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Parameters of Four Multiple Systems from Speckle Interferometry

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Abstract—New or refined visual orbital elements are presented for four double stars (HR 266 AP, 88 Tau AP = CHARA 18, η Ori AB = McA18, ADS 16904 AP = CHARA 149) that are members of multiple systems. Relative photometry and positional speckle measurements with the 6-m telescope and published radial-velocity data for the stars are used. Photometric data and parallaxes from the Hipparcos catalogs are also taken into account. New physical models are proposed for multiple systems.

INTRODUCTION

The impact of high angular resolution techniques in the double and multiple star research is well known. However, until recently, the quantitative information on the components' brightness was missing. With the advent of more sophisticated image acquisition and processing methods like speckle-masking, this difficulty can now be circumvented. The purpose of this paper is to demonstrate the value of modern speckle data in constructing the quantitative models of several multiple stars. The relative photometry and most recent positional measurements are taken from the paper of Schoeller *et al.* (1998)—hereafter Sch+98.

The common identifiers and coordinates of the four multiple systems studied here are given in Table 1. Table 2 contains the elements of visual orbits that are computed or revised in this paper, and individual measurements and residuals are given in Table 8. The next four sections present a detailed analysis of these four systems and the estimates of the physical parameters of their components ("system models"). Conclusions are given in the last section.

HR 266

The most comprehensive previous study of this system is published by Cole *et al.* (1992)—below denoted as C+92. Re consideration is prompted by the speckle-interferometric resolution of the new close companion to the visual primary by Sch+98 (we shall call it here subsystem AP) and by the direct measurement of the parallax by Hipparcos: $\pi_{\mathrm{Hp}} = 5.3 \pm 0.6$ mas (ESA 1997). In the following we assume this distance, which means that the components of HR 266 are unevolved main-sequence stars.

The apparent separation of AP (30 mas) can be used to estimate its orbital period, which must be about five years. This value is suspiciously close to the orbital period 4.84 y of the Bab-Bc system (in C+92 notation). Further interpretation is based on the fact that the systems AP and Bab-Bc are in fact the same. Indeed, the identification of the short (4.24d) and intermediate (4.84y) spectroscopic subsystems with the visual B companion in C+92 is only tentative, as is their adopted model of the system. In particular, these authors could not obtain a satisfactory agreement between the photometric and dynamic distance estimates ($\pi_p = 3.8$ mas and $\pi_d = 5.5$ mas, respectively). This discrepancy can be eliminated.

Now we identify the short and intermediate period subsystems with the visual primary, and call them Aab and AP, respectively. As will be shown, this leads to the consistent model for this system.

The interpretation of the system is further assisted by the fact that magnitude differences of the visual components are now well measured by Sch+98 (Δm(AB) = 0.51, Δm(AP) = 0.71) and Hipparcos (Δm(AB) = 0.42). In fact, Δm = 0.06 given in Sch+98 for AB refer to the magnitude difference between Aa and B; this leads to dm(AB) = 0.51, which is close to the Hipparcos result. We assume that the Δm measured

Table 1. Identification and positions of the stars

HR	HD	ADS	Other names	Positions 2000
266	5408	784	Bul 099	005647 + 602146
1458	29140	3317	88 Tau, CHARA 18	043539 + 100939
1788	35411	4002	η Ori, McA18	052429–022350
	222326	16904	A 643, CHARA149	233921 + 454312

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Table 2. Visual orbital elements

Object	P, years	T	e	a''	$\Omega°$	$\omega°$	$i°$
88 Tau AP	18.05 ± 0.12	1993.00 ± 0.14	0.083 ± 0.008	0.241 ± 0.003	146.6 ± 0.3	222.0 ± 3.0	70.4 ± 0.4
η Ori	9.442 ± 0.012	1991.02 ± 0.11	0.45 ± 0.02	0.0441 ± 0.0015	300.4 ± 1.5	150.0 ± 1.6	102.8 ± 1.8
ADS 16904 AB	151.40	1870.16	0.58	0.221	127.5	95.9	130.3
ADS 16904 AP	15.04	1995.81	0.60	0.049	129.7	272.7	127.1

at 545 nm is equal to the visual magnitude differences ΔV. Consequently, we have the following input data:

Distance modulus	$m\text{–}M = 6.38$ ($\pi_{\mathrm{Hp}} = 5.3$ mas),
Total brightness	$V = 5.55$,
AB magnitude difference	$\Delta V(\mathrm{AB}) = 0.42$ (Hipparcos),
AP magnitude difference	$\Delta V(\mathrm{AP}) = 0.71$ (Sch+98),
Aa–Ab magnitude difference	$\Delta V(\mathrm{Aab}) = 1.3$ (cf. C+92).

