RevMexAA (Serie de Conferencias), **38**, 19–22 (2010)

HOT BINARIES: OBSERVATIONAL RESULTS

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RESUMEN

Se resume el trabajo interferométrico sobre binarias calientes y estrellas múltiples, desde las primeras interferometrías oculares hasta recientes catastros de "speckle" y óptica adaptativa. Se discute la multiplicidad fraccionaria de cúmulos, campos y "runaway" de estrellas O.

ABSTRACT

Interferometric work on hot binary and multiple stars is summarized, from the earliest eyepiece interferometry to recent speckle and AO duplicity surveys. Multiplicity fractions for cluster, field, and runaway O stars are discussed.

Key Words: binaries: general — stars: early-type — techniques: interferometric

1. INTRODUCTION AND EARLY EFFORTS

The purpose of this talk is to summarize the work that has been done on hot stars over the years by various interferometric techniques. I have assumed the term "hot stars" here to include type O, B, Be, and Wolf-Rayet, and have been a bit broad in my definition of "interferometric techniques". The vast majority of these efforts have been duplicity studies –attempts to resolve hot stars into double or multiple stars for statistical analyses– but there has also been followup astrometry for orbit determinations.

Interferometric work on hot stars dates back to the early years of the last century. Anderson, Merrill, and Pease included 11 B stars in the list of 84 bright stars they observed in the early 1920s with the 20-foot beam interferometer on the Mount Wilson 100-inch.[2] Unfortunately none of the 11 were resolved by them, although seven of the objects were later resolved by other interferometric methods.

Abbetti, van den Bos, Finsen, Maggini, Ronchi, and Wilson used eyepiece interferometers between the mid 1920s and early 1970s, making well over 2,000 observations of ~ 500 stars. Of these, 86 were B stars (20 of which were resolved), and two were O stars (one of which, τ CMA, was resolved).

2. DUPLICITY SURVEYS BY SPECKLE AND OTHER SINGLE APERTURE TECHNIQUES

Duplicity work on hot stars really took off after the invention of the speckle technique in 1969, and especially after film was replaced by electronic detectors a decade or so later. Although speckle has its limitations (maximum resolution limited to the largest available single aperture, Δm limit much lower than adaptive optics) it also has a number of advantages –portability, low cost, better astrometric accuracy than adaptive optics, high observing efficiency– that make it well suited to survey work.

The first large scale survey was an attempt by the CHARA group to observe all stars in the Yale Bright Star Catalogue; roughly 1/3 of the catalog was observed with 4 m class telescopes before funding and observing time dried up. Hot stars were not specific targets, of course, but 300+ O and B stars were observed in total (see McAlister et al. 1993).

Later surveys were aimed at stars of specific spectral types or in particular clusters. Cluster surveys of interest here (by speckle and other interferometric techniques) include:

- Pleiades, Praesepe, IC 4665 (Mason et al. 1993): visual speckle; included late B stars.
- Praesepe, α Per (Patience et al. 2002): IR speckle plus HST/NICMOS; types B-early M.
- R CrA (Köhler et al. 2008): IR speckle and AO; included 7 Herbig Ae/Be stars, which were found to include 1 quadruple, 1 triple, 4 doubles
- Trapezium (Petr et al. 1998, Simon et al. 1999, etc.): IR speckle, AO; mostly lower-mass stars.
- NGC 3372, Trumpler 14, Trumpler 16 (Penny et al. 1993): Spectra of the 6 brightest stars in Tr 14, with followup speckle. No short-period binaries and no speckle pairs found.
- NGC 3372, Tr 14, Tr 16 (Nelan et al. 2004): HST/FGS observations of 23 stars, resolving 5 in the 15–350 mas (37–880 AU) range. The "prototype O3 supergiant" HD 93129A was resolved at 55 mas;

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[2] Schwartzschild and Villiger made eyepiece interferometric observations as early as 1895, but observed nothing earlier that A0.

the secondary is physical, possibly an early-O main-sequence star.

