Observations of CNO Processed Matter in Massive Interacting Binary Systems

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Abstract. Ultraviolet observations for nine massive Algol systems (DH Her, TU Mon, AU Mon, Z Ori, RY Per, IZ Per, V356 Sgr, RZ Sct and ET Tau) obtained during their primary eclipses with the *IUE* spacecraft are discussed. Four systems, AU Mon, Z Ori, IZ Per, and RZ Sct, yielded no useful data on the presence of UV emission lines. Four binary systems DH Her, TU Mon, RY Per, and V356 Sgr, displayed a prominent emission spectrum with the notable exception of carbon lines; only one of the studied systems, ET Tau, showed carbon emission. Analysis of these data strongly supports the suggestion that the lack of carbon emission lines in these systems is the product of an inherent carbon deficiency in the transferred material and not due to any ionization effects in the gas. This carbon deficiency is the result of the CNO processed layers of the secondary being exposed as a result of mass transfer. The *IUE* data on TU Mon also indicates that this system undergoes a total, rather than partial, eclipse.

1. Introduction

Observations of strongly interacting, massive, non–degenerate binary systems (a subclass of Algols) with the *IUE* spacecraft have shown that many of these binaries exhibit strong emissions of N V, Si IV, C IV, and other lines in their UV spectra. In general, these emission lines are visible only during the eclipse of the hotter component, usually a B–star, by the cooler, mass–losing component, commonly a subgiant or giant of spectral type A to K. Previous studies of these UV emission lines clearly associate their origin with the mass transfer process but the details regarding the origin, location, and energetics of the line formation region are still uncertain. Collisional processes are the currently favored ionization mechanism primarily because the hottest detectable radiation field is characteristically the 10–20,000 K photospheric spectrum of the B–component. The emission lines are observed both in systems with no detectable accretion disks and in those with extensive disks. Some small variability in emission line strengths ($\lesssim$20%) has been seen on longer timescales ($\sim$years) for the few systems with multiple observations.

2. The Problem

Amongst the problems in understanding the formation of these UV emission lines is an anomaly involving the C IV λ1550 lines. In the majority of binary systems the C IV line is seen in emission with a strength comparable to that of the Si IV and N V

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lines. However, for a small number of systems strong emission is observed in both the N V and Si IV lines but the C IV lines are either totally absent of exceedingly weak. Two mechanisms have been proposed to explain these "missing" C IV lines:

• An ionization mechanism that has the N V and Si IV lines formed in one region and the C IV lines in a separate and distinct region (Sahade and Ferrer 1982). In this case the binary systems without detectable C IV emission simply have a "normal" N V and Si IV line formation region but do not have, or have a greatly reduced, C IV line formation region.

• A composition mechanism that has carbon substantially depleted in the transferred matter (Peters and Polidan 1984). In this case there is only one high ionization line formation region that produces N V, Si IV, and C IV; in the systems without C IV the mass losing star has been stripped down to layers that have experienced heavy CNO cycle processing.

These two hypotheses can be tested with additional *IUE* observations. Analysis of the weaker lines in the emission spectrum, particularly using an *IUE* high resolution spectrum, will resolve the ionization state(s) of the gas. Additionally, if the composition origin is correct then the "missing" C IV line stars must be much more common in the more massive systems (B5 or earlier primary stars) than in the lower mass systems (B7 and later primary stars).

3. The Observations

Low resolution *IUE* SWP observations were obtained during the past year of six systems with B5 or earlier primary stars, DH Her, TU Mon, Z Ori, RY Per, IZ Per, and ET Tau through primary eclipse. The stars were selected from a moderate-dispersion classification survey of Algols (Wade, Polidan, and Corbally 1990). To these data we added *IUE* low resolution SWP eclipse observations of AU Mon and RZ Sct and low and high resolution eclipse observations of V356 Sgr that were obtained between 1986 and 1989. All data were analyzed using standard *IUE* data reduction (RDAF) techniques.

Four of the observed systems, Z Ori, IZ Per, AU Mon, and RZ Sct have relatively shallow partial eclipses in the ultraviolet and no useful information was obtained on the character of any possible UV emission lines. Two systems, DH Her and ET Tau, exhibited deep enough eclipses in the ultraviolet that, after careful subtraction of the B–star continuum, emission lines could be seen. The remaining three systems, TU Mon, RY Per, and V356 Sgr, all have total eclipses and the UV emission spectrum are clearly seen. Our observation of the total eclipse in TU Mon is the first evidence that this system undergoes a total eclipse. All previously published reports on TU Mon have suggested that the eclipse is partial. Our *IUE* data clearly shows a ~1.5–2.0 hour interval in which the ultraviolet flux of the B-star was fully occulted by the A5 star.