With these data, the absolute visual magnitudes of each component can be calculated directly. They are compared to the absolute magnitudes of normal main sequence stars (Lang 1992) and the spectral types of the components are chosen on this basis. Corresponding masses are also taken from Lang (1992), and we obtain the system model (Table 3): in this model the agreement between the observed magnitude differences and spectral types is achieved. The spectral types of Aa, Ab and B agree fairly well with the direct spectral classification given in C+92, as well as with the integral spectral type of the system B9V. Moreover, the mass ratio of the Aab system $q = 0.67$, which was determined from the spectroscopic orbit, agrees with our model which predicts $q = 0.72$. The visual secondary B turns out to be the most massive and the brightest component of this system.

In C+92 the spectroscopic and astrometric orbit of AP is given. Now it is interesting to compare whether the observed position of AP corresponds to this orbit. Of course, the astrometric semimajor axis must be transformed into apparent axis. Also, it must be kept in mind that the astrometric orbital elements of AP are determined in C+92 only crudely. By changing the position angle of the line of nodes Ω from 185 to 147 degrees and by adopting the semimajor axis of $0''.0342$, excellent agreement of the speckle measurement with the AP orbit is obtained. With only one observation it is almost always possible to adjust two parameters to fit it to any orbit. In this case, however, the necessary adjustment is reasonable with respect to the errors of the orbit itself. With the semimajor axis of 34 mas, the period of 4.84y and the mass sum of $7.7M_{\odot}$ solar mass, we calculate the dynamical parallax of AP orbit $\pi = 6.0$ mas. It corresponds well to the dynamical parallax of AB (5.8 mas with our mass sum of $11.0M_{\odot}$), which strengthens our identification of AP with intermediate-period spectroscopic subsystem.

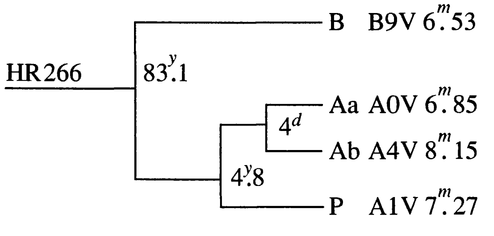

Diagram for the hierarchical multiple system HR 266 = ADS 784

The astrometric semimajor axis $\alpha = 4$ mas can be compared to the apparent semimajor axis $a = 34$ mas derived above. The ratio of these axes is given by the standard formula

$$\alpha/a = -q/(1+q) + r/(1+r), \qquad (1)$$

where q is the mass ratio, and r is the light ratio of the components $r = 10^{-0.4\Delta m}$. With our model $q = 0.54$, $r = 0.53$, and $\alpha/a = 0$, while actually $\alpha/a = -0.12$. This discrepancy cannot be explained now, and we must wait for the calculation of the AP orbit to clarify the issue.

The visual component P is relatively bright, but its lines are not visible in the optical spectrum (C+92). It is likely that it rotates rapidly and its lines are superimposed on the broad ($v\sin i = 240$ km/s) lines of B. The orbital motion of P with 4.84 year period produces only small radial velocity variation ($K = 20$ km/s), which remains undetectable. The combined light of P and B reinforces the impression that the broad-lined component is the brightest, which might account for the wrong attribution of the spectroscopic subsystems in C+92.

In this note, we leave aside the interesting questions concerning the chemical peculiarity of the Aa component (Hubrig and Mathys 1995) and the problem of slow axial rotation of the short-period system components Aa and Ab ($v\sin i = 5$ km/s). The dynamical evolution of this system may also present an interesting research topic. It is possible that the Aab system loses its angular momentum due to the interaction with P and will eventually collapse into a single, rapidly rotating star.

