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OBSERVATIONS OF COLLIDING WINDS IN O-TYPE BINARIES

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RESUMEN

En sistemas binarios cercanos formados por estrellas de tipo O, los vientos estelares chocarán en un arco. La presencia de este contorno reducirá la extensión espacial total de los vientos individuales y, en consecuencia, las líneas espectrales formadas en el viento aparecerán de manera diferente según la orientación desde donde se las vea. Aquí se discuten las variaciones orbitales de las líneas ultravioletas formadas en el viento, en una amplia muestra de binarias de tipo O que han sido observadas con el *Satélite Explorador Ultravioleta Internacional (IUE)*. Regiones de alta densidad en el viento (cerca de las fotosferas y del arco de choque) producirán líneas de emisión en el óptico y se describen aquí las propiedades de la emisión Hα de varios sistemas. Las características físicas de las estrellas que componen estos sistemas binarios, pueden ahora estimarse con mayor precisión mediante la tomografía Doppler, un método numérico para extraer los espectros individuales de las componentes primaria y secundaria.

ABSTRACT

Stellar winds will collide in a bow shock in close binary systems of O-type stars. The presence of this boundary will truncate the full spatial extent of the two individual winds, and thus the spectral lines formed in the wind will appear differently when viewed from different orientations. Here I discuss the orbital variations of the UV wind lines in a large sample of O-binaries that have been observed with the *International Ultraviolet Explorer Satellite (IUE)*. High density regions in the wind (near the photospheres and bow shock) will produce optical emission lines, and I describe the Hα emission properties of several systems. The physical characteristics of the component stars can now be better estimated through Doppler tomography, a numerical method to extract the individual primary and secondary spectra.

Key words: **BINARIES: SPECTROSCOPIC — STARS: EARLY-TYPE — STARS: MASS LOSS**

1. INTRODUCTION

Radiatively driven winds are found in all massive, luminous stars, and in close binary systems the individual winds will collide in a bow shock which will wrap around the star with the weaker wind. The geometrical and physical characteristics of the collision boundary depend on the individual wind density and velocity laws, plus the system separation and orbital velocities, so there will be a great diversity in colliding wind properties among observed binaries. Exploratory hydrodynamical simulations of colliding winds have been made by Stevens, Blondin, & Pollock (1992) and Walder (1995). These show that the enhanced temperature and density in the shock could produce a significant X-ray flux (Corcoran 1996) and emission lines (Moffat 1996).

Several groups have now begun to search for observational evidence of colliding winds in binaries of two O-type stars, since such systems have winds that are strong enough for strong colliding winds to develop but that are not so strong that the stellar photospheres are obscured. Koch and collaborators (Koch 1996) have examined the integrated flux in stellar wind features using light curve synthesis methods to explore the extra flux due to colliding wind effects. Together with my colleagues at Georgia State University, I have been studying the orbital phase related variations in UV and optical line profiles to use Doppler shift information to help determine the site of emission in these binaries. Our work has centered on variations in the UV wind lines (formed by scattering, $\propto n =$ the number density, over a large volume surrounding the stars) and in optical emission lines like Hα (formed by recombination, $\propto n^2$, in high density regions of circumstellar gas).

Here I will review some of the initial results from these spectroscopic studies of O-binaries. Since the wind properties of the individual components depend on the stars' physical characteristics, I will begin with a short description of a new method, dubbed "Doppler tomography," to extract the individual component spectra from the observed composite spectra. The presence of a bow shock in colliding wind binaries imposes a boundary on the spatial extent of the individual winds, and consequently, the P Cygni type line profiles normally observed in the UV spectra of O stars will be altered in shape according to the system orientation. I describe what kind of orbital variations are expected and what we actually observe in a large sample of binaries observed with *IUE*. The optical emission line properties of the O-binaries are still being surveyed (Thaller 1996), but I will describe some of our initial results on several well known systems. The Hα emission properties of these systems were first explored in the pioneering work of Professor Sahade (e.g., Sahade 1962) long before there was an appreciation of the massive stellar winds of O stars, and it is now clear that these emission line observations provide valuable clues about the distribution of circumstellar gas and the nature of colliding winds in these binaries.

