerous new emission features, including weak C IV emission indicative of hot transition-region plasma in the non-coronal giant α Tau (Carpenter, Robinson and Judge 1994), many new fluorescent lines of Fe II, and the first detection of molecular hydrogen and of Ca II recombination lines in the UV spectrum of a giant star (McMurry et al. 1996). We show a small subset of the data here – further examples can be found in Carpenter (1996).

2. MACROTURBULENCE

We have characterized the macroturbulence in the chromospheres of these stars using the profiles and widths of optically-thin emission lines. The best diagnostic for these purposes is the C II (UV 0.01) multiplet of semi-forbidden lines near 2325 Å. These lines show no evidence for opacity broadening, but are much broader than one would expect on the basis of thermal microturbulence (about 6 km/s in these chromospheres). We have used both the GHRS G270M and Echelle-B gratings in these observations. A sample of these data are shown in Carpenter (1996).

Fig. 1. Fits to C II lines assuming isotropic and anisotropic macroturbulence.
The Echelle data clearly show that the lines are broadened at the base relative to the single Gaussian profile expected for simple isotropic macroturbulence. We have found, following a suggestion by David Gray, that the observed profiles are much better fit assuming an anisotropic macroturbulence, in which the macroturbulent velocities are confined to the radial and/or tangential directions, as one might expect at the edges and tops of convective cells. Fig. 1 illustrates the best fits assuming isotropic macroturbulence (dots) and an anisotropic, radial-tangential macroturbulence (dashes) to the observed C II: 2325 Å line in α Ori and α Tau. We present in Table 1 lists our estimates of the mean macroturbulence derived from this fitting process, assuming a pure radial distribution of the macroturbulent velocities.

**TABLE 1. Measured macroturbulence, mean flow velocities and wind acceleration for cool giants and supergiants (in km/s)**

<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 blue-shifted emiss.</th>
<th>Mean Fe II shifted abs. flow</th>
<th>Mean Fe II red-shifted abs. flow</th>
<th>Wind accel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ Dra K5 III</td>
<td>24</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0-70</td>
</tr>
<tr>
<td>α Tau K5 III</td>
<td>24</td>
<td>4</td>
<td>2</td>
<td>-4</td>
<td>14</td>
<td>2-25</td>
<td>2-25</td>
</tr>
<tr>
<td>μ Gem M3 IIab</td>
<td>23</td>
<td>-3</td>
<td>-3</td>
<td>-10</td>
<td>8</td>
<td>9-13</td>
<td>9-13</td>
</tr>
<tr>
<td>γ Cru M3.4III</td>
<td>27</td>
<td>2</td>
<td>2</td>
<td>-10</td>
<td>10</td>
<td>7-14</td>
<td>7-14</td>
</tr>
<tr>
<td>30 Her M6 III</td>
<td>26</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>λ Vel K4Id-II</td>
<td>34</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>α Ori M2 IIab</td>
<td>35</td>
<td>-2</td>
<td>-3</td>
<td>-7</td>
<td>-</td>
<td>0-9</td>
<td>0-9</td>
</tr>
<tr>
<td>TX PscN0C6,2</td>
<td>37</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### 3. PLASMA FLOWS AND WIND ACCELERATION

The large variety of Fe II lines seen in the mid-UV spectral region provide a second very important diagnostic of the velocity fields in these stars. Their profiles are more complicated in appearance than the simple emission lines seen in C II, in that many of the lines have one or more absorption self-reversals superposed on the emission component. Carpenter (1996) shows the Fe II UV 2586 Å line in three stars - γ Cru shows two self-absorption components (a strong, blue-shifted one and a weaker red-shifted one) like all K-M giant stars, while α Ori shows a single blue-shifted absorption and λ Vel shows multiple self-absorptions, all blue-shifted. The blue-shifted components are indicative of formation in an outflowing stellar wind and the variation of their shift with intrinsic line strength provides a way to measure the acceleration of the stellar...
wind with height. The red-shifted self-absorptions may indicate a weaker downflow of some material or the presence of a turbulence field which changes with height (Ensmann & Johnson 1995).

