THE CHROMOSPHERE AND CIRCUMSTELLAR SHELL OF α ORIONIS AS OBSERVED WITH THE GODDARD HIGH RESOLUTION SPECTROGRAPH

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ABSTRACT

We have used the Goddard High Resolution Spectrograph (GHRS) on Hubble Space Telescope to study the far-UV spectrum of the M-supergiant α Ori at low (G140L) and medium (G160M, G200M) resolution, and the Mg II emission doublet near 2800 Å at the highest (Ech-B) resolution. These data markedly improve our understanding of the constituents of the spectra and provide a number of interesting diagnostics of the chromosphere and circumstellar shell. Continuum light is unambiguously detected to wavelengths as short as 1200 Å, with its stellar origin confirmed by overlying atomic and molecular absorptions from the chromosphere and circumstellar shell. The characteristics of the far-UV continuum indicate that it is formed in the chromosphere at temperatures ranging from 3500 - 5000 K. Superposed on this continuum is a series of very strong and broad absorption features, which we interpret as being formed by CO molecules in the circumstellar shell. These features are used to estimate the temperature, column density, and turbulence in that region of the shell. The numerous chromospheric emission features are attributed mostly to fluorescent lines of Fe II and Cr II (both pumped by Lyα) and Si I lines, plus a few lines of O I, C I, and Si II. The weakness of the observed emission in the O I (UV 2) and C I (UV 2) resonance lines, relative to that observed in the intrinsically weaker O I (UV 146) and C I (UV 32) lines, appears to be due primarily to self-absorption of the resonance lines in the upper regions of the chromosphere. Atomic absorption features, primarily caused by C I and Fe II are clearly seen in the G160M spectrum centered near 1655 Å. Narrow circumstellar absorption features, due to Fe I and Mn I are superposed on the chromospheric Mg II emission lines. These are seen at higher resolution and signal-to-noise than previously possible and are used to place constraints on conditions in the circumstellar shell. The strength of these circumstellar absorptions, however, are insufficient to explain the different asymmetries of the Mg II h and k lines, which we believe are due instead to different velocity shifts between emission and self-absorption components in the two lines.

1. INTRODUCTION

The observations of α Ori presented here are part of a GTO program on cool, luminous stars, which is designed to (a) improve our understanding of their far-UV spectrum, (b) study line-formation processes and estimate physical conditions in their chromospheres and circumstellar shells, and (c) develop empirical constraints for models of their outer atmospheric layers. α Ori was selected as the archetype of the M-supergiants. IUE and Copernicus observations have shown that its far-UV spectrum is not at all "typical" of cool stars in general, however. The IUE far-UV spectrum of α Ori shows a severe deficiency in O I (UV 2) flux near 1304 Å (Basri et al. 1981; Jorás 1989; Carpenter et al. 1990), a large flux excess (either true continuum or scattered light in IUE), which varies significantly with wavelength (Stickland and Sanner 1981), and a perplexing general appearance that does not match well the spectra of other cool stars (cf. the M3 giant γ Cru - Carpenter et al. 1988). We have utilized the GHRS to examine the far-UV spectrum of α Ori at both low and medium resolution to investigate these anomalies. We have also obtained high signal/noise and high-resolution line profiles of the Mg II lines near 2800 Å to study the wind and circumstellar material of this supergiant. Preliminary discussions of these data can be found in Carpenter et al. (1991) and Carpenter (1992 a,b).

2. OBSERVATIONS AND DATA REDUCTION

The GTO observations discussed in this paper include the following GHRS spectra of α Ori (M2 Iab):

- G140L (R=1000): 1170 - 1930 Å
- G160M (R=10,000): 1638 - 1671 Å

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- G200M (R=10,000): 1975 - 2014 A
- Ech-B (R=85,000): 2790 - 2805 A

These data were reduced and calibrated using the CALHRS routine developed by the GHRS Investigation Definition Team (IDT). This process includes the following steps:

- correct for paired-pulse effect, non-uniform diode sensitivity, granularity of photocathode, and vignetting
- merge data bins and subtract background
- apply absolute flux and wavelength calibrations

Wavelength calibrations were performed using WAVECAL and/or WAVECAL/SPYBAL exposures obtained close in time and with the same grating as the science observations.

3. FAR-UV CHROMOSPHERIC ATOMIC EMISSION LINES

Figure 1 shows a GHRS G140L spectrum of α Ori, composed of three 17.7 minute exposures through the Large Science Aperture (LSA). These have been merged together and then deconvolved using the Richardson-Lucy algorithm (Lucy, 1974) and a Line Spread Function derived from FOC imagery. Emission lines are identified, with fluorescent Fe II lines produced by Lyα pumping indicated by the highest set of tick marks (with horizontal lines at their top), Cr II lines produced by Lyα pumping indicated by the second-highest set of tick marks, and other ions marked by smaller vertical tick marks accompanied by explicit identifications. The spectrum is dominated by fluorescent features, primarily of Fe II and Cr II, but fluorescent lines of S I and O I are also seen. The detection of these Fe II and Cr II lines provide evidence for the radiative excitation of additional energy levels in these atoms by Lyα.