2. SEPARATING THE SPECTRA OF CLOSE BINARIES

The study of the spectra of close binary stars is generally hampered by severe line blending which has limited investigators to the examination of a small fraction of systems with wide velocity separation at certain orbital phases in spectral regions sparsely populated in lines. There are now several numerical techniques available which can bypass the line blending problem and yield the complete spectra of the components in close binaries from a set of composite spectra obtained at a variety of orbital phases. The methods include Doppler tomography (Bagnuolo et al. 1994), singular-valued decomposition (Simon & Sturm 1994), and Fourier decomposition (Hadrava 1995). These methods can be applied to a wide variety of binary systems (essentially all those where the orbital Doppler shifts are comparable to or larger than the characteristic spectral line widths), and offer the means to study faint companions (since the methods generally provide a $\sqrt{n}$ improvement in signal-to-noise ratio, where n is the number of spectra used).

The Doppler tomography algorithm is an iterative least-squares technique to reconstruct primary and secondary spectra from an ensemble of composite spectra obtained around the orbit. The algorithm uses the radial velocity curves of both components and an estimate of the magnitude difference in the spectral range of the observations. The latter quantity can be revised after spectral reconstruction by comparing the equivalent widths of lines in the primary and secondary spectra with those in single star spectra. The individual spectra can then be analyzed to determine spectral types and luminosity classes, projected rotational velocities, and to search for unusual chemical abundances. The spectral classification yields an estimate of effective temperature, and, taken together with the monochromatic flux ratio, the luminosity ratio can then be estimated. These parameters are key to predicting the individual mass loss rates and terminal wind velocities.

Penny (1996a) has applied the Doppler tomography algorithm to *IUE* high dispersion spectra of some 30 O-type binaries. She has developed UV classification criteria for O stars (Penny, Gies, & Bagnuolo 1996) to apply to the separated spectra (some initial results are given in Table 1), and she has shown how cross-correlation

TABLE 1

SEPARATED SPECTRAL TYPES

Star	Name	Primary	Secondary	M_2/M_1
HD 1337	AO Cas	O9.5 I	O8 V	1.47
HD 37043	ι Ori	O9 III	B0 III	0.49
HD 57060	29 UW CMa	O7.5 Iabf	O9.7 Iab	1.20
HD 47129	Plaskett's	O7.5 I	O6 I	1.18
HD 93403	...	O5	O7 III	0.76
HD 152218	...	O9 III	B0 III	0.68
HD 152248	...	O8 Ib	O7.5 Ib	1.07
HD 165052	...	O6 V	O7 V	1.05
HD 215835	DH Cep	O6 V	O7 V	0.86

functions of the binary spectra with a narrow-lined template spectrum can be used to determine projected rotational velocity (Penny 1996b). She has used the cross-correlation method to measure projected rotational velocities of 177 O stars using spectra from the *IUE* archive. In the course of this work, she has identified 10 new binaries, 20 line profile variables, and found evidence for rotational spin-down by stellar wind angular momentum loss in the most massive stars.

The early results from Doppler tomographic reconstruction of *IUE* spectra of massive binaries have been very rewarding. We have made the first clear detection of the secondary star in one of the most massive binary systems, Plaskett's star (Bagnuolo, Gies, & Wiggs 1992), and we have detected the long sought companion to the Be-binary system, ϕ Persei (Thaller et al. 1995). The secondary in the latter system is a very hot, small star, presumably the stripped-down remains of a once massive object (and a possible pre-cursor of peculiar supernovae). These initial studies demonstrate the great potential of these methods of spectrum reconstruction.

