HST Observations of Carbon Stars

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Abstract:

Ultraviolet spectra obtained with the Goddard High Resolution Spectrograph (GHRS) on the HST of the carbon stars TX Psc, TW Hor, and UU Aur are presented and compared with each other and with spectra of the oxygen-rich cool giants $\mu$ Gem and 30 Her. For TX Psc, we discuss the inferred outer atmospheric flow and turbulent velocities, the relative and absolute strength of emission from C\textsc{II} and Fe\textsc{II}, the ionization fraction of iron, and variations of its spectrum with time. We also discuss two fluorescence processes operating in the atmospheres of carbon stars and compare in detail the Mg\textsc{II} profiles seen in both carbon and O-rich stars.

1. Introduction

We present in this paper a summary of the results of several HST programs studying the UV spectra and outer atmospheric regions of carbon stars, with the goal of improving our understanding of the structure of the chromosphere and wind from these stars, the processes which heat these regions and drive the winds, and how those differ from what is occurring in the O-rich stars. This understanding is important not only in and of itself, but also to understanding stellar evolution along the Red Giant Branch (RGB) and Asymptotic Giant Branch (AGB).

2. Observations and Data Reduction

The observations for this project were acquired with the medium resolution ($R = 20,000$) G270M grating on the GHRS, using the Small Science Aperture (SSA). Each science exposure was accompanied by a wavelength calibration exposure on an internal platinum lamp to optimize the wavelength assignments, and thus velocity measurements. The targets observed are specified in Table 1. Details on the science exposures and information on the calibration spectra are given in Carpenter et al. (1997). The first three stars listed in the Table are carbon stars. For each of them we obtained an exposure of the 2790 – 2830 Å region, containing the Mg\textsc{II} h & k lines and the Fe\textsc{i} fluorescent lines. We chose to study the prototypical carbon star TX Psc in more detail, obtaining spectra of the 2320 – 2368 Å and 2730 – 2776 Å regions as well, to observe intercombination lines

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of C II (UV 0.01) and a variety of Fe II lines. In addition we obtained spectra of two comparison O-rich stars, 30 Her (the 2800 Å region) and μ Gem (the same 3 regions as for TX Psc). These data were reduced using the CALHRS routine developed by the GHRS Investigation Definition Team.

Table 1. Target Stars (GO Programs 4685, 5359, and 5694)

<table>
<thead>
<tr>
<th>Star</th>
<th>HD #</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX Psc</td>
<td>223075</td>
<td>(N0;C6,2)</td>
</tr>
<tr>
<td>UU Aur</td>
<td>46687</td>
<td>(N3;C5,3)</td>
</tr>
<tr>
<td>TW Hor</td>
<td>20234</td>
<td>(N0;C7,2)</td>
</tr>
<tr>
<td>μ Gem</td>
<td>44478</td>
<td>M3 IIab</td>
</tr>
<tr>
<td>30 Her</td>
<td>148783</td>
<td>M6 III</td>
</tr>
</tbody>
</table>

3. The 2790 – 2830 Å Region: Mg II and Fluorescent Fe I

We have observed the 2790 – 2830 Å spectral region in all of our target stars, since it includes the primary diagnostics of cool stellar chromospheres and winds, the Mg II h & k lines, as well as two fluorescent lines of Fe I. In Figure 1 we show this region for the three carbon stars in our sample and for the O-rich star μ Gem. The very strong, self-reversed and mutilated-by-overlying-absorption Mg II lines are seen near 2795 and 2803 Å, and the two Fe I lines can be seen near 2807 and 2823 Å.

The Mg II line profiles in these spectra are very complicated, due to the presence of very broad emission over which are superposed self-absorptions from both the outer atmosphere of the star and the interstellar medium, as well as absorptions by other ions in the circumstellar environment. The h & k profiles from TX Psc and TW Hor are remarkably similar, especially in the multiple absorption structure on the blue side of the k-line and in the overall widths of their emissions. However, the third carbon star in our sample, UU Aur, is dramatically different, with emission persisting out to far higher blueshifts (beyond −200 km s⁻¹) in both the h & k lines than in either of the other two carbon stars. In contrast, the red wings of the emission from UU Aur are very similar to what is seen in the other stars. These profiles are shown in the top two panels of Figure 2. In the bottom two panels of the Figure, we compare the profiles from TX Psc with those from the oxygen-rich star 30 Her and see that the overall widths of the emissions seem similar, although there is more overlying absorption at high velocities in the carbon star, to the blue in the k-line and to the red in the h-line. The vertical tick marks indicate the velocity predicted by Crutcher (1982) for the LISM. The data are consistent with the LISM at that velocity in both lines in the TX Psc and 30 Her spectra, although it is pretty well masked by the intrinsic self-reversal of the lines. In the UU Aur spectrum, the h-line profile is consistent, but the k-line does not seem consistent with significant LISM absorption at that velocity.

