Mass-Loss Rates from Hα Emission: A Caution for Binary Systems

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Abstract. A common diagnostic for mass loss in O stars is Hα emission, formed by recombination in the dense regions of stellar winds. While observations of this kind may be a straightforward method of estimating mass-loss rates in single stars, there may exist a complication in binary systems. If winds in close, hot binaries interact, perhaps even collide to form a bow-shock between the stars, there may be augmented Hα emission which has nothing to do with simple mass loss.

I report the results of an all-sky survey of Hα emission in the spectra of O-type binaries to search for colliding-wind effects. The survey includes 31 systems, of which 10 have emission that extends clearly above the continuum. An additional three systems show small distortions in the Hα profile that may result from weak emission. I compare the distribution of emission systems in HR diagrams for both binary and single stars, using a survey of single O-type stars done by Conti (1974), and a more recent, although less extensive, survey by Kaper et al. (1997). To ascertain whether or not colliding winds have been observed, it is necessary to study the Hα line profile throughout several orbits of each candidate system and look for recurring orbital-phase-related variations. I have completed a preliminary analysis for HD 149404, and I present dynamic spectra of the Hα line for this system as well as a schematic of the proposed mass distribution and flow.

1. Introduction

Radiatively driven winds are found in all massive, luminous stars, and in close binary systems the individual winds may collide in a bow shock which will wrap around the star with the weaker wind. One observational consequence of colliding winds is Hα emission. This emission is caused by recombination, in which the emissivity scales with the square of the density, making this line an excellent probe of dense regions in the wind. Enhanced density is expected in two places, the lower layers of the wind near the photosphere of the generating star, and at the shock. The lower-wind contribution to Hα comes from layers typically between 1.0 and 1.5 stellar radii (Puls et al. 1996). Such base-level emission will show radial-velocity variations similar to the stars themselves. Emission formed in the shock region, on the other hand, will display velocity variations defined

Table 1. Survey Binary Systems (see Section 2 for details).

Star	Name	P(days)	Spectral Types	Ref.	Emission	Ref.
HD 1337	AO Cas	3.52	O9.5 III + O8 V	GIE91	−1.53	GIE91
HD 19820	CC Cas	3.37	O8.5 III + O9 IV	WAL73	n	···
HD 23180	o Per	4.42	B1 III	LYN60	n	···
HD 35921	LY Aur	4.00	O9.5 III	HIL95	1.35	···
HD 36486	δ Ori	5.73	O9.5 II	HOW97	p	···
HD 37043	ι Ori	29.13	O9 III + B1 III	GIE96	p	GIE96
HD 47129	Plaskett's	14.40	O7.5 I + O6 I	WIG92	−7.43	WIG92
HD 48099		3.08	O7 V	HOW97	n	···
HD 53975		6.02	O7.5 V	GIE94	n	···
HD 57060	UW CMa	4.39	O8 Iaf + O	WIG93	−5.25	WIG93
HD 57061	τ CMa	1.28, 154.90	O9 II	GIE94	p	···
HD 75759		33.31	O9 Vn	WAL73	n	···
HD 93205		6.08	O3 V + O8 V	PEN96	n	···
HD 93206	QZ Car	20.74, 6.00	O9 III, O9.5 I	MOR80	−3.82	MOR80
HD 93403		15.09	O5 III + O7 III	PEN96	−0.62	···
HD 97484	EM Car	3.41	O8 V + O8 V	GAR77	n	···
HD 100213	TU Mus	1.39	O8.5 Vn	WAL82	n	···
HD 101205		2.084	O7 IIIn((f))	WAL73	n	···
HD 135240	δ Cir	3.90	O7.5 III	WAL72	n	···
HD 149404		9.81	O8.5 I + O6.5 III	PEN96	−7.01	MAS79
HD 150136		2.7	O5 IIIn(f)	WAL72	n	···
HD 152218		5.60	O9 III + O9.8 III	PEN94	−0.38	···
HD 152248		5.82	O7 I + O7 I	PEN96	−2.02	···
HD 159176		3.67	O7 V + O7 V	WAL73	n	···
HD 163181	V453 Sco	12.01	BN0.5 Iae	SAH65	−7.27	SAH65
HD 165052		6.15	O6 V + O6 V	PEN96	n	···
HD 167771		3.97	O7.5 III + O9 III	MOR78	p	···
HD 198846	Y Cyg	3.00	B0 V + B0 V	HIL95	n	···
HD 206267		3.71	O6.5 V + O9	WAL73	n	···
HD 209481	LZ Cep	3.07	O9 V + O9 V	WAL73	n	···
HD 215835	DH Cep	2.11	O6 V + O7 V	PEN96	n	···

