O Stars in Binaries

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Abstract.

High-angular-resolution measurements of binary stars with large optical interferometers will soon provide fundamental data on the masses and distances of O stars by combining astrometric and spectroscopic orbital solutions. We describe here the first step in this direction, a speckle-interferometric survey of O stars using the CHARA speckle camera with 4-m telescopes in both hemispheres. The camera detects binaries in the angular-separation range $0\overset{''}{.}035 < \rho < 1\overset{''}{.}5$ with $\Delta m < 3$, and we have discovered 15 binaries among 227 O-star systems (nearly complete to $V = 8$). We combine the information on visual binaries with a literature survey of the spectroscopic binaries among the sample. Binaries are common among O stars in clusters and associations ($> 59\%$ have a visual or spectroscopic companion) but less so among field and, especially, runaway stars. There are many triple systems among the speckle binaries, and we discuss their possible role in the ejection of stars from clusters. The period distribution of the binaries is bimodal in $\log P$ but we suggest that binaries with periods of years and decades may eventually be found to fill the gap. The mass-ratio distributions of the spectroscopic and visual binaries appear to differ in the lack of low-mass-ratio systems among the former; however, such systems are difficult to measure, and new, high-S/N spectroscopic observations are required to determine if there is a real deficit of low-mass-ratio, close binaries.

1. Introduction

Binaries are the fundamental source of information on the masses of stars, and eclipsing binaries, in particular, are central to establishing masses for direct comparison of stellar properties with models for stellar evolution. There are only a few dozen eclipsing binaries among the massive O-type stars in the Galaxy, and many of these are the subject of recent and careful work (Burkholder et al. 1997; Harries et al 1997a, 1997b; Hilditch et al. 1996; Penny 1996a; Penny et al. 1997; Simon et al. 1994; Sturm & Simon 1994). These studies offer encour-

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aging agreement with evolutionary codes (after applying small corrections to the effective-temperature scale) except in cases where the stars have probably interacted.

A second method of obtaining masses involves combining the spectroscopic orbit with the angular orbit as projected on the sky (see, for example, Gies et al. 1997 and Torres et al. 1997). The comparison solves the unknown inclination angle for the spectroscopic orbit (and hence leads directly to the masses) while equating the projected and physical semimajor axes yields the distance. Most O binaries have such great distances that their orbits remain unresolved by conventional techniques, but new high-angular-resolution methods will soon change the situation dramatically. We have made the first step in this programme through a speckle-interferometric survey of all the bright O stars in the sky in order to find new close visual binaries. The identification of such binaries is important for the mass problem and for the correct quantitative analysis of composite-spectrum objects. Here we report on some of the main results of the speckle survey (preliminary results were given by Mason et al. 1996).

We will use this sample of O stars to explore several key characteristics of the binaries: their frequency among different groups of O stars, their period distribution, and their mass-ratio distribution. To make the picture as complete as possible, we have also reviewed the available literature on radial velocities in order to account for the short-period spectroscopic binaries (see Gies 1987). There has been considerable progress in the last decade in radial-velocity studies using both optical spectroscopy (by groups associated with Alex Fullerton, Graham Hill, Hugo Levato, Phil Massey, and others) and IUE spectroscopy (especially the series of papers in 'The Observatory' by Dave Stickland, Chris Lloyd, and collaborators). The combined astrometric and spectroscopic binary properties of our sample offer some key insights about the influence of binaries on the dispersal of O stars from their natal clusters and about what kinds of binaries remain undetected.

2. A Speckle Interferometric Survey of O Stars

The Center for High Angular Resolution Astronomy (CHARA) speckle camera (McAlister 1996) was used on a variety of telescopes (including the KPNO 4-m, CTIO 4-m, CFHT 3.6-m, and Mt. Wilson 100-inch) to observe most of the O stars in the sky brighter than $V = 8$. The survey included some 227 O-star systems with a total of 254 individual targets (since we observed multiple components in many systems); some 496 observations were made in total (some systems have been observed repeatedly for a decade or more). The speckle observations were reduced using the 'Directed Vector Autocorrelation' (DVA) algorithm (Bagnuolo et al. 1992). Depending upon the telescope diffraction limit and seeing conditions at the time of observation, the speckle camera can generally detect binaries with projected separations in the range $0''.035 < \rho < 1''.5$ and a magnitude difference $\Delta m < 3$. Fifteen new binaries were discovered in the CHARA programme. We combined our results with other data on visual binaries from the Washington Double Star Catalog (WDS, maintained at the

US Naval Observatory by C. E. Worley[2]); and from the HIPPARCOS Catalogue (ESA 1997) (9 new binaries among our sample, including 3 confirmations of CHARA binaries).

