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FUSE Observations of a Mira Variable Star

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Abstract.

We have obtained a FUSE spectrum of the long-period variable (Mira-type) star S Car. This observation gives us the opportunity to probe the temperature-density structure the *outer* shocked region of the atmosphere of this star using the hydrogen Lyman lines. We obtained an LWRS spectrum on 25 May 2001 when this star was at optical light-curve phase 0.35. We make flux comparisons between Lyman lines and UV emission lines obtained at near coincident phases with the IUE. This is done to study the effect that the radiation field from the *inner*, hotter shocks (where Mg II and the Balmer lines form) have on the outer shocked region (where the Lyman lines form). We also make comparisons to synthetic spectra from dynamic models representative of this star. These NLTE radiative transfer calculations have shown that the radiation field of the inner shocks dominate the ionization throughout the entire atmosphere. The calculations also have shown that the Lyman emission lines form in the outer reaches of the atmosphere where the shocks are much weaker as they propagate outward.

1. Introduction

Emission lines have been seen in the spectra of Mira-type variable stars for over 100 years (see Willson 2000). It has been shown that these emission lines are produced from outward moving shock waves in their atmospheres as these stars pulsate. Two basic types of emission lines exist in the spectra of these stars: *collisionally excited lines* (e.g., Mg II h & k and H I) and *fluoresced lines* (e.g., Fe I (42) at 4202 Å and 4308 Å). Fluoresced lines are pumped by photons from an emission line at a different wavelength from the fluoresced line (e.g., in the case of the Fe I (42) lines, Fe I (UV3) at 2795.006 Å absorb emission-line photons from the Mg II k line at 2795.523 Å, electrons then cascade back down a different transition giving rise to the Fe I (42) features).

NLTE synthetic spectra calculations of hydrodynamics models (Bowen 1988) have given much insight to the formation of many of the emission features we see in Miras (see Luttermoser 1992; Luttermoser & Bowen 1990, 1992; Luttermoser et al. 1993a, 1993b). The hydrogen Balmer lines arise in the innermost shock. The Balmer continuum is also optically thick when this shock just be-

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gins to emerge out of the "photosphere." This has a significant impact on the formation of the Mg II h & k lines. As this shock propagates outward, the temperature and density decrease, which weakens the Balmer-line emission until they disappear around optical light-curve phase 0.6. The Bowen models show that stars with a low dust content will form permanent enhanced temperature regions, called *calorispheres* (somewhat analogous to a stellar chromosphere) by Willson & Bowen (1986), which last throughout the entire pulsation cycle.

It is in these calorispheres where the Mg II h & k lines form. Near phase 0 (when a Mira is visually brightest), the Balmer continuum is optically thick. Meanwhile the source function of the Mg II h & k lines continuously drops off with height, producing pure absorption lines. Later (around phase 0.2), when the innermost shock propagates out to the bottom of the calorisphere, the Balmer continuum becomes transparent in the shock producing a local maximum in the Mg II h & k source functions in the calorisphere, which is demonstrated in the appearance of strong emission features in these lines. This produces a 0.2-0.3 phase shift between the peak H-Balmer line fluxes and the peak Mg II h & k line fluxes.

So through IUE, HST, and many ground-based observations, we have learned a great deal about the inner region of the atmospheres of these stars. But what about higher up in the shocked atmosphere that lies beneath the circumstellar shell of these stars? The above mentioned NLTE calculations indicate that the hydrogen Lyman lines will form there. This paper presents FUSE observations in the *far* ultraviolet (FUV) of the Mira star S Car. A relatively warm (K5-M6 IIIe, $T_{\rm eff}$ (max) = 3800 K), shorter-period (149 days), low metalicity Mira star. This star is well suited in the study of the hydrogen Lyman lines due to the relatively large radial velocity (+289 km/s), which will shift the stellar lines away from the geocoronal Lyman lines.