References: GAR77 = Garrison, Hiltner & Schild (1977); GIE91 = Gies & Wiggs (1991); GIE94 = Gies et al. (1994); GIE96 = Gies et al. (1996); HIL95 = Hill & Holmgren (1995); HOW97 = Howarth et al. (1997); LYN60 = Lynds (1960); MOR78 = Morrison & Conti (1978); MOR80 = Morrison & Conti (1980); PEN94 = Penny, Bagnuolo & Gies (1994); PEN96 = Penny (1996); SAH65 = Sahade & Frieboes-Conde (1965); WAL72 = Walborn (1972); WAL73 = Walborn (1973); WAL82 = Walborn (1982); WIG92 = Wiggs & Gies (1992); WIG93 = Wiggs & Gies (1993).

by the spatial and velocity structure of the circumstellar gas. These velocity curves are often quite different from the motion of the stars

I have completed a census of wind-collision effects in a large sample of binaries in order to elucidate the nature of colliding-wind shocks, the role of mass loss versus mass transfer in massive binaries, and the consequences for their binary descendents (WR binaries, massive X-ray binaries, luminous blue variables, etc.). The survey includes all massive O+O binary systems with $V < 9$. My hope was to detect the presence of colliding winds by two methods: first, to demonstrate a general overabundance of Hα emission in binaries as opposed to single massive stars, and secondly, to follow up on the emission systems and model their mass structure using detailed observations of the variations in the Hα line profile.

2. Observations

Table 1 lists the 31 systems included in the survey. For 23 of the targets, I obtained spectra at Kitt Peak National Observatory (northern stars) and Mount

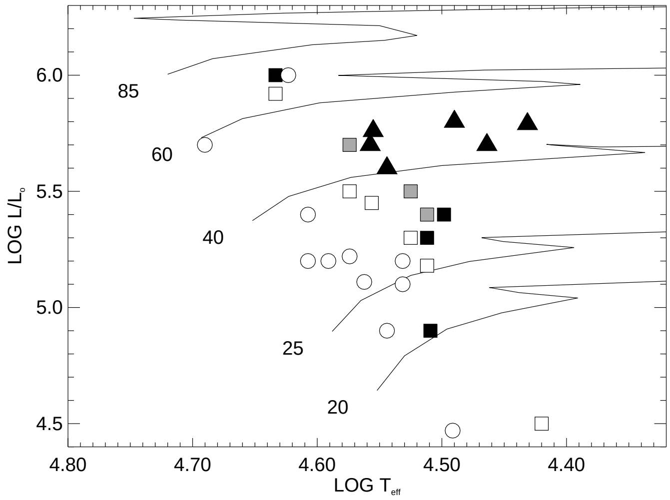

Figure 1. An HR diagram of the primary stars of the binary systems (circle = dwarf, square = giant, triangle = supergiant). Empty symbols indicate no detected emission, shading indicates weak distortion of Hα, and filled symbols indicate emission above the continuum.