3. ORBITAL VARIATIONS IN THE UV WIND LINES

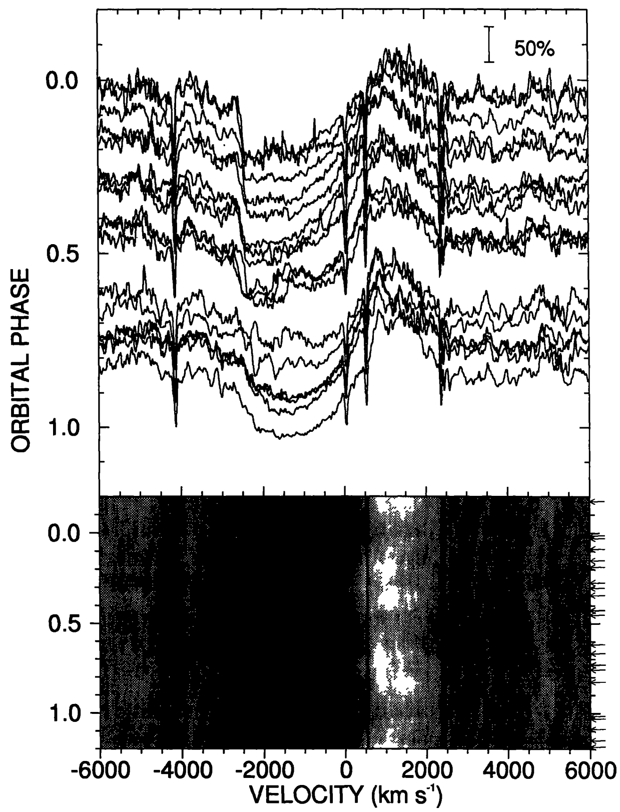
The strong P Cygni profiles observed in the ultraviolet spectra of most luminous O-type stars are formed by scattering in a large volume of the wind. When two O-stars are found in close proximity in a binary, the situation immediately becomes more complex because there are now two sources of photons for scattering and two wind structures in which scattering can occur. The simplest case occurs where the wind and luminosity of one star dominates the binary. Auer & Koenigsberger (1994) discuss this case (applicable to some WR + O binaries) and show how the P Cygni profiles vary with orbital phase as the disk of the fainter star occults various portions of the dominant star's wind (and vice versa). However, in many O-type binaries (particularly the double-lined systems) both stars will have significant winds, and the full complication of scattering in two winds must be considered.

An important first step was an investigation by Stevens (1993) who made Monte-Carlo simulations of photon scattering in colliding wind binaries with the express purpose of studying the orbital variations in the P Cygni lines. He presents results for an idealized system of equal luminosity stars, with equal momentum in their winds, observed from the orbital plane ($i = 90°$). In these models the bow shock is a zero-width plane, and scattering processes associated with the high densities in the shock front are simply ignored. Thus, these simulations are meant to illustrate how the P Cygni lines will vary due to (1) the spatial truncation of the individual winds by the shock, and (2) the scattering of photons from one star by the wind of the other star. The models do not include the orbital motions of the stars, but since orbital speeds are generally small compared to wind speeds, these models should offer broad guidance about what we might expect to observe.

Three of these simulations are immediately relevant to O+O binaries. (1) When both stars have optically thick winds, minimal variability is found since scatterers in the wind of the foreground star always compensate for lost scattering ions from the star behind that are blocked by the bow shock. (2) However, when only one wind is optically thick, the P Cygni line displays large changes when the star with the optically thin wind is in front. The extreme blue-edge velocity, $v_{\rm edge}$, declines (since the wind of the star behind strikes the bow shock before reaching terminal velocity) and the absorption trough weakens (since photons from the foreground star stream unimpeded in the observer's direction). (3) If the winds have different terminal velocities, the model profiles show significant variations in $v_{\rm edge}$ as the fast and slow winds pass in front of the system.