2. Observations & Reductions

We observed S Car (HD 88366) on 25-26 May 2001 with FUSE through the LWRS aperture under night-time observing conditions for 15 ksec, when this Mira variable was at optical light-curve phase 0.35. We wrote software packages (in IDL V4.0) to reduce (FUSEREDUCE) and analyze (FUSEANALYZE) our FUSE data. One begins by running FUSEREDUCE. Besides retrieving information from the headers in the FUSE FITS files, this code also accesses two additional files containing stellar data (e.g., star names, angular sizes, variability periods, and dates of peak brightness — obtained from the AAVSO). The program then supplies this information to the GUI widget. The user then *co-adds* spectra from the various FUSE detectors and merge these spectra from various detectors into one output file. Finally, one has the ability to smooth the final spectrum through a Gaussian filter. Once a final spectrum is in hand, one runs the FUSEANALYZE to identify the features and determine various information about the line (e.g., peak flux, integrated flux, FWHM). The plots displayed in this paper are generated with IDL procedure FUSEPLOT which plots spectral files generated by FUSEREDUCE. FUSEPLOT was written by the authors as well.

Unfortunately, since any emission lines a Mira variable will be shifted due to nonuniform macroscopic velocity flows in their atmospheres, we cannot use such lines to calibrate velocity shifts in the observed wavelength vector. No continuum is seen for these cool stars, and as such, we cannot use ISM lines either. The FUSE team has noted that the geocoronal lines are shifted from rest in the calibrated wavelength grid (T.B. Ake – private communication), which means that the geocoronal lines cannot be used either. As such, we are forced to use the supplied calibrated wavelength vectors as our final wavelength grid. As such, the uncertainty in wavelength space may be as great as ±50 km/s.

3. Analysis

Since the angular size of S Car is unknown and its distance very uncertain (*Hipparcos* measured 405±138 pc), we used the following technique to estimate the flux of Ly-β. The flux ratio of Ly-β to the Mg II h line is determined at the stellar surface based on the NLTE synthetic spectra mentioned above. In Mira stars, Mg II k is known to have a tremendous amount of overlying circumstellar absorption from neutral metal lines which hides much of the k-line flux (see Luttermoser 2000). Fortunately, the h-line has minimal obscuration from circumstellar material. We then multiply this ratio by the observed IUE flux of the Mg II h line as reported by Bookbinder et al. (1989). Unfortunately, no color excess has been determined for this star (note that it is remarkably difficult to determine color excesses for Miras). As such, we carried out the following procedure to estimate the amount of interstellar dust absorption for this star. Li & Greenberg (1997) calculate a unified model of interstellar dust and carry out the calculations down to 1000 Å. Their Figure 10 shows the final model calculated where $A(\lambda)/A(V)$ is plotted versus $1/\lambda$. For $\lambda = 1026$ Å (Ly-β), $A(\lambda)/A(V) = 4.7$ and for $\lambda = 2800$ Å (Mg II), $A(\lambda)/A(V) = 2.1$. This means that a line at 2800 Å would only be one-tenth as bright if viewed at 1026 Å. We also estimate that circumstellar dust will further diminish the Lyman-line flux by only 10% for S Car. Interstellar Lyman-line absorption will not be present in S Car due to its high radial velocity.

Figure 1 displays the NLTE synthetic spectrum of the hydrogen Lyman series generated with PANDORA for a Bowen (1988) hydrodynamic model representative of S Car near optical light-curve phase 0.35. Here the flux has been scaled as described above. Figure 2 shows the calibrated FUSE spectrum we obtained binned by 4 pixels. In order to make comparisons to Mg II in IUE spectra, we have smooth the spectrum shown in Figure 2 with a 0.1 Å Gaussian (Figure 3). As can be seen from Figure 3, there is no Ly-β feature at the stellar rest frame of this line at the predicted flux. There is, however, a possible emission feature at about one-third that flux, shifted by 70 ± 50 km/s blueward of the stellar rest frame. Note that this velocity shift for the peak of Ly-β is consistent with the velocity shift seen in the Mg II h & k lines of past IUE spectra (see Bookbinder et al. 1989). Note that the uncertainty of the flux is rather large (1σ is $\sim 0.3 \times 10^{-14}$ erg/s/cm^2/Å) for this feature. Though the observed flux is less than that predicted by PANDORA, we claim that these fluxes are consistent with each other due to rather large uncertainty in our flux scaling.