4. THE UV CONTINUUM

Both the low and medium resolution GHRS data clearly show a very strong far-UV continuum, with superposed chromospheric and circumstellar atomic and molecular absorptions that confirm its stellar origin. Figure 2 shows a comparison of the observed UV-visual α Ori flux distribution (GHRS + IUE + Cardelli (unpublished)) with several Kurucz (1991) flux distributions. The observed UV flux is much larger than that expected from the photosphere of a 3500 K star such as α Ori. Although the excess can be roughly fit using multiple photospheric flux distributions (e.g. the 6000 and 10000 K models shown here), the derived source sizes do not correspond to either the size of real stars or to that expected for hot plages or convective cells. A good fit to the flux distribution requires a continuum of formation temperatures which increase to shorter wavelengths (see insert). We thus believe that this far-UV continuum is formed in the chromosphere of α Ori, as suggested by Stickland and Sanner (1981). The increase in formation temperature with decreasing wavelength below 3500 Å reflects a rise in opacity toward shorter wavelengths and an increase in the height sampled by the observations.

5. FAR-UV CHROMOSPHERIC ATOMIC ABSORPTION LINES

The presence of a far-UV continuum allows the detection of atomic absorption lines formed in the upper chromosphere of the star. Figure 3 shows a GHRS G160M LSA spectrum compared with synthetic absorption spectra computed for:

- a 10000 K, log(g)=2 Kurucz atmosphere using the SYNTHETE radiative transfer code
- a uniform absorbing slab at 3000 K & N(H)=5.0e+22
- a similar slab at 6000 K.

Although none of these are expected to represent the actual physical situation, the similarities are many and the behavior of the features in each spectrum provides valuable clues on the conditions in the various line formation regions. In particular, the synthetic spectrum produced using the low-gravity Kurucz atmosphere agrees surprisingly well in this spectral region, suggesting that formation at upper chromospheric temperatures, which are similar to those in this photospheric model, is a reasonable interpretation of these
Figure 1: A deconvolved LSA G140L spectrum of α Ori, with identifications indicated.
Figure 2: Scaled flux distributions from Kurucz (1991) compared with observed, dereddened UV + optical fluxes of α Ori. The $T_{\text{eff}}$ and log(g) of each model, along with the scaling factor required to convert the computed surface fluxes to match the observed fluxes at earth, are given above the plotted flux of each model. The variation of the flux creation temperature versus wavelength in the far-UV spectrum is shown in the insert.

data. Identifications are indicated on the upper panel for the major features.

6. WEAKNESS OF O I AND C I RESONANCE EMISSION LINES

Since IUE data had shown us that the O I (UV 2) flux was very deficient in α Ori, relative to less luminous late-type stars, one purpose of the GHRS observations was to examine the region around the resonance and secondary lines of both O I and C I in the hope of understanding this observation. Figure 4 shows the spectral regions containing the O I and C I resonance lines (UV 2) and their associated secondary transitions at 1641 and 1994 A. The resonance lines are difficult or impossible to detect, while the much weaker transitions represented by O I (UV 146) and C I (UV 32) are observed to be quite strong (“line leakage”, Johansson & Jordan 1984). Preliminary calculations (e.g. Figure 3a) suggest the resonance lines are self-absorbed in the upper layers of the chromosphere, in a region of decreasing temperature (i.e. above the temperature maximum), although an overlying circumstellar absorption band of the CO A-X system may be responsible for some of the attenuation of the O I (UV 2) emission.

7. ABSORPTIONS FROM THE CIRCUMSTELLAR SHELL

In addition to the numerous chromospheric emission lines seen in the GHRS G140L data, strong circumstellar molecular absorptions are also seen. These features are due to the (0,0) - (0,8) bands of the CO 4th-positive A-X system. Figure 5 presents the original (i.e. no deconvolution) G140L spectrum, in which these absorptions are best seen, and compares it with a synthetic spectrum computed using a simple slab model, with $T$=500 K, $V_{\text{turb}}$=5 km/s, and N(CO) = 1.0x10$^{18}$ cm$^{-2}$ (Waligren et al. 1992).

The circumstellar shell is also visible in the GHRS Echelle-B (R=85,000) observation, shown in Figure 6, of the Mg II emission doublet near 2800 Å, which show strong circumstellar absorption from Mn I and Fe I. Dual-Gaussian fits to the Mg lines, one emission + one central absorption for each line, are shown as a dotted line. Previous suggestions (e.g. Bernat & Lambert 1976, Dupree 1984) that the different asymmetries of the h (2803 Å) and k (2795 Å) lines are due to the absorption produced by Mn I and Fe I in the violet wing of the k-line are not supported by measurements and modeling of these data (Carpenter et al. , in
Figure 3: Comparison of calculated UV spectra with a GHRs G160M spectrum.

Figure 4: GHRs spectra of the OI and CI resonance and secondary lines.
Figure 5: Circumstellar CO (1,0) bands in the far-UV spectrum of α Ori.

Figure 6: Echelle-B spectrum of the Mg II emission lines near 2799 Å in α Ori.
The difference appears to be due to different velocity shifts between the emission and self-absorption components in the two Mg lines, so that more of the violet wing flux is self-absorbed in the h-line than in the k-line. Analysis of the Fe I & Mn I absorptions indicate CS turbulence of about 6-12 km/sec and column densities on the order of $1 \times 10^{19}$, assuming pure absorption, or $6 \times 10^{19}$ cm$^{-2}$, assuming pure scattering.

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