

MASSIVE BINARIES

Speckle Interferometry of O, B, and WR stars

Brian D. Mason

U.S. Naval Observatory, 3450 Massachusetts Ave., NW, Washington, DC 20392, U.S.A.
bdm@draco.usno.navy.mil

Douglas R. Gies

Center for High Angular Resolution Astronomy, Georgia State University, Atlanta, GA 30303, U.S.A.
gies@chara.gsu.edu

William I. Hartkopf

U.S. Naval Observatory
wih@draco.usno.navy.mil

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Abstract Due to the typically large distances and low space densities of massive stars, combined (astrometric and spectroscopic) studies of hot stars are lacking. This is unfortunate, since combining orbital solutions from these techniques provides an important means of measuring mass and distance. However, in the last decade the situation has improved considerably as significant efforts led to the systematic investigation of the brightest (and closest) O stars. While the period overlap between binaries detected by these techniques is not likely to be fully explored until optical interferometry has matured, the results obtained thus far have been quite tantalizing. We also made speckle interferometric surveys of the Wolf-Rayet stars and luminous B giants and supergiants at the time of the O star survey, and we summarize here our results on the incidence of astrometric binaries among these related groups.

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1. O STARS

The starting point for models of massive binary star evolution is a set of reliable distributions for binary period and mass ratio plus an estimate of the overall fraction of massive stars found in binary or multiple systems. There are considerable uncertainties surrounding all these parameters in large measure because of the observational selection effects surrounding different kinds of observations and sample completeness. Over the last few years we have undertaken several surveys of the massive stars using the technique of speckle interferometry to find new visual binaries down to the resolution limit of 4-m telescopes (approximately 30 milliarcsecond). This work has led to the discovery of many new binaries including some close enough that the prospect exists for combined spectroscopic — astrometric orbital solutions (which yield both masses and system distance). Our most complete survey was made of Galactic O-type stars mainly brighter than $V = 8$, and we begin here with an updated discussion of the O-stars which extends the main survey results of Mason et al. (1998; hereafter Paper I).

1.1. ASTROMETRY UPDATE

An initial step in this analysis of O stars was to update the astrometry for visual systems in Paper I with their current status in the Washington Double Star Catalog¹ (hereafter, WDS). While updating all system information is certainly advisable, of greatest concern were those systems with only one astrometric observation, as unconfirmed binaries may be spurious for one reason or another (wrong object, false detection, etc.). These single detections are summarized in Table 1.

Table 1 Resolved doubles with $N = 1$ in Mason et al. (1998).

Number of Observations	Δm_v (mag)	Number of Systems
$N > 1$	—	25
$N = 1$	$\Delta m \geq 5$	17
$N = 1$	$3 \leq \Delta m < 5$	12
$N = 1$	$\Delta m < 3$	4
$N = 1$	<i>unknown</i>	9

¹<http://ad.usno.navy.mil/ad/wds/wds.html>, also, see Worley & Douglass 1997

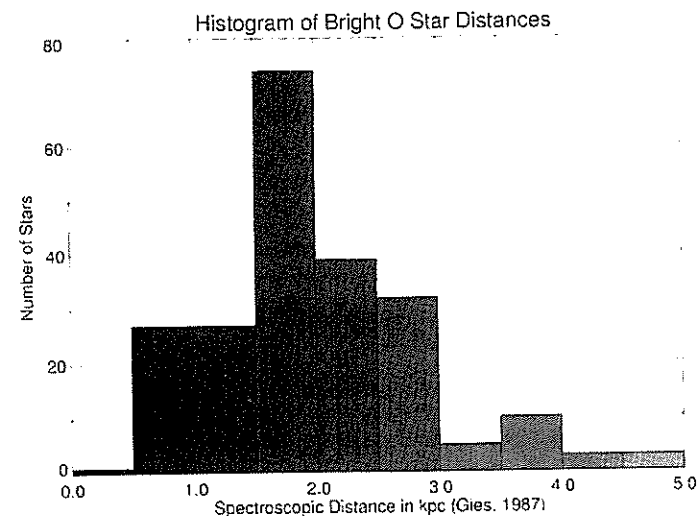


Figure 1 Histogram of spectroscopic O star distances.