The new binaries include several very interesting targets. The MK standard 15 Mon (O7 V((f)); Walborn 1972) is a binary with a 23.6-yr orbital period (Gies et al. 1993, 1997) which is now close to periastron. A preliminary radial-velocity curve is available, but new radial-velocity measurements are urgently needed at this epoch. The secondary appears to have a broad-lined spectrum (Fullerton 1990) with a classification of O9.5 Vn. Another intriguing target is HD 193322 (O9 V:((n)); Walborn 1972) which has an orbital period of approximately 31 yr and is also close to periastron at the moment. The primary is a single-lined spectroscopic binary with a period of 311 d (McKibben et al. 1997), so the A component of this system is a triple. The B component (at a separation of 2.″7) is probably a double-lined spectroscopic binary (Fullerton 1990), and at least 3 other visual components exist. Such complex systems have very interesting dynamical implications which we will discuss in the next section.

3. Duplicity and Environment

Gies (1987) showed that binaries are relatively rare among O stars outside of clusters and associations, and in this section we re-assess this issue using the sample from the speckle survey. Each star was assigned to one of cluster and association (72.2%), field (19.4%), or runaway star (8.4%) groups according to the criteria outlined by Gies (1987). The cluster and association memberships were generally taken from those given in the 'Luminous Star Catalog' described by Humphreys & McElroy (1984). The visual multiplicity of each star was assigned to one of 4 categories based on the speckle survey, HIPPARCOS results, and WDS listings: VB = visual binary; VMS = visual multiple system; OPT = optical double (Lindroos 1985); and S = single star. From a review of the spectroscopic literature, we placed each star into one of 7 categories: SB2O = double-lined spectroscopic binary with an orbital solution; SB1O = single-lined system with an orbit; SBE = an eclipsing binary with known period but without orbital elements; SB2? = suspected double-lined binary (cf. Penny 1996b and Howarth et al. 1997); SB1? = radial-velocity range in excess of 35 km s^{-1} (due presumably to orbital motion); C = constant velocity; and U = unknown. Our tabulated results will be published elsewhere, and we plan to place the full table in the electronic 'Double Star Library[3]' (maintained by W. I. Hartkopf) for WWW access. Table 1 presents a summary of the binary properties for each spatial group.

Visual-binary and multiple stars are clearly much more common among association and cluster stars than among field stars (and are totally absent among the runaways). This trend is reinforced by our finding that all of the binaries resolved in the CHARA speckle programme are association/cluster members. A similar result is seen for the spectroscopic binaries where a range in binary

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[2]URL: `http://aries.usno.navy.mil/ad_home/wds/wds.html`

[3]URL: `http://www.chara.gsu.edu/DoubleStars/intro.html`

Table 1. Binary Frequency

Group (Number)	Cluster/Association (164)	Field (44)	Runaway (19)
A. Visual Multiplicity			
VB	30	7	0
VMS	38	2	0
Total ...	41%	20%	0%
OPT	4	4	1
S	92	31	18
Total ...	59%	80%	100%
B. Spectroscopic Properties			
SB2O	26	4	1
SB1O	20	2	0
SBE	4	2	0
SB2?	13	4	1
SB1?	27	8	3
Less SB?	34%	20%	5%
Total ...	61%	50%	26%
C	57	20	14
Total ...	39%	50%	74%
U	17	4	0
C. Fraction with Any Companion			
Less SB? .	59%	35%	5%
Total	75%	58%	26%

fraction exists depending on the inclusion of the SB2? and SB1? cases. Binaries are very rare among the runaway stars. The sole confirmed binary among our sample of runaway stars is Y Cyg (HD 198846), a double-lined eclipsing system with a large absolute value of systemic velocity (Burkholder et al. 1997).