Stromlo and Siding Spring Observatories (southern ones). In addition, I added the results of individual studies of four systems observed previously by Gies and collaborators: AO Cassiopeiae (Gies & Wiggs 1991), Plaskett's star (Wiggs & Gies 1992), ι Orionis (Gies, Wiggs & Bagnuolo 1993; Gies et al. 1996), and 29/UW Canis Majoris (Wiggs & Gies 1993). I have also added four systems recently observed by Kaper et al. (1997): HD 53975, HD 57061, HD 101205, and HD 150136. I divided the target systems into three categories based on the strength of Hα emission. Column 6 in Table 1 lists the emission category assigned to each target. The letter 'n' designates systems showing no visible emission or distortion of the Hα line. A 'p', for 'possible emission', designates systems where small distortions in Hα are present, but no emission extends above the continuum. The remaining stars show strong emission, and for these sources an equivalent width is given in Ångstrom. Ten binaries show strong emission, and this survey is the first detection of Hα emission for four of them: HD 35921, HD 93403, HD 152218, and HD 152248. The binary HD 152248 is composed of two supergiants close to filling their Roche surfaces (Penny 1996). In this case, Hα emission is expected due to the large luminosities and mass-loss rates of the stars. The other systems, however, contain giants. In these cases the emission detection is more interesting, as Hα emission is less common in these stars.

3. Discussion

Figure 1 shows the distribution of the binaries in an HR diagram. The diagram includes theoretical evolutionary tracks for stars of 20–85$M_\odot$ from Schaller et al. (1992). Only the position of the primary star in each of the systems is plotted, with circles representing dwarfs, squares giants, and triangles supergiants. The degree of shading of the symbols indicates the extent of the emission: empty symbols denote no emission, shading denotes a small distortion in the Hα line profile, and filled symbols denote strong emission. Figure 2 shows the single stars surveyed by Conti (1974) and Fig. 3 shows single stars surveyed by Kaper et al. (1997). Both sets of single stars are plotted on an HR diagram in the same format as Fig. 1. Conti's sample is more inclusive, but his data are of lower quality and resolution than Kaper et al.'s survey. It should be noted, however, that for stars common to both surveys, the emission detections are identical. In both cases, the single and binary groupings were assigned according to data from Gies (1987).

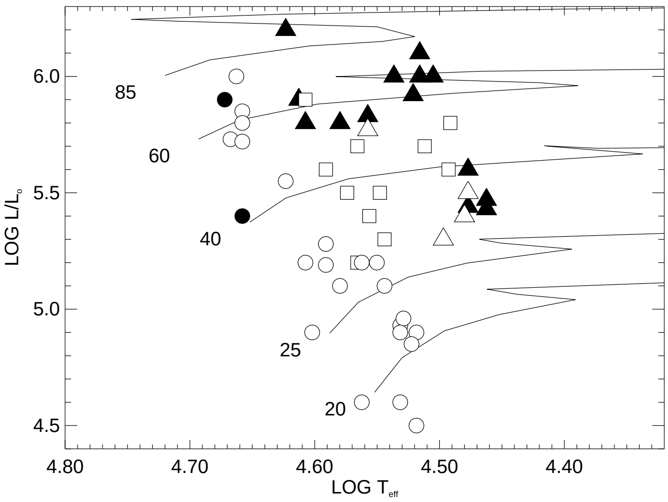

Figure 2. An HR diagram of single stars surveyed by Conti (1974) in a format similar to Fig. 1. Filled symbols denote emission above the continuum.

It is apparent that emission correlates strongly with the evolutionary phase of the primary star. Emission in main-sequence systems is extremely rare, and is completely absent in my sample of binary stars. Among binary stars, 53% of the systems containing O-type giants show some emission, while no single giants in either Conti's or Kaper et al.'s sample do. In the case of supergiants, 78% of Conti's and 71% of Kaper et al.'s single stars show emission, while all supergiant binaries show strong emission.

Detection of Hα emission in a system does not necessarily indicate the presence of colliding winds. Emission may come from a variety of sources: stellar-wind mass loss (Puls et al. 1996; Ebbets 1982; Leitherer 1988; Lamers & Leitherer 1993), a disk around a rapidly rotating star (Conti & Leep 1974), a corotating circumstellar structure (Stahl et al. 1996), or a gas stream due to Roche-lobe overflow. Hα emission is expected in luminous and evolved stars due to the strong stellar winds and mass-loss rates of these objects. However, the fact that binaries have a higher incidence and strength of emission in post-main-sequence stages (especially among the giants) may indicate that wind interactions are a common source of emission in massive binaries.