The results of two distinct fluorescence processes can be seen in the carbon star spectra in Figure 1. The Fe I line at 2823 Å has been known for long time
Figure 1. GHRS Spectra of the region near 2800 Å in 3 carbon (TX Psc, TW Hor, & UU Aur) and 1 oxygen-rich star (μ Gem).

Figure 2. GHRS Profiles of the Mg II h & k lines plotted on a velocity scale in the rest frames of several stars. The vertical tick marks indicate for each star the LISM velocity predicted by Crutcher (1982).
Figure 3. Two fluorescence processes active in the outer atmospheres of carbon stars. The UV 13 Fe I transition picks up photons from the C II 2325 Å line which are re-emitted in the UV 45 line at 2807 Å, while the UV 44 line at 2795 Å picks up photons from the Mg II k-line which are re-emitted at 2823 Å.

to be the result of radiative excitation of its upper energy level by the Mg II k-line at 2795 Å (Carpenter et al. 1988) and is seen in both oxygen-rich and carbon stars. However, the Fe I line at 2807 Å, which is pumped by the C II line near 2325 Å is seen only in the spectra of carbon stars (Johnson et al. 1995, Carpenter et al. 1997) and Mira variables (Luttermoser, this volume). These two processes are illustrated in Figure 3, which shows the pumping lines, the wavelength of the pumped lines, and the two fluorescent products.

4. C II and Fe II

When comparing the spectra of TX Psc with that of the oxygen-rich stars, e.g., μ Gem, the most remarkable difference we see is in the absolute strength of the Fe II lines, and in their weakness relative to the C II lines. This can be seen in Figure 4, which has the lines identified in TX Psc marked. The strong, unmarked lines seen in μ Gem belong to Fe II and are invisible on this flux scale in TX Psc. The Fe II lines which are visible in TX Psc are much more narrow than their counterparts in the μ Gem spectrum (indicating less opacity broadening) and do not show the self-reversals which indicate high line opacity in μ Gem and other O-rich stars. This absolute and relative weakness of the Fe II lines in TX Psc suggests that the ionization fraction of iron (Fe II/Fe I) is substantially lower in the outer atmosphere of the carbon star than in the O-rich stars.
Figure 4. C II and Fe II lines in TX Psc (thick line) and μ Gem (thin line). The μ Gem spectrum in the upper panel has been divided by 10, while the μ Gem spectrum in the lower panel has been divided by 20, to facilitate comparison with TX Psc.

5. Line Widths and Turbulent Broadening

Another observable which is significantly different in TX Psc is the relative widths seen for the C II and Fe II lines. In our previous observations of O-rich stars, we have found the width of the intercombination lines of C II near 2325 Å a good metric of the turbulent broadening in the chromosphere. This was based on the assumption that the lines were optically thin (i.e., not opacity broadened) — an assumption apparently verified by the lines being narrower than even the weakest collisionally excited Fe II lines and of comparable width to the purely fluorescently excited Fe II lines. In TX Psc however, we find that the C II lines are considerable broader than many of the Fe II lines, which places the assumption that the C II lines are optically thin under great doubt. We therefore think it likely that the latter are opacity broadened in TX Psc and that the narrowest of the Fe II lines place a better upper limit on the turbulence, though we cannot be sure that even those lines do not suffer a limited amount of opacity broadening and thus bias our estimate of turbulence toward a slightly higher value. The width of the narrow Fe II lines indicates that the turbulence low in the chromosphere is on the order of 16 km s\(^{-1}\) (FWHM), considerably less than that seen in the oxygen-rich giants (≈ 24 km s\(^{-1}\)). If, on the other hand, the C II and moderate strength Fe II line widths are still controlled by turbulence, then they must both be formed higher in the chromosphere than the narrow Fe II lines and we would infer that the turbulence increases with height up to a value of about 34 km s\(^{-1}\). Judge & Carpenter (1998) have recently noted that
the inconsistent line ratios (implying different electron densities) within the C II UV 0.01 multiplet in α Ori are due to significant optical depth in the lines, although in that case the opacity does not appear to be sufficient to explain the breadth of the lines, whose width is still controlled by turbulence in the α Ori atmosphere (consistent with the Fe II lines being broader still).

