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**COLLIDING STELLAR WINDS IN O-TYPE CLOSE BINARY SYSTEMS**

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**FINAL TECHNICAL REPORT**

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## 1. INTRODUCTION

This report summarizes a study of the stellar wind properties of O-type close binary systems conducted in the Department of Physics and Astronomy of Georgia State University. The main objective of the program was to search for colliding winds in four systems, AO Cas,  $\iota$  Ori, Plaskett's Star, and 29 UW CMa, through an examination of high dispersion UV spectra from *IUE* and optical spectra of the H $\alpha$  and He I  $\lambda$ 6678 emission lines obtained at the University of Texas McDonald Observatory. The luminous O-type stars continuously shed their outer gaseous layers in a supersonic outflow or stellar wind. In systems of close binary stars, the winds from each star will collide between the stars and be diverted along a bow shock (Luo, McCray, & Mac Low 1991, *Ap. J.*, 362, 267). The high velocity part of the flow is best observed in the UV resonance lines formed in the wind (Howarth & Prinja 1989, *Ap. J. Suppl.*, 69, 527), while the low velocity, high density component can be traced through optical emission lines (Ebbets 1982, *Ap. J. Suppl.*, 48, 399). Our program was designed to combine these two types of data to develop a consistent picture of how stellar winds interact in close binary systems.

We obtained the *IUE* spectra during a visit in August 1989 to the NASA *IUE* Regional Data Analysis Facility at the University of Colorado in Boulder. The data consist of high resolution spectra of the N V  $\lambda$ 1240, Si IV  $\lambda$ 1400, C IV  $\lambda$ 1550, He II  $\lambda$ 1640, and N IV  $\lambda$ 1718 line profiles. There are typically ten to thirty spectra of each star which are well distributed in orbital phase. These spectra have been reduced to a common rectified format for analysis. Similarly, all the McDonald Observatory optical spectra were reduced to a common format for straight forward comparison with the UV data.

The analysis of wind features formed the basis of a Master of Science Degree thesis by Michael S. Wiggs (under the direction of D. R. Gies), and the results are summarized in §2. In brief, we have found evidence for high density regions between the stars in three of the four systems, and each of these regions probably form the apex of a bow shock. The UV line profiles also show orbital phase related changes that are consistent with the existence of bow shocks in these systems.

During the course of this work, we also began a study of photospheric lines in the UV spectra using a tomography algorithm familiar in medical applications to derive the separated spectra of each component star. The algorithm for this application was developed

by W. G. Bagnuolo, Jr., and our results to date are summarized in §3. A full bibliography of published work associated with this project appears in §4.

The NASA ADP support has made possible (through matching funds) the purchase of a DECstation 3100 computer (plus tape drive and laser printer) which has been the primary tool for this analysis. We are grateful for this financial support that has been so important for the completion of this project.

## 2. EVIDENCE FOR COLLIDING WINDS

### AO Cas

We began our search for spectroscopic evidence of colliding stellar winds in binary systems of O-type stars with a study of AO Cas, a short period, double-lined spectroscopic binary. We examined the orbital phase related variations of the  $H\alpha$  and He I  $\lambda 6678$  line profiles to derive the location and motions of high density circumstellar gas in the system. We compared these profile variations with those observed in the UV stellar wind lines in *IUE* archival spectra. The *IUE* spectra were also used to derive a system mass ratio by constructing cross correlation functions of a single-lined phase spectrum with each of the other spectra. The resulting mass ratio,  $q = M_s/M_p = 1.47 \pm 0.08$  is consistent with the rotational line broadening of the primary (more luminous) star, if the primary is rotating synchronously with the binary system. The other system dimensions were estimated by comparing model light curves and line profiles with the observations. The best fit models have an inclination of  $i = 61.1^\circ \pm 3.0^\circ$  and have a primary which is close to filling its critical Roche lobe. The primary is undermassive for its spectral classification (O9 III), and the secondary has a mass and radius typical of a late O-type main sequence star. We formed  $H\alpha$  difference profiles by subtracting model photospheric lines from the observed profiles, and the velocity curve of these profiles indicates that the emission originates near the hemisphere of the secondary that faces the primary star. The large peak-to-peak width and the lack of significant equivalent width changes in the  $H\alpha$  difference profiles suggest that the emission forms in a bow shock near the secondary where the winds collide.

The UV stellar wind lines are dominated by the wind of the primary, and the absence of any large changes in the absorption edge velocities of these lines indicates that the bow

shock never substantially occults the primary. However the red emission peak of the Si IV P Cygni type line reaches a maximum intensity near superior conjunction of the primary which is consistent with a lack of wind material in the region where the primary's wind sweeps past the secondary.

### Plaskett's Star

The strong  $H\alpha$  emission found in this system apparently contains two components, a sharp emission peak that displays a radial velocity curve similar to that of the primary star, and a very broad emission plateau that shows no discernible orbital motion but does change significantly from night to night. The former component probably forms in a bow shock very close to the primary while the second component may form in instabilities in the shock region between the stars. Placement of the bow shock close to the primary star suggests that the secondary star in fact has the stronger wind which is surprising given the relative weakness of the spectral lines of the secondary. On the other hand, there is evidence from the tomographic analysis (§3) that the secondary is a rapid rotator so that its lines appear weak due to large rotational Doppler broadening.