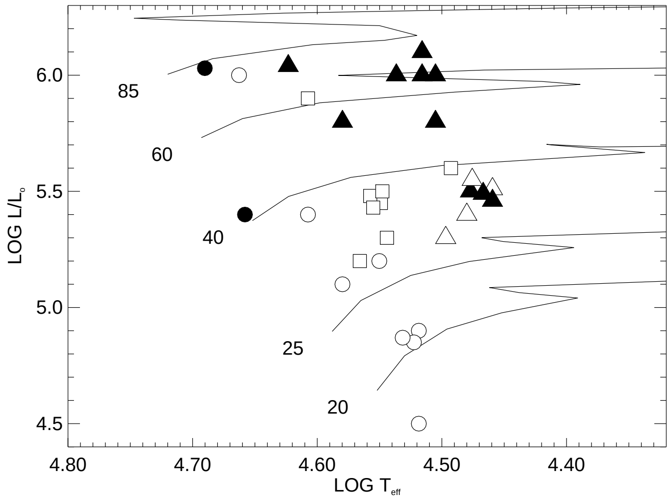

Figure 3. An HR diagram of single stars surveyed by Kaper et al. (1997) in a format identical to Fig. 2.

4. HD 149404

Another method of detecting colliding winds is the close examination of variable spectral lines. Studying orbital phase-related variations in the Hα profile, for example, can help to establish the site of the emission through a study of its radial-velocity curve. A case in point is the supergiant binary HD 149404. The first orbital elements for this system were determined by Massey & Conti (1979), who set the period at 9.813 days. Massey & Conti hypothesized that the large Hα emission seen in this system could be indicative of current large mass loss. They also discovered that the primary (O8.5 I) was less massive than the secondary (O6.5 III). Stickland & Koch (1996) have revisited this system and found a similar period of 9.8145 days, again with the secondary as the more massive component. As the more massive star is the less evolved, the system seems to have had a past epoch of mass transfer. If mass transfer has occurred, one would expect the rotational and orbital velocities to be synchronized. This is not the case, since both stars appear to be rotating at almost twice the synchronous rate (for $i = 21°$), and the inclination required for the primary (secondary) to be rotating synchronously is $44\overset{\circ}{.}4$ ($40\overset{\circ}{.}9$), higher than the maximum inclination Penny (1996) finds for this system.

In the case of HD 149404, the emission is composed of a broad feature that shows little variation and two peaks, one slightly stronger than the other, that show radial-velocity variations with the same period as the binary orbit. Figure 4 shows plots of the Hα line for HD 149404, placed in the upper portion of each diagram so that their continua are aligned with the orbital phase of the observation; $\phi = 0$ is defined as the maximum positive radial velocity of the primary star. The bar at the upper right indicates the intensity scale relative to the continuum. The lower portion of the figure shows the same spectra portrayed as a grey-scale image in which spectral intensity is directly proportional to grey-scale intensity (the stronger the emission, the brighter the shading). The