6. Flows in Chromosphere

We can estimate the mean flow velocities of specific ions in the chromosphere by measuring the observed wavelengths of the emission features. The results for TX Psc indicate that both the thermally and fluorescently excited emissions originate in chromospheric layers approximately at rest relative to the mean stellar radial velocity, i.e., before significant wind acceleration has taken place. That a wind does eventually form is confirmed by the presence of blueshifted self-reversals in the Mg II lines indicating a mean outflow of 9 – 10 km s⁻¹. Circumstellar absorption features which overlay the Mg II lines appear to indicate a circumstellar shell expanding at about 5 – 6 km s⁻¹ relative to the photosphere, suggesting that the wind may decelerate some at large distances from the star.

7. Time Variations

The three hours of integration with GHRS on the C II (UV 0.01) lines in TX Psc were examined by Carpenter et al. (1997) for variations that might be the signature of shocks passing through the atmosphere, since their presence would suggest that acoustically generated shocks could be important for chromospheric heating and/or the initiation of the stellar wind acceleration. No statistically significant variations were seen in the data. Insufficient time coverage was available during the acquisition of the other GHRS data frames to allow any statement about variability of the Fe II and Mg II lines on a similar timescale.

The situation on longer timescales is dramatically different, as can be seen by comparison of a 1984 IUE high resolution spectrum of TX Psc with the GHRS 1994 spectra. Although the faintness of the C II lines prevented their detection by IUE, numerous Fe II and the Mg II h & k lines were seen in the spectrum obtained by Eriksson et al. (1986). Their analysis indicated that the star was in a state of high-UV line flux in 1984, compared to what had been seen in earlier low-resolution IUE spectra. The GHRS spectra confirm this, in that the line fluxes seen in 1994 with GHRS are also considerably lower than seen 10 years earlier with IUE.

In Figure 5 we compare several IUE and GHRS Fe II profiles. The IUE fluxes shown here have been divided by a factor of 3 to facilitate the comparison. Although the IUE spectrum clearly is noisier, we can see that the Fe II line fluxes are comparable after this division, thus indicating that the Fe II fluxes were roughly a factor of 3 brighter in 1984 than in 1994.

We compare the IUE and GHRS Mg II profiles in Figure 6. The IUE fluxes shown here have been also been divided by a factor of 3 and we see that the spectra at the time of the IUE observation still shows more line flux, indicating that the Mg II fluxes were more than a factor of three brighter in 1984 than in 1994 and that fluxes from this ion changed even more than the fluxes from Fe II.
Figure 5. Fe II variations in TX Psc. The “X” marks IUE data affected by a reseau mark on its detector.

Figure 6. Mg II variations in TX Psc. The IUE data have been set to $7.0 \times 10^{-14}$ in the region from 2800 – 2803 Å where it is badly affected by a reseau (marked by an “X” and a noise hit “#”).
8. Summary and Conclusions

The TX Psc spectra indicate that both thermal and fluorescent chromospheric emission lines are formed near the stellar rest velocity, in a region below that in which the stellar wind is accelerated. Absorption self-reversals in the Mg\textsc{ii} emission confirm the presence of an outflowing stellar wind at a mean velocity of about 9 – 10 km\text{s}^{-1}. Circumstellar absorption features overlying the Mg\textsc{ii} emission indicate a cool shell expanding at about 5 – 6 km\text{s}^{-1} relative to the photosphere. The FWHM of various emission lines indicate that the chromospheric turbulence is at least 16 km\text{s}^{-1}, but that it may increase with altitude to as much as 34 km\text{s}^{-1}. Fluorescent processes producing two lines of Fe\textsc{i}, at 2807 and 2823 Å, in the carbon star spectra are identified. The former line is seen only in spectra of carbon stars, while the latter is also seen in the O-rich stars. The Fe\textsc{ii} UV 32, 62, and 63 multiplets are seen, but are weaker relative to the UV 165 lines and to the C\textsc{ii} and Si\textsc{ii}] lines than in the O-rich stars. The weakness of the Fe\textsc{ii} lines and the presence of the 2807 Å Fe\textsc{i} line suggest that the ionization fraction of iron (Fe\textsc{ii}/Fe\textsc{i}) is significantly lower in the outer atmospheres of carbon stars. Fluxes in emission lines of Fe\textsc{ii} and Mg\textsc{ii} are \textgtr2 – 3× lower than in a 1984 \textit{IUE} spectrum of TX Psc, confirming that the latter was obtained at an epoch of unusual UV brightness for the star. The Mg\textsc{ii} profiles are even more heavily mutilated by overlying absorption than in 1984. The TX Psc profiles are very similar to those seen in TW Hor, but dramatically different than those in UU Aur, whose lines show violet wing emission out to much shorter wavelengths.

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References