4. Results

4.1. Ionization State of the Gas

From *IUE* high resolution SWP observations of V356 Sgr during total eclipse a study can be made of the weaker emission lines that are present in the spectrum and of the emission line profiles. The following emission lines (with their ionization potentials) have been identified in the V356 Sgr high resolution SWP eclipse spectrum: N V (97.9 eV), N IV (77.5 eV), O IV (77.4 eV), Si IV (45.1 eV), S III (34.8 eV), Si III (33.5 eV), Fe III (30.7 eV), and Al III (28.5 eV). If a C IV (64.5 eV) line is present it must have a total line flux of less than ~5% of the line flux in either N V or Si IV. In addition, all the emission lines, from N V to Al III, appear to have the same line profile, a broad quasi–gaussian with a ~central self–absorption (see Polidan 1989), suggesting that they are formed in a single line formation region. Thus, NO evidence was found to support the existence of two (or more) line formation regions in V356 Sgr. A comparison of the low resolution observations of V356 Sgr with similar data obtained on the other three binary systems exhibiting weak carbon lines show little fundamental difference in their emission lines, thus the same ionization arguments discussed above regarding C IV will apply to them as well as V356 Sgr. The emission lines in each of these binaries can be understood in terms of a single line formation region with an ionization temperature in the range of 80–100,000 K. The absence of carbon emission lines thus cannot be due to "ionization effects."

4.2. The Photospheric Spectrum of the A2 Star in V356 Sgr

A comparison of the ultraviolet photospheric spectrum of the A2II star in V356 Sgr with reference stars in the *IUE* archives showed that this star displays a typical A2 spectrum with one marked exception: *NO* carbon lines, C I or C II, were detected in the photospheric spectrum of the A2II star in V356 Sgr. Photospheric lines arising from species with similar ionization potentials to C I and C II were present at their expected strengths in the spectrum. Thus, in the case of V356 Sgr the absence of carbon lines is most easily understood in terms of abundance anomalies rather than ionization effects.

4.3. Systems with Carbon Deficiencies

In our survey of 9 binary systems, 5 systems gave information on the characteristics of their UV emission lines. Of these, four (DH Her, TU Mon, RY Per, and V356 Sgr) showed clear evidence of a substantially reduced C IV line emission with respect to that of Si IV and N V. Only one system, ET Tau, gave any indication of a normal C IV line strength. "Missing" or greatly weakened C IV (or C II) absorption lines have been reported in additional binaries with mid– or early B type primary stars (see, for example Peters and Polidan 1984) but there have been no reports of reduced or absent carbon lines in any of the less massive binary systems, those with a B7 or later primary star.

The deficiency of carbon (C IV or C II) in these earlier B-type systems and its presence in the later B-type systems is the expectation from combined stellar evolution and mass transfer calculations (see, for example De Greve 1989). The carbon is burned in the convective core of the current mass losing star while it was on the main sequence. Once mass transfer began (early "Case B" mass transfer) the outer layers of this star were quickly stripped away, uncovering the initial stellar core before any onset of convection in the mass losing star's envelope. This set of circumstances will occur only in the more massive binary systems. In lower mass systems the mass losing star will develop a convective envelope before the carbon poor layers are exposed and the convection will then mix normal carbon material into the carbon depleted layers, reducing the carbon deficiency to small, generally undetectable, levels.

5. Conclusions

Analysis of *IUE* data on four binary systems (DH Her, TU Mon, RY Per, and V356 Sgr) strongly supports the conclusion that the lack of carbon lines in their circumstellar matter is the product of an inherent carbon deficiency in the transferred material and not due to any ionization effects in the gas. The carbon deficiency in these systems is the result of CNO processed layers being exposed as a result of mass transfer. Only one of the studied systems, ET Tau, gave indication of a normal carbon abundance.

The four binary systems discussed here offer a unique opportunity to directly observe matter that was recently deep in the energy producing interior of a star, providing an interesting test of binary star evolution theory and a direct test of stellar evolution CNO reaction rates.

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