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88 TAU

This interesting multiple system is situated in the region of Hyades, but does not belong to this cluster. The bright visual primary is a known eclipsing and spectroscopic binary star with 3.57 d period. Burkhart and Coupry (1988) = B88 discovered five independent line systems in the high-resolution spectrum and called it a "spectroscopic quintuple". Indeed, since 1985, this star is observed as an interferometric binary CHARA 18, so it is at least triple. Now the orbit computation is possible. Here we report the first orbital solution and a preliminary model of CHARA 18, called here AP in order to distinguish the resolved interferometric components from the spectroscopic ones. The orbital elements of AB are given in Table 1.

Additional data come from the Hipparcos mission (ESA 1997): parallax π = 21.7 ± 0.8 mas (distance module $m-M$ = 3.3) and magnitude difference of AP ΔHp = 2.17 ± 0.08. The photometry of Sch+98 gives ΔR = 1.85 ± 0.15. Here we assume an intermediate value $\Delta V = 2.0$ which agrees with both these measurements within their errors. Let us begin to construct the system model.

The visual magnitudes of A and P are 4.41 and 6.41. The masses of the components of the eclipsing pair Aab are known from their spectroscopic orbit: $M_{\rm Aa} = 1.87 M_\odot$ and $M_{\rm Ab} = 1.12 M_\odot$. Thus the secondary Ab must be a F7 V dwarf, which has a magnitude difference with the primary of 2.4m. We assume that P is a close spectroscopic binary with yet unknown period, as stated in B88. Its components are taken to be equal for the moment, so their magnitudes can also be estimated. With these estimates, we obtain the following model of the system (table 4).

Assuming the mass sum of AP to be $5.4 M_\odot$ according to the above model, we obtain from our orbit a dynamical parallax $\pi_{\rm dyn}$ = 19.6 mas. On the other hand, if we use the Hipparcos parallax, the orbit corresponds to the mass sum of $4.2 \pm 0.5 M_\odot$. There is therefore a slight discrepancy between the dynamic and the trigonometric parallaxes. It would be still more pronounced if we assumed that AP contains not four, but five stars of comparable luminosities and masses, as suggested by B88; on the other hand, if P is not binary, the discrepancy would disappear.

The visual secondary B (V = 7.84, F8 V) shares the proper motion with AP and has the same radial velocity. It was found to be a long-period spectroscopic binary by Tokovinin, and a spectroscopic orbit will be determined in a few years. To the best of our current knowledge, this system appears to be sextuple. New high-resolution spectroscopic studies are needed to determine the orbit of Pab.

η Ori

This unique young multiple system has been the subject of several studies (Zizka and Beardsley 1981; Waelkens and Lampens 1988 (WL88); DeMey *et al.* 1996). Surprisingly, no definitive visual orbit is yet known for the nine-year interferometric system. The orbit of McAlister (1976) was a first preliminary attempt to fit few speckle measures. Since then, three revolutions were observed by speckle interferometry. However, the system is resolved only at maximum separations and interferometric data alone are not sufficient for visual orbit computation.

Here we attempt to use the published radial velocities of Zizka and Beardsley 1981 and all available speckle measurements to construct a combined orbit, using the finding of WL88 that the true orbital period is about 9.5 years.

The radial velocity curve obtained with the new period from the systemic velocities of the 7.8-day Aab system published by Zizka and Beardsley 1981 shows a large scatter of data. An examination reveals that most of the scatter is related to the recent velocities (1966–1972) and to the 1920 data. Excluding these data sets, as well as five other deviating points (1902.137, 1915.164, 1915.186, 1924.199, and 1928.223) reduces the rms scatter from 5.5 to 3.04 km/s. Thus, we use only the remaining 111 velocities in the orbit refinement.