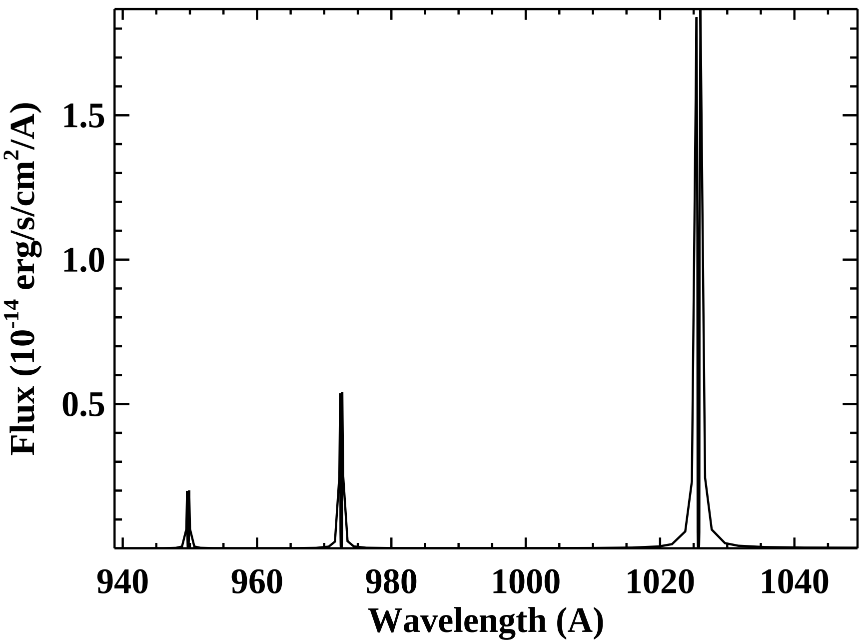

Figure 1. The Lyman series (Ly-δ, Ly-γ, and Ly-β) as produced by the NLTE radiative transfer code PANDORA with a 3600 K, 0.8 $M_\odot$, 145 $R_\odot$, and 149 day pulsation cycle hydrodynamic model of Bowen (1988). The spectrum is not convolved with the instrument profile, however, its flux has been scaled for S Car as described in the text.

4. Conclusion

We have made a possible detection of the Ly-β line at a flux consistent with NLTE synthetic spectra predicted from the Bowen (1988) hydrodynamic models of this star. It is hoped that with additional FUV observations, taken at a few different phases of the pulsation cycle of this star, we will get a more secure identification of this feature. These observations will push FUSE to the limit, but we think they are worth pursuing in order to get a better understanding of the outer atmospheres of these stars.