These results are generally consistent with the expectation that the runaway stars and some of the field stars were ejected from their birthplaces in clusters by processes which tend to disrupt binaries. The foremost possibilities are a supernova explosion in a binary star (Blaauw 1961; van den Heuvel 1994) and close gravitational encounters involving binaries (Gies & Bolton 1986; Leonard & Duncan 1990; Clarke & Pringle 1992), and both processes probably play an important role. Proponents of the supernova (SN) model originally predicted that systems would remain bound at the time of the SN because of extensive mass loss in the progenitor prior to the event, and, thus, the runaways were expected to have neutron-star and black-hole companions. However, spectroscopic searches (Gies & Bolton 1986) and pulsar searches (Philp et al. 1996; Sayer et al. 1996) among the runaways have yielded no collapsed companions. The problem is partially resolved by the realization that neutron stars receive substantial 'kick' velocities at birth due to small asymmetries in the supernova explosion, and the binary-survival probability may be small. The massive X-ray binaries represent such survivors, and it is uncertain whether this group is kinematically similar to the runaway stars (van Oijen 1989). There is now evidence that the massive X-ray binary Vela X-1 has a runaway speed, based on the morphology of a nearby interstellar bow shock (Kaper et al. 1997), and this provides a clear example of a runaway with a neutron-star companion.

The gravitational-encounter model, on the other hand, suggests that dense stellar environments are responsible for the runaways. The dynamical evolution of a young cluster will often lead to the formation of a hierarchical double binary (through mass segregation of the heavier binaries to the cluster core). Subsequent perturbations from cluster stars cause a decrease in the semimajor axis of the double binary and an increase in eccentricity. Eventually the components will collide during a periastron passage, usually resulting in the disruption and ejection of the more weakly bound binary (although in unusual cases entire binaries are also ejected). The speckle survey offers new evidence of such dense stellar systems in which gravitational collisions might occur (for example, the 8-member multiple, HD 193322). Among the 25 binaries with separations less than 1 arcsec that we detected in the speckle survey, 20 systems (80%) have a primary component which is a confirmed or suspected close, spectroscopic binary. This large fraction of 'hard' binaries in such close triple and higher multiple systems lends considerable support to our expectation that close encounters with binaries will occur.

4. Period Distribution

We next examine the trends in the distribution of orbital period for the binaries in our O-star sample. The periods are well known for systems with orbital solutions (including several visual binaries), but for most of the visual binaries the periods are too long for any realistic solution to be made. Instead we estimated the probable period by assuming that the projected separation equals the semimajor axis (ignoring real differences in orientation and system eccentricity). We used spectroscopic distances to calculate the separation, and we took the spectral-classification–mass relationship of Howarth & Prinja (1989) to determine the period from Kepler's Third Law (in most cases we estimated the total mass by assuming $M_2 = 0.75 M_1$, which is appropriate to the small magnitude differences usually found for the speckle binaries). The period estimate for any particular visual binary may be poor but the overall distribution in $\log P$ (shown in Fig. 1) will not be compromised by these simplifications.

The apparent period distribution is clearly bimodal with peaks corresponding to the most common spectroscopic and visual binaries. However, the gap between these peaks contains those binaries which are the most difficult to observe (15 Mon was the first system to bridge this observational gap), and we therefore suggest that the result is biased by selection effects. Abt & Cardona (1984) found that the distribution in $\log P$ is flat for the nearer B-type stars, and if this is also true for the O stars, then we are still missing about half the binaries (mainly with periods of years to decades). If this gap *is* filled by future

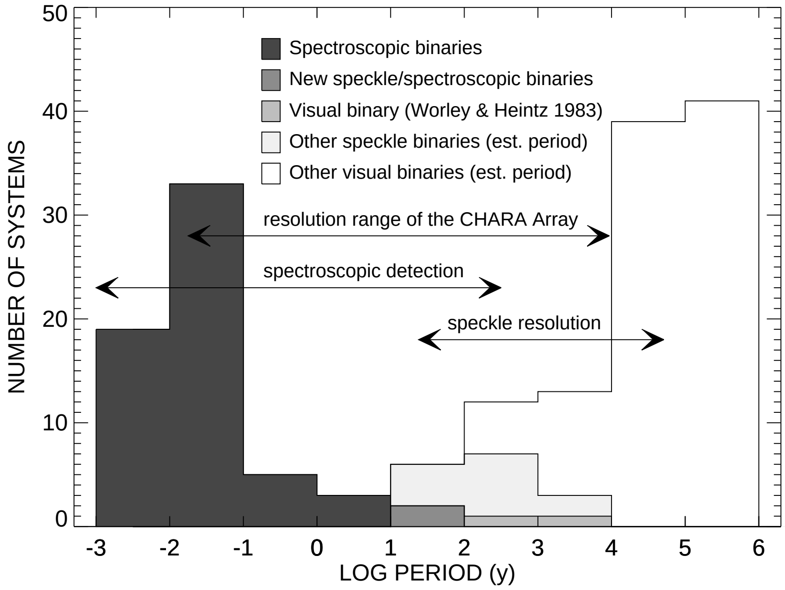

Figure 1. The number distribution of orbital period for all binaries in the speckle survey of the O stars. The upper envelope is the total number from various kinds of binaries (shown as different shaded regions as given by the legend).

observers, then the true binary frequency of O stars in clusters and associations may well be close to unity (see Table 1).