The result of least-squares fitting of all nine orbital elements is given in table 2 (for visual elements), and the spectroscopic elements are: $K_1 = 19.14 \pm 0.44$ km/s and $V_0 = 29.95 \pm 0.26$ km/s. The available data still do not constrain the elements very well, and simultaneous fitting of all elements was not possible. We therefore fitted the elements sequentially or in groups, trying to reduce χ^2. Formal errors are nevertheless obtained in the usual way from the diagonal elements of a covariance matrix. These error estimates should be viewed with great caution. It can be seen that new orbit is significantly different from the McAlister (1976) orbit, e.g., now the inclination i = 100 deg instead of 90 deg and the exact coplanarity between Aab-Ac and the eclipsing system Aab is excluded.

Table 3. Model of the system HR 266

Component	m_V	Spectral type	Mass $M_\odot$	M_V
B	6.53	B9V	3.3	0.15
P	7.27	A1V	2.7	0.89
Aa	6.85	A0V	2.9	0.47
Ab	8.15	A4V	2.1	1.77

Table 4. Model of the system 88 Tau

Component	m_V	Spectral type	Mass $M_\odot$	$m-M$
Aa	4.52	A2V	1.87	3.4
Ab	6.92	F7V	1.12	3.1
Pa	7.16	F7V	1.22	3.3
Pb	7.16	F7V	1.22	3.3

Let us refine the estimates of the physical parameters of the components. The masses of the 7.8-day eclipsing system components Aa and Ab are $11.0M_\odot$ and $10.6M_\odot$, according to the latest orbit (DeGeus *et al.* 1996). The minimum mass of the interferometric secondary Ac is $12.8M_\odot$ from the mass of Aa+Ab and our orbit. Since orbital inclination is close to 100 deg., the true mass of Ac is close to $12.8M_\odot$. With mass sum of Aabc of $33.4M_\odot$, the dynamic parallax of the interferometric orbit is $\pi_{\rm dyn}$ = 3.08 mas, which corresponds to the distance modulus m–M = 7.56. This distance estimate is in excellent agreement with the photometric distance m–M = 7.58 obtained by WL88. The Hipparcos parallax $\pi_{\rm Hp} = 3.62 \pm 0.88$ mas does not contradict our dynamic parallax.

New photometry of Sch+98 and of the Hipparcos mission can be used to adjust slightly the components' magnitudes calculated by WL88. All measurements were made in the different passbands. Let us, however, ignore for the moment the color differences between the components and assume that magnitude differences in the V band are equal to the values given above. The available photometric data are summarized in Table 5.

Comparing these data with WL88, we see that magnitudes of Aa and B are changed little, while Ab and Ac are 0.7–0.8 fainter in our model. The adopted spectral types correspond to the photometric distance moduli m–M = 7.2.–7.6 for all components (the extinction A_V = 0.61 as estimated by WL88 is taken into account). Summary of components' parameters is given in Table 6.

An intriguing conclusion from our new orbit is that the component Ac is the most massive member of this system, but not the most luminous one. In addition, all masses are somewhat smaller than usual for given spectral types. Thus, there is no sense in further refinement of the model, because the components of this young multiple star do not to fit exactly the standard stellar data relations like mass-luminosity and mass-spectral type, etc. We hope that further observations will help to establish their physical properties with better accuracy.

ADS 16904

This visual binary has a 292-year orbit calculated by Heintz (1967). More recently, the orbit was revised by Zulevic (1994)—henceforth Zul94; the new value of the period is 238 years. In 1986, the primary was shown to be itself a close interferometric binary called CHARA 149. Below we call it AP.

The four measurements of AP available now are just sufficient to calculate its first preliminary orbit. It also became apparent that the orbit of AB computed by Zul94 leaves large residuals with the new speckle data. It can be slightly corrected. However, the arc covered by AB since its discovery in 1903 is only 110 degrees and does not yet include the periastron, so the AB orbit remains poorly determined. Here we suggest another orbit of AB, which is entirely different from Zul94 orbit and fits the available data quite well. The orbital elements for AB and AP are listed in Table 2.