• Orion Nebula Cluster (Preibisch et al. 1999): IR speckle (K′ band); observed 13 O/B stars, finding 8 companions. After including SBs, etc., they conclude there are at least 1.5 companions per primary, versus 0.5 for low-mass stars.

• NGC 6611 (Duchêne et al. 2001): AO survey of 96 stars, separation range 0.1–1.5″ (200–3000 AU), ΔK<5 mag. They found a binary frequency of 18±6%, with a higher frequency in the cluster than in the field.

A number of surveys were made of stars of specific spectral classes, including speckle surveys of Be stars (Mason et al. 1997), O stars (Mason et al. 1998), and Wolf-Rayet stars (Hartkopf et al. 1999), as well as an I-band AO survey of O stars (Turner et al. 2008). Results from these surveys have been superceded by the recent massive star survey of Mason et al. (2009), which also includes all data from the above efforts. Findings are discussed below.

3. THE MASSIVE STAR SURVEY

The latest survey of massive stars was a followup to the original 1998 survey by Mason and colleagues, using a more sensitive detector for the speckle observations and combining those data with published AO, speckle, spectroscopic, and visual work. Reasons for repeating and expanding upon observations after 10 years included:

• reobserving pairs which may have changed (e.g., opened up so that they are now resolvable),

• looking for orbital/linear motion in known pairs,

• confirming pairs discovered earlier, and

• looking at pairs discovered in the near-IR (e.g., Trapezium; Schertl et al. 2003) at visible wavelength, in order to possibly set limit on magnitude difference, color, and object type.

The overall results included resolution of 41 of 385 O stars, 4 of 7 W-R stars, and 89 of 139 B stars; these included 14 new companions to O/B stars. The B star sample was enriched with known doubles, observed for future orbit/mass determination, so no conclusions should be drawn from this large duplicity fraction. The W-R sample, although larger than reported in the earlier paper, is still too small to draw many conclusions. However, we now have speckle data on 360 of the 370 stars in the Maíz-Apellániz & Walborn (2004) *Galactic O Star Catalog.*

Limitations to the survey must be noted, including incomplete sky coverage (for example, the AO survey was limited to $\delta > -42°$), incomplete period/separation coverage (periods too long for easy spectroscopic discovery but too short for direct resolution are missing), and sample bias (the sample is magnitude limited, so biased to more luminous stars). Overall results of the survey (summarized in Table 1) tend to confirm earlier findings:

TABLE 1

MULTIPLICITY OF GALACTIC O-STARS[a]

Category	Cluster or Assoc.	Field	Runaway
A. Visual Multiplicity			
Total no. systems	249	56	42
Double/multiple	108	14	11
Duplicity fraction	43%	25%	26%
B. Spectroscopic Properties			
Total no. stars	272	56	42
Double/multiple	66	6	8
Suspected (SB?)	60	12	4
Constant RV	97	21	30
Unknown	49	17	0
Duplicity fraction	57%	46%	29%
Duplicity(less SB?)	30%	15%	19%
C. Fraction with Any Companion			
Less SB?	66%	41%	37%
Total	75%	59%	43%

[a]From Table 5, Mason et al. (2009).

• most massive stars are born in binary/multiple systems,

• the binary frequency is lower in field and runaway stars than in clusters and associations,

• binaries found in runaways tend to be close systems with ∼ equal mass companions and neutron-star companions.

4. INDIVIDUAL SYSTEMS

A number of massive stars have been extensively followed interferometrically for orbital analysis, etc. A few of these systems are noted briefly:

4.1. *15 Mon = CHR 168*

A *very* preliminary orbit of this O7Ve pair was derived by Gies et al. (1993). Since the time of this orbit an extensive series of HST FGS measures has been obtained, as well as another speckle measure and one measure from NPOI. The result is a much different solution (see Figure 1). Analysis of this system is in preparation by Doug Gies and colleagues.