Table 1 (specifically, columns 10–13) from the online O Star Speckle Survey² has been updated to reflect the current astrometric information on O stars. This supersedes all astrometric information given in Paper I.

1.2. DISTANCES TO O STARS

Column 14 of Table 1 of Paper I presented the spectroscopic distance to O stars from Gies (1987) and Humphreys & McElroy (1984). These distances are presented in histogram form in Figure 1. The distribution peaks just below 2 kpc.

Figure 2 is a plot of spectroscopic parallax (triangles) and Hipparcos parallax and error (line) for the 34 systems (stacked in the y -dimension) where $\frac{\pi}{\sigma\pi} > 2$ (145 other systems have the ratio ≤ 2). The Hipparcos parallaxes appear to be systematically larger than the spectroscopic parallaxes. It should be noted that Høg et al. (2000a, 2000b) find Hipparcos proper motion errors underestimated by about 30% for double stars. A similar problem may exist with the parallax. Be that as it may, the source of the systematic error is uncertain. What is not uncertain is that, while distances for O stars in clusters where main-sequence fitting

²<http://ad.usno.navy.mil/dsl/Ostars/ostars.html>

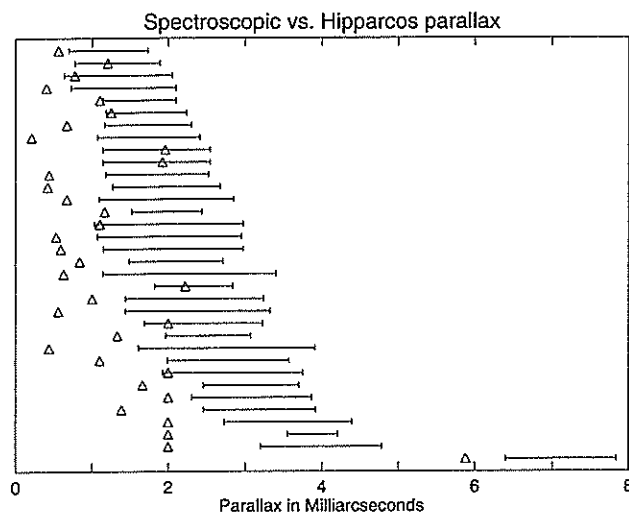


Figure 2 Spectroscopic distances and Hipparcos distance

is possible may not be too bad, distances to O stars are only known in the most gross sense.

1.3. NEW ASTROMETRIC WORK

Several O stars have been the subject of significant work since Paper I. These are detailed below.

15 Mon. Since the original 1988 resolution first reported by Gies et al. (1993), the binary 15 Mon has shown significant evolution in orbital elements due to the paucity of original data. Figure 3 is a plot of the relative orbit. In this figure, the scale is in arcseconds and the shaded circle centered on the origin is the 30 milliarcsecond (mas) resolution limit of a 4-m telescope in V.

Available data come from speckle interferometry (filled circles) and HST-FGS (H), and are connected to the current orbit calculation by O-C lines. Earlier orbit calculations by Gies et al. (1993, 1997) are shown as dashed curves. Speckle points are from 1988 (CFHT) and 1993 (KPNO & CTIO). HST-FGS measures are from 1996, 1997, and 1999. An HST-FGS observation is scheduled for April 2001 as well as in cycles 9, 10, and 11 and speckle observations are scheduled for 2001. Also shown are the current (2000.6; i.e., at the epoch of the Brussels

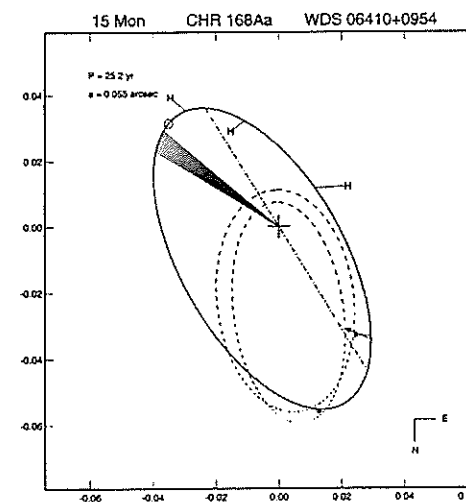


Figure 3 Relative orbit of 15 Mon

meeting) position, shown as an open circle. Radial lines from the origin to the orbit indicate predicted orbital motion during 2001.