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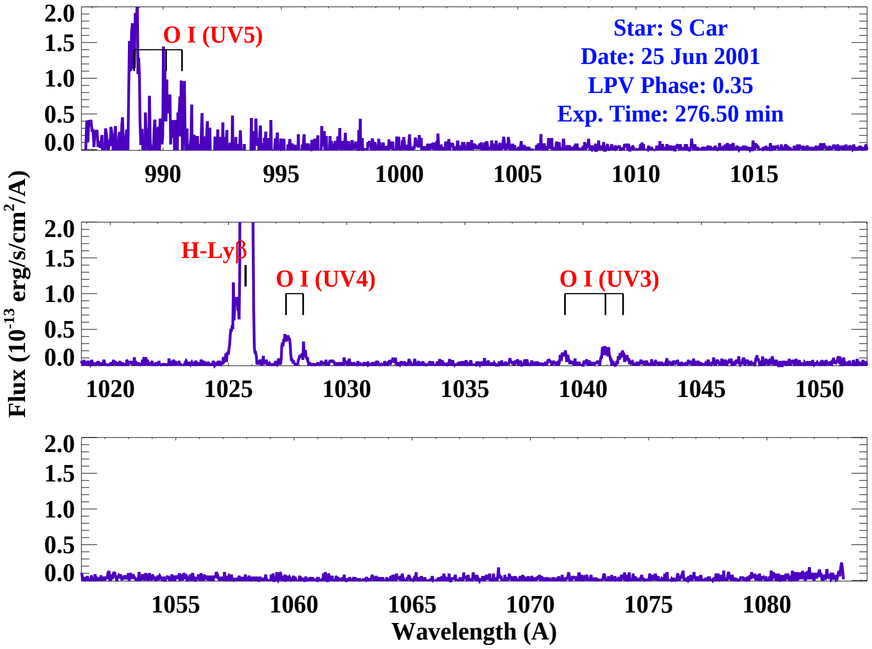

Figure 2. The FUSE spectrum of S Car taken with the LiF-1a detector. This spectrum was reduced with a 4 pixel binning. The prominent geocoronal lines are identified.

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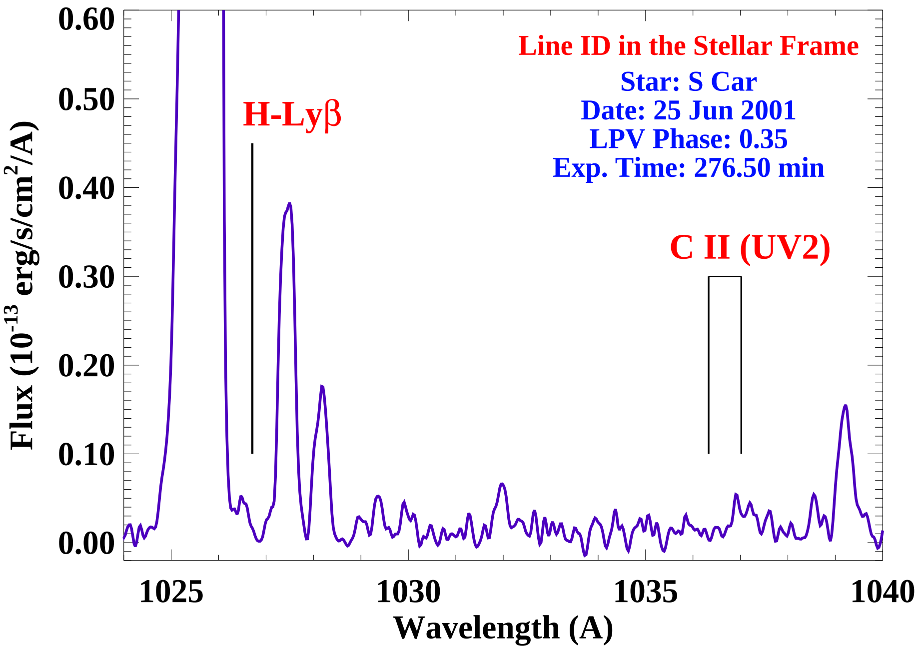

Figure 3. A region of interest in the LiF-1a spectrum, now convolved with a 0.1 Å Gaussian. The three strongest emission features from the NLTE synthetic spectra runs, Ly-β and the C II (UV2) resonance doublet, are marked in the stellar rest frame. No C II lines are seen, but there is a suspicious *bump* shifted approximately 70 km/s blueward of the stellar rest frame position of Ly-β and redward of the geocoronal Ly-β line. Mg II h & k also show such a velocity shift in past IUE spectra. This feature also is evident in the unconvolved spectrum of Figure 2.

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