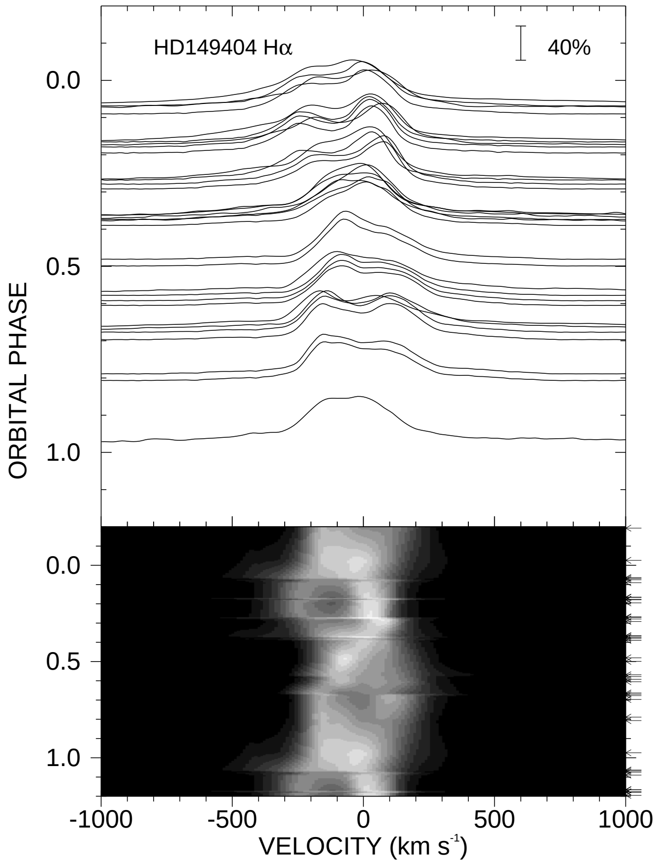

Figure 4. Upper panel: Hα line profiles plotted against heliocentric radial velocity, arranged in order of increasing orbital phase. Lower panel: Grey-scale representation of the profile variations shown above. The spectrum at each phase in the image is calculated by a linear interpolation between the closest observed phases.

spectrum at each orbital phase was calculated by a linear interpolation between observations with the closest phases.

Both emission components show clear orbital motion, indicated by the distinctive opposite 'S' patterns in the gray-scale. For the spectra from my original survey, I measured radial velocities for each peak by fitting Gaussians to the profiles. Figure 5 shows the velocities for each component plotted against orbital phase, assuming the orbital ephemeris of Stickland & Koch (1996). The filled circles are measurements for the stronger of the two emission peaks, while the open circles represent the weaker component. The dotted lines show the orbits of the two stars. From this diagram, it is clear that although the emission follows some kind of orbital motion, the motion is not centred at the photosphere of either star. Thus the dense regions of gas producing these emission lines must exist somewhere else in the system, presumably between the two stars.

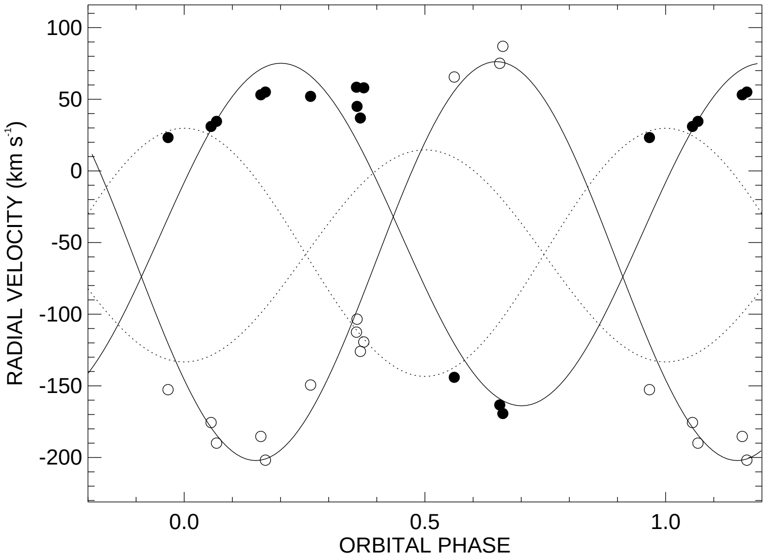

Figure 5. Radial-velocity curves for the Hα emission components. Filled circles represent the stronger emission peak, open circles the slightly weaker peak. Dotted lines show the radial-velocity curves of the two stars.

As a preliminary analysis, I present a schematic drawing of HD 149404 viewed from above the orbital plane in Fig. 6. This view is probably very close to the way the binary actually appears in the sky, due to the low inclination of the system. The radial velocity of the stronger emission component suggests that it arises in a focused wind from the secondary towards the shock. The maximum radial velocity of this component occurs at $\phi = 0.20$, which corresponds to a flow from the secondary to the shock combined with a deflection in the direction of the rotation of the secondary. Similarly, the smaller emission component's velocity variations correspond well to a flow or focused wind from the primary towards the shock. Maximum radial velocity for this component occurs at $\phi = 0.63$, which again agrees well with gas motion towards the shock, deflected by the rotation of the primary. An additional broad, stationary emission component may arise from gas near the shock apex. A shock cone partially wrapped around the secondary would explain the high-velocity wing asymmetries in the Hα profile. This makes intuitive sense, as the primary is more evolved and is expected to have the denser wind.