These simulations demonstrate that the presence of colliding winds can, in some circumstances, lead to orbital phase variations in the shapes of the composite UV wind lines in O-binaries. Thus we are making an observational search for such variations in a sample of 30 O+O close binary systems for which there is good orbital phase coverage with high dispersion (SWP/H) *IUE* spectra. This group represents most of the double-lined systems in sky brighter than $V < 8$. Studies are complete for four binaries: AO Cas (Gies & Wiggs 1991), Plaskett's star (Wiggs & Gies 1992), 29 CMa (Wiggs & Gies 1993), and ι Ori (Gies, Wiggs, & Bagnuolo 1993). We obtained new spectra for many systems, but fortunately there are a huge number of archival spectra available (thanks to the observing programs of Sally Heap, Bob Koch, Dave Stickland, and other *IUE* observers). The full survey of the P Cygni line variations in these systems is the subject of Thaller's dissertation (in preparation), but here I present a brief summary of preliminary results (see Gies 1995 for a more complete summary).

The orbital phase variations of the C IV λ1550 doublet in the spectrum of Plaskett's star (Fig. 1) provide a good illustration of the behavior seen in many binaries (see also Sahade & Brandi 1991). A tomographic analysis of its UV photospheric spectrum by Bagnuolo et al. (1992) revealed that the "secondary" is actually the more massive star, and it eluded easy detection in the past because its spectral lines are broad and shallow ($V \sin i = 310$ km s^{-1}). The N IV λ1718 feature appears as a P Cygni profile in the secondary's reconstructed spectrum and as an absorption line in the primary's spectrum which indicates that the secondary has the stronger wind. At secondary superior conjunction (orbital phase 0.5), the P Cygni absorption weakens as the



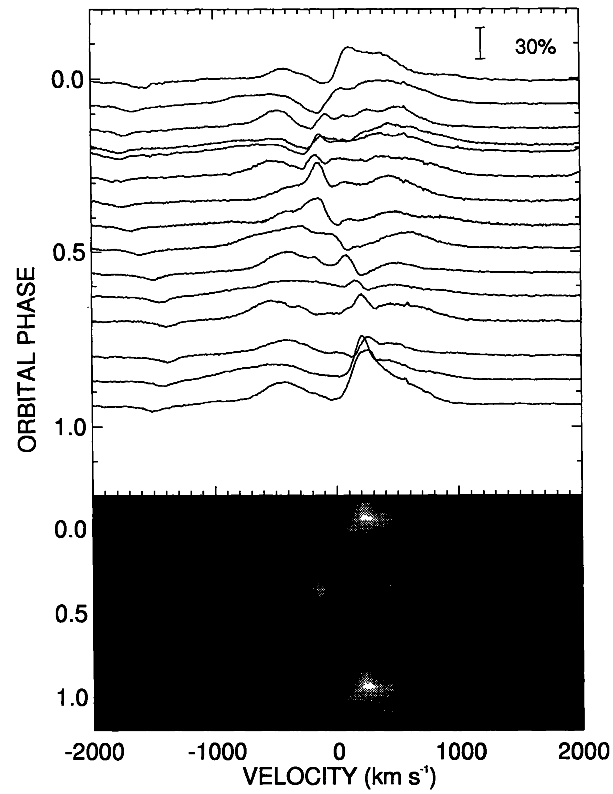


Fig. 1. C IV λ1550 profiles of Plaskett's star plotted against radial velocity (based on the blue member of the doublet). The spectra in the upper panel are arranged with the continuum level (set to unity) located at the orbital phase of observation. The lower gray-scale representation of the spectral variations is the result of a linear, orbital phase interpolation of the spectra. Note the decrease in absorption strength near superior conjunction of the strong wind secondary (phase 0.5).

Fig. 2. Hα profiles of Plaskett's star plotted against radial velocity (in the same format as Fig. 1). The weak absorption feature at the left edge is He II λ6527.

weak wind star (the primary in this case) passes in front. This is very similar to the prediction of Stevens' case (2), described above, in which there is reduced scattering in the foreground wind of the primary star. In contrast, the emission part of the profile remains approximately constant throughout the orbit.