5. Mass-Ratio Distribution

Garmany et al. (1980) found that the mass ratios tended towards unity in their study of binaries among 67 O stars, and they suggested that the deficit of low-mass companions might be due partially to the short lifetimes of the O stars compared to the long pre-main-sequence lifetimes of solar-mass stars. However, Lindroos (1986) has identified several cases of pre-main-sequence companions in visual binaries with massive primaries. Furthermore, the discovery of black-hole binaries with solar-mass companions (among the X-ray novae) points to an origin in a close binary containing an O star and a solar-mass star. Here we use our sample to reconsider the mass-ratio question for both visual and spectroscopic binaries.

We estimated the mass ratio, $q = M_2/M_1$, for a subset of the visual binaries by using the Howarth & Prinja (1989) calibration of mass and absolute magnitude as a function of spectral classification, and using the observed magnitude difference and the mass–luminosity relationship for main-sequence stars. The visual-binary sample was taken from those with probable physical orbits, a single bright primary (no SB2O or SBE primaries), and a primary-star luminosity class of V–III (since the absolute magnitude range is larger among supergiants).

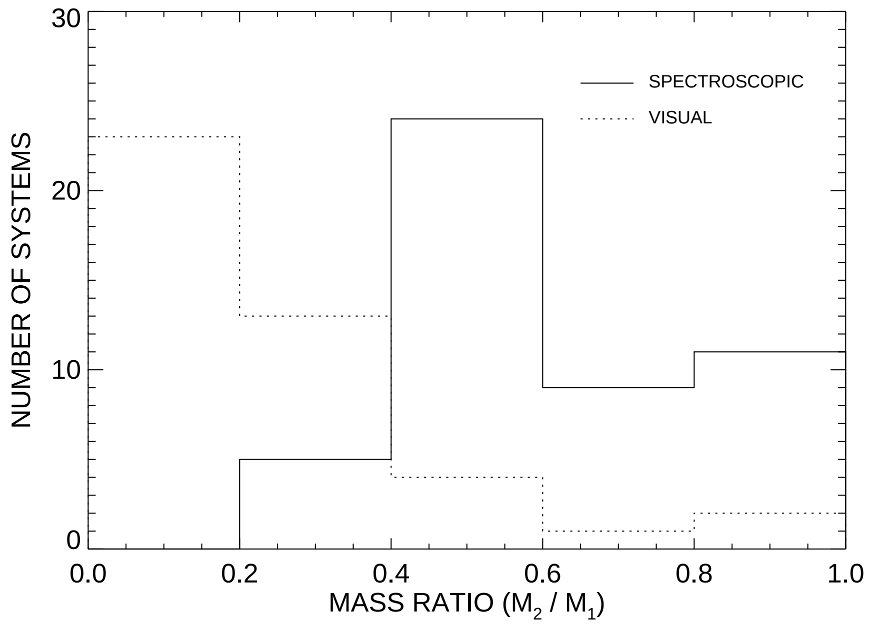

Figure 2. The number distribution of mass ratio (always defined as < 1) for the spectroscopic and visual binaries in the speckle survey.

The distribution in q for this sample of 42 binaries is illustrated in Fig. 2 (dotted line).

The mass ratio for the SB2O systems is known directly from the ratio of the semi-amplitudes, but for the SB1O systems we relied on the statistical method of Mazeh & Goldberg (1992) to estimate their mass ratios. We omitted from consideration binaries with very evolved companions, and the SB1O system HD 152623, which suffers from line blending with a stationary spectral component. The resulting distribution of q for spectroscopic binaries is also plotted in Fig. 2 (solid line).

The mass-ratio distribution for spectroscopic binaries shows a lack of low-q systems similar to that found by Garmany et al. (who consider the inverse ratio, $Q = M_1/M_2$). However, we caution that binaries with low mass ratios ($q < 0.4$) are often extremely difficult to measure because of line-blending problems (see the case of HD 53975; Gies et al. 1994), and at least part of the deficit of low-q systems must be due to observational bias. The visual binaries, on the other hand, are dominated by low-q systems, in accordance with expectations for the initial mass function. There may indeed be real differences between these distributions, but the issue remains contentious pending a better understanding of the observational biases against spectroscopic detection of low-q systems.