The residuals of speckle measurements of AP (1983.7–1994.7) to both T98 and corrected Zul94 orbits are large and systematic, and differ little between these two solutions. Evidently, the motion in the AP subsystem is reflected as a perturbation of the AB motion. Qualitatively, the behavior of the residuals is in agreement with our AP orbit. Unfortunately, the visual measurements are far too inaccurate to show this effect, and hence are of no use in improving the orbital period of AP. Speckle data on AB do not yet permit the computation of the full "speckle-astrometric" orbit of AP. We can assert only that the semimajor axis of the photocenter orbit of AP is at least 20 mas.

The dynamic parallaxes given above are computed with the estimated component masses. These were obtained in the following way. First, the relative photometry of components from Sch+98 is taken into account. Disregarding that these measurements refer to the Hα spectral region, we assume that the visual magnitude differences are the same. Also, the spectral type of the A component is known to be A2. This leads to an

Table 5. Photometric data for η Ori

System	Total absolute magnitude M	Δm	Passband	m_1	m_2	Reference
AB	3.35	1.31	Hip (~B + V)	3.64	4.95	Hipparcos
Aab–Ac	3.64	1.41	Hα	4.24	5.65	Sch+98
Aab	4.24	1.40	~B	4.50	5.90	WL88

Table 6. Model of the system η Ori

Component	m_V	Spectral type	Mass $M_\odot$	m–M
Aa	4.50	B1V	11.0	7.4
Ab	5.90	B3V	10.6	7.6
Ac	5.65	B3V	12.8	7.3
B	4.95	B2V	?	7.2

Table 7. Model of the system ADS 16904

Component	m_V	Spectral type	Mass $M_\odot$
A	8.42	A2V	2.76
P	10.02	F0V?	1.70
B	8.59	A2V	2.76

estimate of component magnitudes, spectral types, and masses (Table 7).

The dynamic parallax which were computed from AB and AP orbits (4.0 and 4.8 mas, respectively) are in agreement with the Hipparcos parallax, $\pi_{Hp} = 3.7 \pm 1.3$ mas. Consequently, our orbital solutions and the model of the components must be close to the truth. When the small interstellar reddening is taken into account (we assume $E_{B-V} = 0.2$, $R = 3.5$), the photometric distance module corresponding to our model is $m-M = 6.6$ or $\pi = 4.8$ mas.

Disagreement exists, however, between our model and the semimajor axis of the photocentric orbit of AP. The measured light ratio of A to P is $r = 0.23$, and the mass ratio taken from the model is $q = 0.61$. These two numbers correspond to the ratio of the photocentric to the full axes $\alpha/a = -0.2$, according to (1), while in fact α must be about -0.40. The agreement would be achieved if the mass of P would be about $4.7 M_\odot$! solar masses! For the moment we can tentatively suggest that P is a close pair of G dwarfs instead of a single FOV star. Further observations will clarify the situation and will allow the mass of P component to be measured directly.

It is worthwhile to note that the orbits of AB and AP, as known presently, are almost coplanar, although coplanarity was not explicitly assumed in the computation. Similarity of the longitude of periastron is notable. The integer ratio $P(\mathrm{AB})/P(\mathrm{AP}) = 10$, implying a resonance, remains a more speculative suggestion, but it is already clear that because of the small period ratio, this system is not very far from the stability limit. Another point worth mentioning is the fact that the motion of AP photocenter introduces a systematic component in the measured motion of AB, because the average position of AP does not coincide with its center of mass. Future refinement of the AB orbit must take this effect into consideration.

Our analysis should be considered preliminary, because the full orbital period of AP has not yet been observed.

CONCLUSION

This study demonstrates the power of modern speckle techniques for the multiple star research. Two of the systems considered here will soon have reliable visual orbits both for the inner close subsystem and for the outer visual pair, and hence the relative direction of their angular momenta will be determined. Our analysis indicates that angular momenta are likely to be coaligned. This, however, is not a general rule (Tokovinin 1993). The number of multiple systems with the visual orbits known for two adjacent hierarchical levels remains very small, and each new case adds substantial data for the study of orbit coplanarity.

Another interesting consequence of this work is that now we know the component masses and mass ratios in these multiple systems with much better confidence. When a larger body of similar data becomes available, a sound statistical analysis of mass ratio distribution in multiple stars will be attempted. Such a study can give new clues for the investigation of multiple star formation.

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