We have measured the offset of the mean wavelength of the C II and Fe II emission profiles, and, for Fe II, of the self-absorptions, from the laboratory wavelength values, adjusted for the stellar radial velocity, to obtain estimates of the mean flow velocities of these ions in the chromospheres. These flows are tabulated in Table 1. The mean flows of the emission components of both ions agree well with each other, generally showing either a slight inflow or slight outflow of 2 - 4 km/s. The mean flows of the blue-shifted Fe II self-absorptions indicate means outflows of several to as much as 10 km/s, while the mean apparent velocities of the weaker "inflows" are seen at 8 to 14 km/s. The observed blue-shift of the strong Fe II reversals increases with increasing line strength, thus indicating that the outflow, i.e. the stellar wind, is accelerating with increasing distance from the stellar photosphere. This follows since the self-reversals of the stronger, more opaque, lines are formed higher up in the atmosphere. We quantify the relative line strengths by a relative line center opacity (tau), computed for a temperature of 6000 K, a hydrogen column density of 1.0 x 10^{22} cm^{-2}, a microturbulence of 6 km/s, an electron density of 1.0 x 10^9 cm^{-3}, and a solar Fe II/H abundance. Fig. 2 shows the observed shift in the \gamma Cru rest frame, of the stronger Fe II self-absorption versus this relative log(tau).

![Graph showing the relationship between relative log(tau) at 6000 K and the observed shift in Fe II self-absorption.

Fig. 2. The increase of Fe II self-absorption blue-shift with increasing line strength (height in chromosphere), reflecting the acceleration of the wind in \gamma Cru.
In γ Cru, we are first able to detect the wind at about 7 km/s (where the Fe II absorption first becomes thick enough to observe) and can follow it higher into the atmosphere, as it accelerates up to about 15 km/s. We cannot sample higher, perhaps faster-moving regions since none of the Fe II lines are sufficiently opaque. To sample higher regions in giant stars, we must use other, more opaque, lines. One good diagnostic of these higher regions is the O I UV 2 multiplet which consists of three lines near 1304 Å. These lines are also self-reversed, but even stronger than the strongest of the observed Fe II lines (the 2756 Å line). Fig. 3 compares the observed profiles of the O I lines to the Fe II 2756 Å and 2737 Å lines in the K-giant α Tau. The use of the O I lines allows us to follow the wind up to about 25 km/s in this star.

![Graph showing wind absorption and velocity from line center](image)

**Fig. 3.** The acceleration of the wind in α Tau as seen in the increasing blue-shift of the Fe II and O I self-reversals with increasing line strength.

4. **NON-CORONAL vs HYBRID STAR CHROMOSPHERES**

Among the giant stars, there is a well-known “dividing line” Linsky and Haisch (1979) at about K2, which separates the warmer sun-like stars, with transition regions and coronae and high-speed but low-mass winds, from the cooler “non-coronal” stars, which lack strong transition regions and coronae.
and have slow-moving but massive winds. In addition, there exists a third class of cool giant star, the “hybrid” star which exhibits traits of coronal stars even though they are to the red of the dividing line.

We have observed with GHRS the region around 1550 Å in two K4 giants, γ Dra and α Tau – a hybrid and non-coronal star, respectively – for the purpose of measuring (or placing better upper limits on) the amount of flux arising from hot (transition region) material in these stars. These spectra were surprizing in that we detected a C IV surface flux from the non-coronal giant comparable in strength to that in the hybrid star, suggesting a non-trivial amount of transition-region material in the non-coronal star (see Fig. 4). However, the higher density, cooler temperatures in the slower-moving, non-coronal stellar wind is spectacularly evident in the spectrum of α Tau in the form of a myriad of narrow fluorescent emission lines from Fe II and H₂, and recombination lines of Ca II. These lines are weak or absent in the hybrid star, but dominate the spectrum of the non-coronal star (see McMurray et al. 1996).

![Graphs showing emission lines in spectra of α Tau and γ Dra.](image)

**Fig. 4.** The region near C IV (UV 1) in a non-coronal and a hybrid giant.
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