HD 193322. Figure 4 shows of the relative orbit of CHARA 96 (HD 193322) from Hartkopf et al. (1993). At the time of the 1993 orbit it was unresolved from a 4-m telescope, but is now near the maximum predicted separation for this 31.3 year period. The positions for 2001 (when a speckle observation is scheduled) are shown here as well as the position at the time of the Brussels meeting. Symbols are as Figure 3.

In a spectroscopic investigation of this system by McKibben et al. (1998) the A component was revealed to be an unresolved spectroscopic binary with a period of 311 days.

Theta Orionis. The Orion Trapezium system has many close, and mostly unconfirmed IR companions from Prosser et al. (1994), Simon, Close, & Beck (1999), and Weigelt et al. (1999). The new companion noted by Weigelt et al. is to θ Orionis C and separations from 33 and 37 mas were measured in 1997 and 1998. The Δm of this companion was determined to be 1.46 in H-band and 1.24 in K. The new companion is believed to be a very young, intermediate or low mass ($M < 6M_{\odot}$) star. While it is unclear what the Δm is at visual wavelengths, the expected magnitude difference in visual band is < 4.5 ; this possibly accounts for

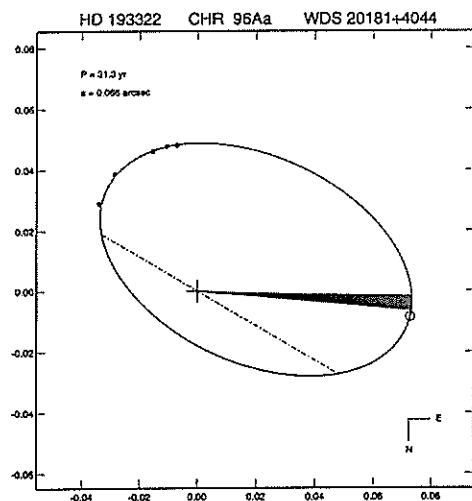


Figure 4 Relative orbit of HD 193322

the lack of detection in the speckle survey of Paper I. It is unclear how many of these new companions are physical, or just nearby components of the cluster. Repeated observation and the establishment of Keplerian or non-Keplerian motion will be required to ascertain this.

Zeta Orionis. A striking example, and a useful demonstration (if one were actually needed) of the utility of optical interferometry was the detection of the new 4th magnitude companion to ζ Orionis A by Hummel et al. (2000). Hanbury Brown, Davis, & Allen (1974) first reported the likely non-singular nature of ζ Orionis based on correlations significantly below 1 obtained at the Intensity Interferometer at Narrabri. However, it was unresolved. The duplicity of ζ Orionis remained doubtful in spectroscopic analyses by Bohannon & Garmany (1978) and Levato et al. (1988), although the latter reported a small (< 35 km/s) radial velocity variation.

Hummel et al. utilized the Navy Prototype Optical Interferometer (NPOI) in 1998 and 1999 to resolve the new companion a total of 12 times at separations ranging from 42 to 47 mas and a Δm of 2.0 (in wavelengths ranging from 520 to 850 nm). While an orbital analysis of the ζ Orionis A system has not been made, it is possible that the non-detections cited in Paper I may place limits on the relative astrometry of the system at those epochs.

1.4. BINARY FREQUENCY

While the discoveries of ζ Orionis Aa,Ab and θ Orionis Ca,Cb (as well as other companions of this complex system) are quite intriguing, they occur in systems already designated as “visual multiple systems,” in Table 3 of Paper I, so do not effect the statistics.

Paper I did, however, miss two visual binaries, one optical and one physical:

- 10440–5932 = CPD–58 2620 : Was noted as having a constant radial velocity in Penny et al. (1993) The known visual component not listed in Paper I is SEE 123.
- 22469+5805 = HD 215835 = DH Cep : The companion missed here is clearly not the 2.1-d spectroscopic companion of Penny, Gies, & Bagnuolo (1997), but a more distant companion designated HJ 1810 in the WDS.