Stevens' models make no prediction about orbital motion, but there is evidence of some orbital motion in the emission peak in the UV wind lines of binaries like AO Cas. The scattering ions responsible for the P Cygni emission peak are mainly found relatively close to the photosphere, and this part of the profile will often show the Doppler shifts associated with the photosphere (especially where one star in the binary has a dominating wind). On the other hand, orbital motion in the blue edge of the absorption trough is never observed (see Fig. 1). This lack of orbital motion is probably due to the great distance of the scattering ions from the star (near terminal velocity); here the integrated column density includes wind contributions that originated at all orbital phases, and any orbital variations are averaged out.

4. UV AND Hα CASE STUDIES

Observations of the UV wind line variations help map out large wind structures while spectroscopy of recombination lines like Hα probe the the high density portions of the wind (close to shock fronts and photospheres). Here I describe a few systems where both kinds of observations are in hand.

4.1. Plaskett's Star (HD 47129)

The dramatic Hα emission in this system was first studied by Struve, Sahade, & Huang (1958). A high signal-to-noise study of Hα was made by Wiggs & Gies (1992) using Reticon spectra from the University of Texas McDonald Observatory 2.1-m telescope (the same telescope used by Struve and Sahade in their investigations of massive binaries). The orbital variations in Hα are illustrated in Figure 2. The Hα emission has two main components: (1) a broad stationary feature which displays large night-to-night variations (non-orbital), and (2) a sharp emission "spike" that follows the velocity curve of the primary with a small phase lag.

The UV wind and Hα variations can be explained in the framework of the colliding winds model. The strong wind of the secondary star hits the wind of the primary and forms a broad bow shock that flows around the primary (see Fig. 3). The lower density of scatterers behind the bow shock causes a reduction in the P Cygni absorption around and following secondary superior conjunction (orbital phase 0.5; see Fig. 1). The bow shock geometry shown in Figure 3 is based on a model of Girard & Willson (1987) for a wind momentum ratio of $mw = 10$.

The spike component of Hα emission has a radial velocity curve that can be expressed as the vector sum of orbital motion (for a position centered on the primary) and gas flow (from secondary to primary), and thus this emission probably originates in post-shock gas near the primary (shaded region in Fig. 3). The intensity variations of the spike feature suggest that the emission cloud is elongated along the axis corresponding to the Coriolis deflection of the bow shock. The second, high velocity component of Hα emission displays no orbital motion, and it probably forms in high density knots in the vicinity of the shock region (the time scale of variations in the high velocity component is similar to the wind flow time between the stars which Stevens et al. 1993 show is the time scale for the development of instabilities in the flow).

4.2. AO Cas (HD 1337)

Struve & Sahade (1958) first studied the variable Hα emission in AO Cas. Gies & Wiggs (1991) made high signal-to-noise Reticon observations of Hα and formed residual profiles by subtracting the predicted photospheric lines. The velocity curve of the residual Hα emission line indicates that most of the emission originates close to the hemisphere of the secondary facing the primary. The width of the Hα emission is consistent with a scenario in which the winds collide and spread out along a bow shock wrapped around the secondary (with a probable Coriolis deflection). Gies, Bagnuolo, & Penny (1996) show how the close proximity of the bow shock to the photosphere of the secondary will preferentially heat one hemisphere of the secondary and cause variable secondary line depths.