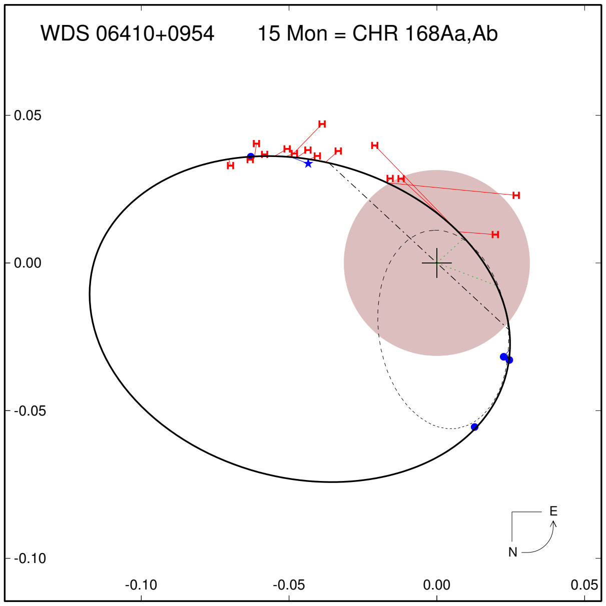

Fig. 1. Orbit of 15 Mon. Speckle measures are shown as filled circles, an NPOI measure as a filled star; "H" symbols are HST FGS measures. "$O-C$" lines connect data points to their predicted locations on the orbit. The large shaded circle represents the Rayleigh resolution limit of a 4 m telescope. Dotted lines from the origin denote predicted positions of two unresolved measures. The dot-dash line is the line of nodes; the dashed ellipse is the orbit of Gies et al. (1993). Scales are in arcseconds.

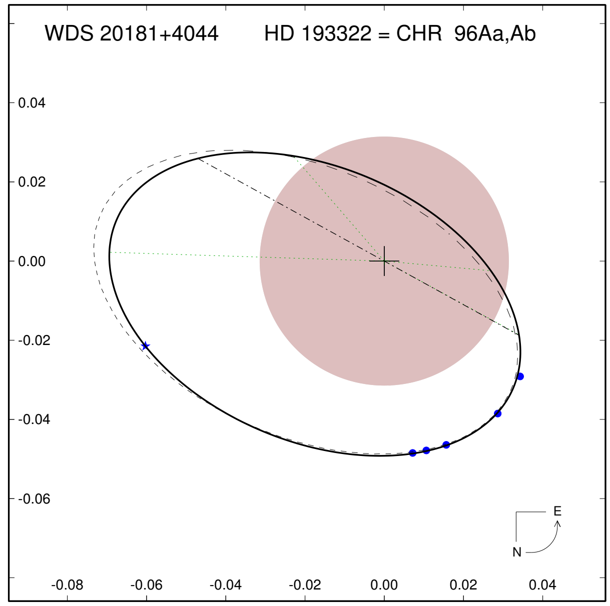

Fig. 2. Orbit of HD 193322. Symbols are as in the earlier figure, with the star now indicating a CHARA Array measure. The dashed ellipse here represents the orbit of Hartkopf et al. (1993).

4.2. *HD 193322 = CHR 96*

Discovered in 1985, the first orbit (Hartkopf et al. 1993) was based on very limited coverage. Subsequently the Aa component was determined to be a 311d SB. The CHARA Array has followed this system since 2005, with the goal of getting better orbits for both the SB and this "wide" speckle pair. Figure 2 shows only the initial 2005 Array measure, together with the speckle measures which defined the original orbit. Four wider components to this system have all remained essentially unchanged in separation from A for 100+ years. Unfortunately the proper motion for A is small, so it is uncertain whether the companions are all physical.

4.3. *δ Sco = LAB 3*

This Be star has been the subject of several orbital analyses over the past 15 years (Bedding 1993; Hartkopf et al. 1996; Miroshnichenko et al. 2001). Miroshnichenko's radial velocity data tied down the eccentricity at 0.94. The latest orbit (Mason et al. 2009) gives a system mass of 27 $M_{\odot}$ for a distance of 140 pc. Periastron is predicted to occur about 2 years from now, and CHARA Array observations are anticipated for some time on either side of T_0.