5. Conclusion

The fact that two independent single-star surveys show less emission than my binary survey makes a convincing case for binaries having an overabundance of Hα emission. Not only do both groups of single stars have less emission than binaries, but the percentages of emission detections for each luminosity class are remarkably consistent. The emission may or may not be due to colliding winds, but in either case, obtaining mass-loss rates from Hα emission in binary systems

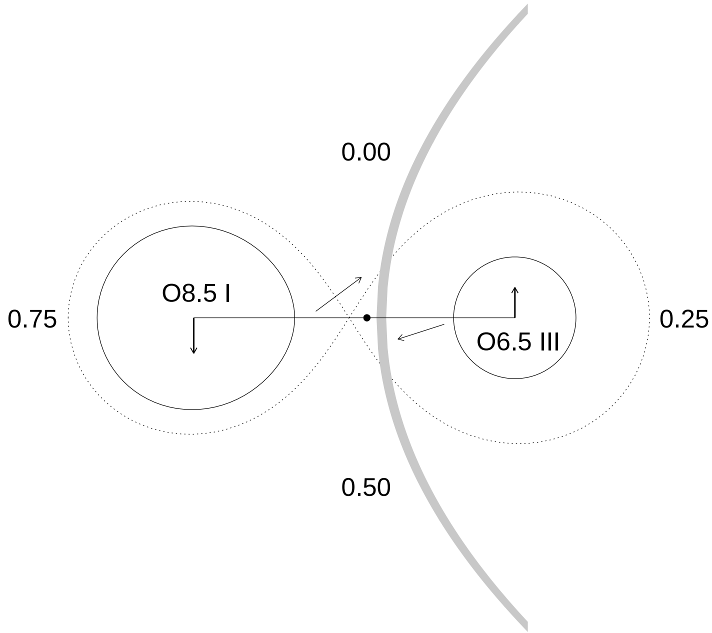

Figure 6. Cartoon view of HD 149404 as seen from above the orbital plane. The dotted line indicates the classical Roche surfaces. The solid circles show the presumed photopheres of the stars. The shaded area indicates the likely location of the shock. The connected arrows show the orbital velocity vectors for the stars; the isolated arrows show the vectors of the Hα emission peak components. The numbers placed around the cartoon indicate the orbital phase of the system when viewed from that direction.

may lead to an over-estimation. When estimating mass-loss rates for stars in other galaxies, where often no radial-velocity information exists, it will be useful to keep this added complication in mind.

The fortunate side of this complication is that Hα emission does indeed seem to be a good diagnostic for colliding winds. In addition, detailed follow-up analysis of line-profile variations gives a clear picture of the mass distribution and flow in systems, as exemplified by HD 149404. Similar analyses are underway for other candidate colliding-wind systems identified by this survey, such as HD 152248 and HD 163181.

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References

Conti, P. S., 1974, ApJ, 187, 539

Conti, P. S., Leep, E. M., 1974, ApJ, 193, 113

Ebbets, D., 1982, ApJS, 48, 399

Garrison, R. F., Hiltner, W. A., Schild, R. E., 1977, ApJS, 35, 111

Gies, D. R., 1987, ApJS, 64, 545

Gies, D. R., Barry, D. J., Bagnuolo, W. G., Jr., Sowers, J., Thaller, M. L., 1996, ApJ, 469, 884

Gies, D. R., Fullerton, A. W., Bolton, C. T., Bagnuolo, W. G., Jr., Hahula, M. E., Weimker, R., 1994, ApJ, 422, 823

Gies, D. R., Wiggs, M. S., 1991, ApJ, 375, 321

Gies, D. R., Wiggs, M. S., Bagnuolo, W. G., Jr., 1993, ApJ, 403, 752

Hill, G., Holmgren, D. E., 1995, A&A, 297, 127

Howarth, I. D., Siebert, K. W., Hussain, G. A. J., Prinja, R. K., 1997, MNRAS, 284, 265

Kaper, L., Fullerton, A. W., Baade, D., 1997, preprint

Lamers, H. J., Leitherer, C., 1993, AJ, 106, 1354

Leitherer, C., 1988, ApJ, 334, 626

Lynds, C. R., 1960, ApJ, 131, 122

Massey, P., Conti, P., 1979, in Mass Loss and Evolution of O-Type Stars, eds. P. Conti & C. W. H. de Loore (Reidel, Dordrecht), p. 271