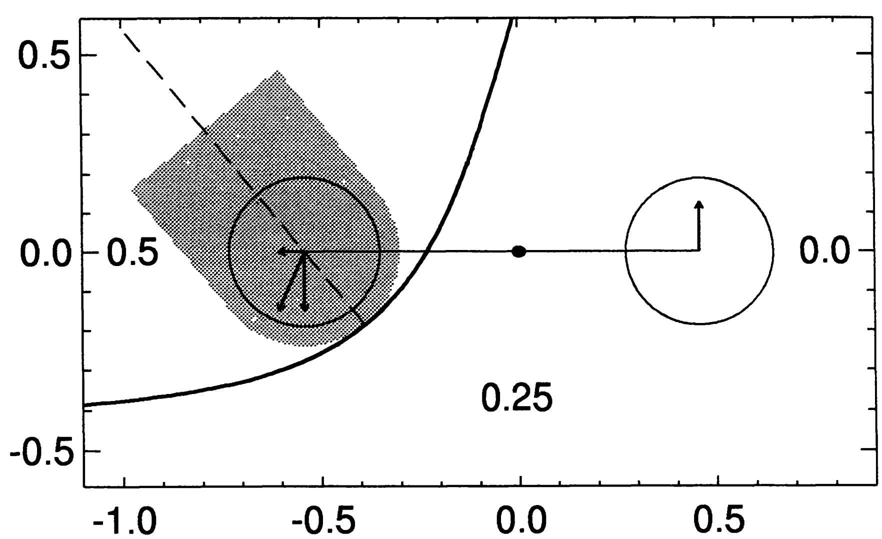


Fig. 3. A schematic diagram of Plaskett's star as seen from above the orbital plane. A colliding winds bow shock (*thick line*) wraps around the weaker wind primary ((*left*), and displays a coriolis deflection (*dashed line*) due to orbital motion. The arrows show vector components of orbital and Hα emission spike motion.

4.3. 29 UW CMa (HD 57060)

The Hα emission variations were first investigated by Struve et al. (1958). New Hα observations from McDonald Observatory (Wiggs & Gies 1993) indicate that Hα consists of (1) a P Cygni component that shares the motion of the primary (and which originates at the base of its wind), and (2) a broad, stationary emission component. The broad emission component probably forms in a plane midway between the stars where the winds collide (in a similar way to the broad Hα component in Plaskett's star). The UV P Cygni lines appear to be more influenced by the primary's wind since the red emission peaks follow the primary's motion. A bow shock wrapped around the secondary might be expected because of this dominance of the primary's wind, but a planar bow shock is possible if the secondary has an optically thick and fast wind (probable for a B0 I star; see Bagnuolo et al. 1994). In this scenario, the secondary's wind provides the scattering ions to maintain P Cygni absorption when secondary is in front (see Stevens 1993).

4.4. V453 Sco (HD 163181)

Sahade & Frieboes-Conde (1965) studied this massive binary (B0.5 Iae + an emission line star), and obtained a mass ratio ($M_2/M_1 > 1$) based on the radial velocities of the emission lines. Hutchings (1975) observed absorption lines he associated with the secondary spectrum, and determined $M_2/M_1 = 1.7$. With my colleagues at GSU, I have begun an analysis of eight *IUE* high dispersion spectra of the system. Radial velocities from cross-correlation functions of the target spectra with a reference spectrum clearly reveal the secondary, and indicate a mass ratio in the range $M_2/M_1 = 1.4-1.7$. A preliminary tomographic reconstruction suggests a secondary of type B2.5 I with strong wind features (the UV flux ratio is $F_2/F_1 \approx 0.7$). Thaller (in preparation) has recently obtained new high quality Hα spectra of this system from Mount Stromlo Observatory.

5. SUMMARY

The foundations of this work were set by Sahade during the "Struve Revolution," and it is now clear that his observations of the orbital variations in Hα and other emission features contain important clues about the dense circumstellar material and can be used to study the location and velocity of gas near the bow shock region. On the other hand, the orbital variations in the UV wind lines act as a probe of the large scale wind geometry, and the common occurrence of absorption reductions when the strong wind star is behind indicates that colliding vind effects are present in most O-binaries. These kinds of investigations will lead to a better understanding of mass flows in O-type binaries, and will help elucidate the nature of shocks due to colliding winds, the rôle of mass loss versus mass transfer in massive binaries, and the evolutionary paths of massive binaries and their descendants (WR binaries, massive X-ray binaries, binary pulsars, etc.). In the near future, many of these targets will be resolved with optical interferometers (such as the GSU Center for High Angular Resolution Astronomy Array, a 5 element instrument with a 350-m baseline), and our current studies will provide the background to help interpret these much anticipated observations.

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