Hipparcos “problem” O Stars. The Hipparcos satellite made measurements of over 9,734 known double stars, 3,406 new double stars, and 11,687 unresolved, but possible double stars. These 11,687 objects, designated “problem” stars, are objects whose duplicity status ranges from near certain (unresolved, but with orbit solutions) to dubious (anomalous results, some simply carrying the catch-all note “suspected non-single”). These objects are designated in the Hipparcos (ESA 1997) Catalogue with a G, O, V, or X in column H59 or an S in column H61. Mason et al. (1999, 2001) have discussed the applicability of speckle interferometry to investigate these systems, the status of these “problem” stars, compared with their astrometric status is given in Table 2.

In Table 2, column 1 categorizes the O stars into one of three main groups, cluster/association members, field stars, or runaways. The status of astrometric companions, whether known or single is given in column 2, while the number of “problem” stars is given in column 3. The final column lists by HD number the specific “problem” stars. The known systems typically fall into one of three categories. While most either have a larger Δm than Hipparcos measured and some were closer than Hipparcos measured, others were relatively wide and had a more moderate Δm . These would mostly have fallen into the category of a Hipparcos “double-entry” system, however, the known double was not identified in the Hipparcos Input Catalogue as double, were treated as single stars. Stray light may have caused the problem and led to the conclusion given in the Hipparcos Catalogue.

Of note are the those components designated single in the astrometric survey. Of the three cluster objects, their spectroscopic status is notable.

Table 2 Hipparcos O type "Problem" Stars

O group status	Astrometric Survey Status	Number of Systems	HD number
Cluster/ Association	known	9	36456, 47043, 46150, 71304, 75821 96254, 148937, 152270, 206183
	single	3	100099, 101131, 226868
Field	known	0	
	single	2	48149, 169515
Runaway	known	0	
	single	1	198846

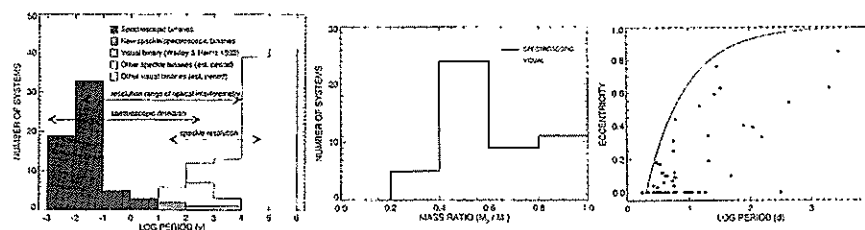


Figure 5 Statistical figures from Paper I.

- the three cluster objects were classified SB1? (suspect single-lined binary, radial velocity excusion is excess of 35 km s^{-1}), SB2? (double-lined, but no orbit), SB1OE (single-lined binary with orbit and eclipsing or ellipsoidal variable),
- the two field objects were classified USB (unknown spectroscopic status) and SB2OE (double-lined binary with orbit and eclipsing or ellipsoidal variable), and
- the runaway object was classified SB2OE.

While the statistics of Table 3 do not change, but they do add credence to those questionable spectroscopic binaries. A modified version of Table 3 (from Paper I) is provided.

1.5. OTHER STATISTICS

Other statistical information from Paper I have not been updated, and the Figures from that paper are here presented in a three-part Figure 5.

Table 3 Binary Frequency

Group (Number)	Cluster/Association (144)	Field (44)	Runaway (19)
A. Visual Multiplicity			
Visual Binary	31	7	0
Visual Multiple System	38	2	0
Total	42%	20%	0%
Optical	5	4	1
Single	90	31	18
Total	58%	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%
Constant	57	20	14
Total	39%	50%	74%
Unknown	17	4	0
C. Fraction with Any Companion			
Less SB?	59%	35%	5%
Total	75%	58%	26%

The left panel provides the number distribution of orbital periods for all binaries in the speckle survey of the O stars. The bimodal distribution is probably a selection effect. While the gap is being filled in to a certain extent by operational optical interferometers (e.g., NPOI; see Section 1.3.4 above), at present these instruments are limited to the brighter targets (and the O stars are fainter in the red and near-IR colors used in most interferometers). Both speckle/spectroscopic binaries (15 Mon and HD 193322, plotted in the center of the figure) appear in the new “5th Catalog of Orbits of Visual Binary Stars” (Hartkopf, Mason, & Worley, 2000)³.