4.4. *θ^1 Ori C*

This might be the best target for determining a dynamical distance to the Orion Nebula Cluster. To underscore the interest in it, at least seven sets of orbital elements have been published in the past two years. Two very recent papers found quite different results:

• Patience et al. (2008) observed the pair from February 2006–March 2007 using NPOI. Combined with previous results these data yielded an orbit with P=26±13 yr, a=41±14 mas, and e=0.16±0.14. Photometry indicates the mass is at least 40 $M_{\odot}$, and even the minimum value gave an unrealistic distance of 730 pc.

• Kraus et al. (2009) used VLTI data from 2007–2008 and speckle data from 1997–2008 together with RV data to derive an orbit with P=11.2±0.4 yr, a=42±3 mas, and e=0.56±0.06. The system mass is 44 ± 7 $M_{\odot}$, the dynamical distance 410±20 pc.

The difference in results from these two orbital analyses appears to be due to quadrant ambiguity in some of the measures, leading in one case to an incorrect solution. This is unfortunately a common problem with interferometric data, especially the earlier measures.

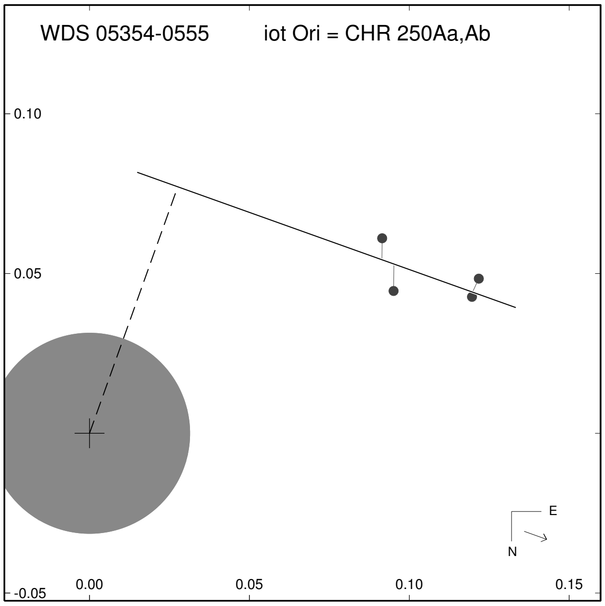

Fig. 3. The ι Ori speckle pair. This rectilinear fit made to speckle measures dating from 1994.7–2006.2 predicts the pair reached a closest apparent separation of $0''.076$ in 1966. We may of course be viewing a small arc of an orbit instead, but the period of such an orbit would be much longer than 40 years.

4.5. *ι Ori = CHR 250*

This member of the famous AE Aur/μ Col/ι Ori binary-binary collision system is a close spectroscopic pair (P=29^{d}), with a speckle companion discovered at about $0''.1$. If the system is hierarchical, this would imply a period of order 40 years for the speckle pair, according to Gualandris et al (2004). However, they argue that the runaway scenerio seems to rule out physical companionship, despite such close proximity. Additional measures obtained in our second phase of O-star speckle observations are consistent with either a linear fit or an orbit with period much longer than 40 years (see Figure 3).

4.6. *Atlas and the distance to the Pleiades*

Finally, an example of the usefulness of dynamical parallax is in order. Our knowledge of the distance to the Pleiades was thrown into some confusion by the 1997 Hipparcos result, which placed the cluster at 118±4 pc, about 10% closer to us than previously determined. This finding of course had many other ramifications, which won't be discussed here. Pan et al. (2004) later published an orbit of the B8 giant Atlas based on Mark III data; the resulting dynamical distance (135±2 pc) was in good agreement with pre-Hipparcos results. Other efforts at about this same time (Munari et al. 2004; Soderblom 2005; Southworth et al. 2005) found similar results, although re-reductions of the Hipparcos data (van Leeuwen 2004, 2007) agreed more closely with the original 1997 finding.

Thank you to the meeting organizers for their invitation and hospitality. Thanks also to JPL and the SIM Science Program for travel support, and to Ken Johnston and USNO for their support of the double star program.

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