The UV wind profiles show little evidence of orbital motion and consequently these profiles cannot be used directly to infer which star has the dominant wind. However, the C IV and N V P Cygni absorption troughs show a significantly weakening following inferior conjunction of the primary star. We suggest that this weakening is caused by the trailing bow shock surrounding the primary star. The density of scattering ions within the shock cone is significantly lower than in the undisturbed wind of the secondary, and thus at orbital phases when the bow shock cone is projected against the wind of the secondary there is a reduction in number of scattering ions in our direction and the absorption trough weakens.

### 29 UW CMa

The strong  $H\alpha$  emission in this binary system shows little evidence of orbital motion, which suggests an origin between the stars close to the center of mass. The emission intensity peaks at both conjunction phases. If the line emission is optically thick then the emission strength depends on the projected area of the emitting cloud, and thus we

suspect that the cloud forms a disc shaped region with a surface normal to the axis joining the stars.

The  $H\alpha$  emission suggests the existence of a bow shock between the stars with a wide opening angle. The UV wind lines also support this picture. The blue edge velocities of the P Cygni absorption troughs decrease near primary superior conjunction when the bow shock occults the wind of the primary, and the bow shock effectively removes the highest velocity part of the flow oriented in our direction during these phases. We also find that the P Cygni emission peaks reach greatest intensity at the conjunction phases when the bow shock volume enclosing the secondary presents the smallest projected area on the sky.

### $\iota$ Ori

This system has the highest eccentricity in our sample ( $e = 0.76$ ) and we are particularly interested in how the wind conditions change near periastron. The  $H\alpha$  profile in this system shows no trace of emission except very close to periastron when broad, weak emission slightly alters the appearance of the profile. The UV P Cygni features appear relatively constant with orbital phase (particularly the blue edge velocity) but there is some evidence of the orbital motion of the primary in the red emission peak of C IV, which suggests that the primary has the dominant wind as expected. The results suggest that the wind of the primary is relatively undisturbed through most of the orbit, but the wind may become focused in the direction of the secondary close to periastron passage when the primary comes close to filling its effective Roche volume (Stevens 1988, *M.N.R.A.S.*, 235, 523).

## 3. TOMOGRAPHIC SEPARATION OF COMPOSITE SPECTRA

The UV spectra of hot stars contain many weak photospheric lines in addition to the resonance lines formed in the wind. However in close binary systems, the lines of the individual components are often too blended to permit an analysis of the line strengths or allow a spectral classification. We have begun a program of separating the individual component spectra by using a tomography algorithm to re-construct the individual spectra from a set of combined spectra of differing orbital Doppler shifts. The tomography algorithm is an iterative method that makes successive corrections to the spectra of each

component using an assumed intensity ratio and the velocity curves for each component. The resulting spectra tend to have a better  $S/N$  ratio than any individual spectrum since data from many spectra are combined in the re-construction. Furthermore, because the UV photospheric lines form in higher excitation transitions than optical lines, the resulting spectra are less prone to contamination from circumstellar emission components. Tomography appears to be an extremely useful technique for studying the spectra and physical properties of both the primary and especially the less luminous secondary components of binary systems. Here we summarize the results from tomography for three of the program stars; we plan to study the fourth star,  $\iota$  Ori, later this year.

### AO Cas

The *IUE* data were analyzed with the tomography algorithm to produce the separate spectra of the two stars in six spectral regions. The spectral classifications of the primary and secondary, O9.5 III and O8 V, respectively were estimated through a comparison of UV line ratios with those in spectral standard stars. We also estimated the intensity ratio to be in the range 0.5 – 0.7 (primary brighter) at 1600 Å through a comparison of line strength in several features.

### Plaskett's Star

A cross-correlation analysis showed that the secondary produces significant lines in the UV, and we fitted the cross-correlation functions for both components to derive a velocity curve for the secondary star. The resulting mass ratio is  $q = 1.18 \pm 0.12$  (secondary slightly more massive). Tomography was again used to produce the separate spectra of the two stars in six spectral regions. From a comparison with spectral standard stars, we derive interpolated spectral classifications of O7.3 I and O6.2 I for the primary and secondary, respectively. The intensity ratio in the UV is  $0.53 \pm 0.05$  (primary brighter). However, the secondary apparently has a stronger stellar wind since we find that the N IV  $\lambda 1718$  line is a well developed P Cygni profile in the secondary star spectrum while the feature is a pure absorption line in the spectrum of the primary. The secondary lines are rotationally broadened, and we estimate the projected rotational velocity to be  $310 \pm 20 \text{ km s}^{-1}$ .

## 29 UW CMa

A preliminary cross-correlation study of the UV photospheric lines indicates that the secondary is visible in the UV but it is faint (intensity ratio  $\approx 0.25$ ). A velocity curve for the secondary derived from the cross-correlation functions yields a mass ratio of  $q = 0.95 \pm 0.18$ . The spectral classifications are approximately O7 I and O9.5 III for the primary and secondary, respectively, from a preliminary tomographic analysis. The N IV  $\lambda 1718$  feature is a P Cygni profile for the primary only, and so the primary clearly possesses the stronger wind.

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