The center panel is an illustration of the number distribution of mass ratio for the visual and spectroscopic binaries in the survey. Visual binaries include those with probable physical orbits, and a single bright primary (i.e., strictly double systems), and the primary of luminosity class V-III. The mass ratio is based on the magnitude difference using tables from Howarth & Prinja (1989), and is thus model dependent. Spectroscopic binaries include both SB2O and SB1O systems. The mass-ratios for the latter are based on the statistical methods of Mazeh & Goldberg (1992), and the SB1O sample excludes those with very evolved companions and the triple HD 152623 (where the interpretation of the spectroscopy suffers from line blending of the features of the spectroscopic primary with the “stationary” lines of the third star).

The right panel provides the distribution of orbital eccentricity as a function of $\log P$ (days). The solid line traces the boundary for a periastron separation greater than $23 R_{\odot}$ for a binary with a total mass of $40 M_{\odot}$. All spectroscopic binaries are plotted. From the figure, it is noted that

- 1 there is an absence of high- e /short- P systems, confirming the expectation that binaries with periods < 4 days tend to circularize due to tidal interaction, and
- 2 there is a lack of low- e /long- P systems. This may be due to circumbinary disks driving eccentricity to higher values (an effect seen in low-mass binaries), though the number of systems is small.

2. WR STARS

As in Section 1, the starting point for the discussion of Wolf-Rayet stars is a paper in the literature, specifically, the survey of Hartkopf et al.

³web version available now at <http://ad.usno.navy.mil/ad/wds/hmw5.html>, cd version in mid-2001

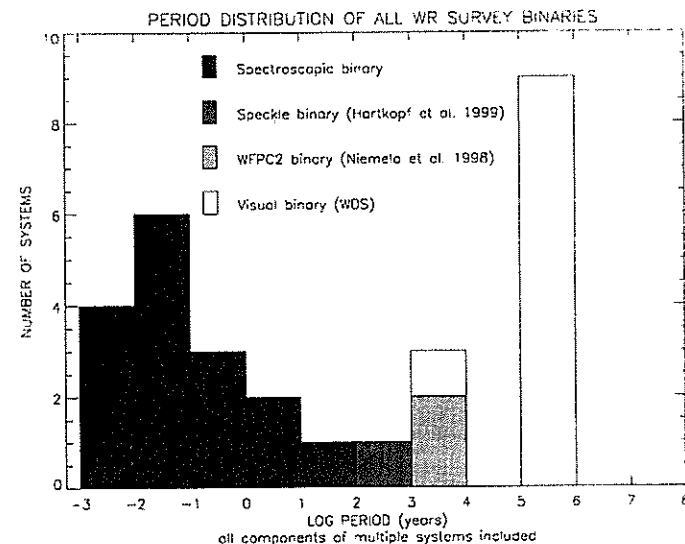


Figure 6 Number distribution of orbital periods for all binaries in the WR survey.

(1999; here after Paper II). Not provided in Paper II is a period distribution for known WR binaries. This is shown in Figure 6.

The bimodal distribution is, again, a selection effect. All visual binary periods are estimates based on literature distances (possibly wildly inaccurate) and a mass sum of $30 M_{\odot}$ (probably wrong, but possibly good enough for statistical purposes). The number of WR systems is quite small, and what are needed most are astrometric measures of short- P systems, as the known visual binaries have very long periods.

Figure 7 is a plot of the relative positions of CHR 247 (θ Muscae). Symbols are as Figure 3. The speckle measure is from Paper II, and the HST-FGS measure is from D. Wallace (private comm.). Also, Grant Hill (private comm.) in an analysis of the 18-d short period system finds “stationary” spectral lines of an O-supergiant (narrow C III $\lambda 5696$) which presumably originates in the speckle companion. While there is significant uncertainty in the motion of the system, speckle observations will at least be attempted in 2001.