Morrison, N. D., Conti, P. S., 1978, ApJ, 224, 558

Morrison, N. D., Conti, P. S., 1980, ApJ, 239, 212

Penny, L. R., 1996, PhD dissertation, Georgia State University

Penny, L. R., Bagnuolo, W. G., Jr., Gies, D. R., 1994, Bull. AAS, 184, 604

Puls, J., Kudritzki, R. P., Herrero, A., Pauldrach, A. W. A., Haser, S. M., Lennon, D. J., Gabler, R., Voels, S. A., Vilchez, J. M., Wachter, S., Feldmeier, A., 1996, A&A, 305, 171

Sahade, J., Frieboes-Conde, H., 1965, ApJ, 141. 652

Schaller, G., Schaerer, D., Meynet, G., Maeder, A., 1992, A&AS, 96, 269

Stahl, O., et al., 1996, A&A, 312, 539

Stickland, D. J., Koch, R. H., 1996, The Observatory, 116, 145

Walborn, N. R., 1972, AJ, 77, 312

Walborn, N. R., 1973, AJ, 78, 1067

Walborn, N. R., 1982, AJ, 87, 1300

Wiggs, M. S., Gies, D. R., 1992, ApJ, 396, 238

Wiggs, M. S., Gies, D. R., 1993, ApJ, 407, 252

Discussion

Kudritzki: Although it's easier to find these effects if Hα is in emission above the continuum, you shouldn't throw away those objects with absorption. In my experience, *every* O-star Hα profile is filled in with stellar-wind emission, and you could probably detect effects even in those cases.
Thaller: Yes, absolutely. Where I tabulated a 'possible' detection, that meant a distortion of the line profile. Because I'm trying to finish my thesis really fast [laughter], I stopped there.
Hilditch: DH Cep appeared in something called 'A Reference Atlas of IUE Spectra', or something like that, in the early '80s, as a representative example of a C IV P-Cygni line from an O-star wind. In your table, it was listed as having no visible Hα emission; but there's nevertheless an enormous wind.
Thaller: That's often the case, actually; most of my targets have strong P-Cygni resonance lines in the UV. So, as you imply, all massive stars have winds, but not all massive stars have *colliding* winds.
Willis: Do you have any information on the radio and/or X-ray properties of your sample?
Thaller: I don't know of any radio studies, but the X-rays are currently being observed, mostly by Mike Corcoran. What he's found is that some of these close systems have a phase-dependent X-ray flux. If these winds are generating a shock, that is what you might expect; the only problem is the binaries with the strong X-rays don't have Hα emission.
Owocki: Hα requires high density, and if you have high density there's a good chance you're going to attentuate a lot of the X-rays that might be produced in the inner part of the collisions, so that might be one of the reasons.
Maeder: What do you think happens to this material after it goes through the collision? Is it lost to the system?
Thaller: In Plaskett's star we actually see a very sharp spike, which seems to come from gas which is post-shock, and which is still 'hanging around' very close to one of the stars. I suppose there's some chance of that material being accreted, but the radiation pressure in that system is just off the scale. So my expectation is that most of the material gets lost.
Howarth: You showed a sketch illustrating Roche lobes modified by radiation pressure; I just wanted to mention that, if you believe von Zeipel's theorem applies in these stars [audible equivalents of raised eyebrows] – okay, *if* – then away from the poles the gravity is dropping off, and where the gravity is dropping off the temperature is dropping off, and so the radiation pressure is also dropping off. Under those circumstances, it turns out that the lobe geometry is *unaffected* by radiation pressure.
Thaller: Okay, you may be right. In any event, many of these stars are clearly close to filling their critical lobes.
Hilditch: Some of the plots you showed of Hα emission as a function of orbital phase look exactly like those you get with cataclysmic variables, and you could be trying to use tomographic techniques to map exactly where the emission is coming from.
Thaller: Oh, my whole Department works on doppler tomography, they're not going to ignore that!