6. Conclusions

Our speckle survey and literature review shows that binaries are very common among the O stars (and especially among members of clusters and associations).

Binaries will influence the dynamics of young clusters by ejecting stars through SN explosions in binaries and close gravitational encounters with binaries. At least one third of the O stars have close companions and will become 'interacting binaries' in some sense during their lifetime. Both the period distribution and, probably, the mass-ratio distribution of the binaries suggest there remain a significant number of undetected binaries with periods of years to decades and/or extreme mass ratios. It will be an important observational task to pursue high-S/N and high-dispersion spectroscopy to search for these binaries with low radial-velocity amplitudes. Such studies are especially timely, because the next decade will see the start of widespread studies with large optical interferometers (such as the CHARA Array, a 5-element instrument with a 350-m baseline, which is now under construction at Mt. Wilson Observatory[4]). The CHARA Array, for example, will resolve massive binaries at a distance of 1 kpc with periods as small as one week. The combination of the spectroscopic and astrometric orbits will provide accurate masses and distances for binaries of all kinds.

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Discussion

Dufton: I thought that the theoretical prediction was that about 50% of close binaries should survive supernova explosions. If that's the case, do your results imply that most runaways have, rather, been ejected from clusters?

Gies: That's a good point; I think the answer is that what happens when a supernova explodes in a binary is very controversial now. Originally, based on work by Blaauw, and later by Ed van den Heuvel and the Dutch school, we expected that the progenitor would lose about half its mass through stellar winds and perhaps other processes, so that when it exploded as a supernova it would not disrupt the system. On the other hand, we now know, from work by Lyne & Lorimer (1994, Nature, 369, 127) and others, that pulsars have very high random velocities due to some asymmetry in the supernova explosion. If we properly account for this kick velocity, then it may well be that many more systems are disrupted; on the other hand, we observe massive X-ray binaries, so clearly some do survive. The significant lack of neutron-star companions among the runaway stars suggests to me that gravitational encounters with binaries must also be an important process for ejecting runaway stars.

Venn: With the CHARA array, have you thought of searching for planets as well?

Gies: Yes, we've looked at that quite closely; we're very interested in searching for astrometric perturbations in a binary-star system. When looking at a very small area of sky, usually much less than one arc-second square, you need some sort of fiducial point to refer everything to; when you have a binary, you can use the stellar orbit to provide that frame of reference.

Langer: Can you say something about the distribution of eccentricities, and whether there's a trend with the period?

Gies: We will present a $(\log P, e)$ diagram in the final paper describing this work. We find that circular orbits prevail generally in systems with periods less than 4 d, and that longer-period systems have a wide range in eccentricity. Unfortunately, there are few orbital solutions for the visual binaries because of their long periods.

Hilditch: I think the general result among detached systems is that eccentricities tend to go to zero at periods below something like 6–8 days, and then the eccentricities can increase substantially at longer periods. For the interacting systems you have two effects: tidal forces circularize the orbits, but supernova explosions can make them very eccentric again – we know that because we see high eccentricities in binaries that contain radio pulsars with non-degenerate companions.

Jeffery: What sort of initial masses do you expect for the components of ϕ Per? If they're low, does that suggest another mechanism for generating O stars?

Gies: That's an excellent question – to be honest, I haven't thought about the question in depth. My main impression comes from a discussion with Dany Vanbeveren (Vrije Universiteit Brussel); he modelled ϕ Per as a system that started with a mass ratio very close to unity and which subsequently went through Roche-lobe overflow. The big question is, how conservative was that process? At the moment the system is about $10M_{\odot}$, so it could possibly have started as a pair of $5M_{\odot}$ B stars, transferred mass between stars without loss from the system, and ended up with a stripped-down companion of $1M_{\odot}$. On the other hand, if the overflow was a very messy process, it could have started as a pair of O stars that lost a lot of mass to the surroundings. But you're right, if you started with two B stars and dumped enough material over, you could end up with an O star – the primary of ϕ Per is B0.5 V–IIIe, so it's nearly there. Incidentally, the HIPPARCOS distance to the system is about 210 pc, and if that value's believed then the primary is truly overluminous for its mass $(9M_{\odot})$.