3. B GIANTS AND SUPERGIANTS

Unlike the O and WR sections, no results from the luminous B star survey have yet been published. Table 4 presents the systems which were observed. These observations were made at the time of the O and

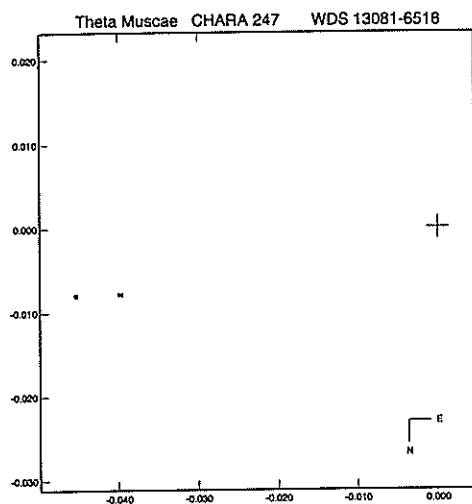
Figure 7 Measures of θ Muscae = CHR 247.

Table 4 B giants and supergiants surveyed for duplicity

Bright Star Catalogue number							
1131	2595	2699	3456	3825	4611	5027	6356
1713	2596	2789	3494	3940	4644	5036	
1903	2618	2815	3571	4135	4653	5358	
2004	2627	2827	3654	4147	4806	6260	
2187	2653	3090	3703	4250	4817	6261	
2294	2657	3203	3708	4338	4887	6262	

WR surveys, however, no companions, new or known, were measured in the separation range $30 \text{ mas} < \rho < 2''$. By their very nature, companions of B giants would be difficult to find. Due to their luminosity, only stellar companions of approximately the same MK class would be noticed in V-band. Coupled with the very short lifetime of B giants, the chances of observing a binary is quite small.

Despite this, significant work has been done in the past year on known B giants that were not in the sample above. A significant recent addition is the three dimensional orbit of the triple system 64 Ori by Scarfe, Barlow & Fekel (2000). Unfortunately, the 13.0-yr pair is only single-

Table 5 BIII orbits

Discovery Designation	HD	P (yr)	a (")	Reference
MCA 24	41040	12.98	0.0471	Scarfe et al. 2000
BTZ 1	45542	13.00	0.1826	Mason 1997
FIN 322	49643	171.4	0.261	Seymour et al. 2000
HU 1594	87652	174.	0.371	Seymour et al. 2000
HU 200	196662	420.	0.48	Heintz 1998

lined, so no orbital parallax is possible. As Table 5 shows, all B giant orbits contained in the 5th Catalog are recent additions. The situation is improving, but more work is needed.

4. FUTURE WORK

4.1. THE USNO CMOS SYSTEM

There remain a plethora of systems which have not been detected because of a large magnitude difference, Δm . USNO astronomers have begun a program to search for faint companions using both a CCD and a CMOS type detector. Tests with the Lick astrograph and a conventional CCD have demonstrated the capability to resolve systems as close as $2''$ and Δm values of up to 5. The CMOS is a logarithmic, continuous readout detector system which allows a Δm of 7 to be reached. However, the continuous readout demands extremely accurate tracking. After testing is complete, a regular program to survey the bright stars for faint companions can be initiated. See Winter (2000) for more information.

4.2. ADAPTIVE OPTICS OF MASSIVE STARS

Low mass companions to massive stars are notoriously difficult to detect due to the large magnitude difference. Adaptive optics observations of these stars can aid in a similar manner to the CMOS system in that large magnitude differences can routinely be detected (see Turner et al. 2001). A program specifically designed to look for these companions is planned for early 2001 using the AMOS system on Haleakala (ten Brummelaar 2000).

4.3. OPTICAL INTERFEROMETRY

Still in its infancy, optical interferometry has the potential to directly resolve many of these systems (as demonstrated in Section 1.3.4 above); these instruments are, at present, magnitude limited, however.

4.4. FAME

One of the most significant areas where improvement can be made in massive star research is the determination of their distances. As shown in Figure 1, bright O star distances peak at about 2 kpc. The FAME satellite (scheduled for launch in 2004, see Johnston 2000) will measure positions, proper motions, and parallaxes to 40 million stars, as well as determining their companion properties from astrometric signatures. At a distance of 2 kpc, the error is expected to be less than 10%. The determination of O star distances for mass determination of single-lined spectroscopic and visual binaries and the calibration of the absolute magnitude scale for hot stars is but one outcome of this very cost effective mission (costing roughly, \$4 U.S. per star).

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II

OBSERVATIONS OF EVOLVED BINARIES