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ORBIT OF BINARY 15 MONOCEROTIS

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Abstract. In the paper new orbital elements obtained from speckle interferometric measurements only for 15 Mon are reported. For this binary they were determined earlier by combining spectroscopic and speckle measurements and spectroscopic and astrometric measurements. A new speckle measurement dating after the periastron passage of the secondary has a significant discrepancy from the ephemeridal value. Our revised orbit has a period significantly longer than the earlier ones. This pair is bright (apparent magnitude of primary 4.66, i.e. 5.9 of secondary), of an early spectral type (primary O7V, secondary O9.5Vn) and is a member of open cluster NGC 2264. By analyzing the available data we find that the distance to 15 Mon is most likely about 750 pc, i.e. the total mass most likely about $53.4\mathcal{M}_{\odot}$. The new orbital elements combined with this distance yield a total mass expected for the spectral types of the components.

1. INTRODUCTION

The bright O star 15 Monocerotis (15 Mon) in the Washington Double Star Catalog (WDS) (Mason et al. 2006) has a designation WDS06410+0954, whereas that of the discoverer is CHR 168 Aa. The identification numbers in other catalog are HIP 31978, HR 2456, HD 47839 and 1725 in The ninth catalog of spectroscopic binary orbits (SB9). According to WDS the primary has a visual apparent magnitude of 4.66 and spectrum O7Ve, whereas for the secondary one finds in the literature (Gies et al. 1993) 5.90 and O9.5Vn, respectively. In the Hipparcos Catalog (ESA 1997) a trigonometric parallax of 3.19±0.73 mas is given. The first preliminary orbital elements were determined by combining the speckle and spectroscopic measurements (Gies et al. 1993). A few years afterwards new radial velocity measurements and the first astrometric one formed a base to a minor revision of these elements (Gies et al. 1997).

On the basis of published mean radial velocities over the period 1902 - 1993 Gies et al. (1993) determined the spectroscopic orbital elements for 15 Mon and the remaining ones using the speckle measurements (Table 1. - first orbit). The companion in this pair was firstly detected from the speckle measurements in 1988 and by 1993 two more speckle measurements were made. Assuming the values for P, T, e and ω obtained from the spectroscopic measurements the ones for a, i and Ω were obtained from the speckle measurements. So Gies et al. (1993) find a period of 25.2 years. The same authors assumed that this binary is at a distance of 950 pc, a value found by Perez et al. (1987) for the distance of NGC 2264. In this way it became possible to determine the masses of the components of this early spectral type binary: $34\mathcal{M}_\odot$ for the primary and $19\mathcal{M}_\odot$ for the secondary. Besides, there is a large gap in the radial velocity data for the period 1923 - 1969 so that the authors admit that the orbital period can be even twice as long.

After four years, based on new radial velocity measurements and the first astrometric one of the massive binary 15 Mon made with the Hubble Space Telescope Fine Guidance Sensors (HST FGS), Gies et al. (1997) published new orbital elements combining spectroscopic and astrometric data (Table 1. - second orbit). These measurements confirmed that the companion is very near the periastron. The new value for the period found then was 23.6 years. The orbital elements (Gies et al. 1997) are in the Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf and Mason 2006) and in The ninth catalog of spectroscopic binary orbits (Pourbaix et al. 2004). After assuming a distance of 950 pc and combining it with the new orbital elements the authors mentioned above found masses of $35\mathcal{M}_\odot$ and $24\mathcal{M}_\odot$ for the primary and secondary, respectively.

The distance to open cluster NGC 2264, in which 15 Mon is a member, has been determined many times. In the article by Perez et al. (1987) one finds about twenty cited references concerning this distance determination. From these values a mean value equal to d=735±106 pc was derived. Also using photometric and spectroscopic measurements Perez et al. found that NGC 2264 is at d=950±75 pc from the Sun. In the more recent literature we find that for the distance to NGC 2264 values between 700 pc and 800 pc have been largely proposed (Ramirez et al. 2004, Dahm and Simon 2005, Kharchenko et al. 2005, Dahm et al. 2007, etc). Consequently, the distance of 950 pc seems to exceed the true one. On the other hand, the trigonometric parallax given in Hipparcos appears to be unrealistic because a too small value of only 313 pc results. Experience has shown that the HIPPARCOS parallaxes of order of a few mas are very unreliable.

2. ORBITAL ELEMENTS FROM THE SPECKLE MEASUREMENTS

In the Fourth Catalog of Interferometric Measurements of Binary Stars (Hartkopf et al. 2006) we find another measurement from the epoch 2001.0197 made by Mason and coworkers which took place after the periastron (when due to the small separation the components could not be resolved by using speckle interferometry). The residuals from the ephemeridal values are large, −108.9 degrees in the position angle and 16 mas in the separation (Table 2). It should be borne in mind that the earlier orbital elements were derived from measurements covering a short arc of the orbit and from uncertain radial velocities. The last speckle measurement enlarges significantly the observed arc of the orbit and makes possible a more reliable determination of the orbital elements. In addition, it makes possible the determination of the orbital elements from the precise speckle measurements only made with a large telescope (4m).

In our calculations of the orbital elements the Kovalski-Olević method (Olević and Cvetković 2004) is applied. Due to the short arc covered by the speckle measurements we obtain several good fits with periods of 62-75 years and our final orbit (Table 1) is chosen only after fitting the radial velocity measurements to our orbital elements (Fig. 2).

Table 1: Orbital elements for 15 Monocerotis = CHR 168 Aa

Orbit	P[yr]	T	$a[''$]	e	$i[^\circ]$	$\Omega[^\circ]$	$\omega[^\circ]$
First orbit	25.2	1922.75	0.0339	0.67	30.4	15.0	169.
	-	-	±0.015	-	±10.0	±2.5	-
Second orbit	23.6	1926.0	0.0339	0.78	35.	16.8	168.
	-	-	±0.0005	±0.02	±20.	±1.2	±3.0
Our orbit	74.00	1996.07	0.0885	0.76	62.4	42.6	82.6
	±0.30	±0.29	±0.0028	±0.017	±0.4	±0.4	±1.5

Table 2: Residuals

			first orbit		second orbit		our orbit	
Epoch	θ	ρ	(O-C)$_\theta$	(O-C)$_\rho$	(O-C)$_\theta$	(O-C)$_\rho$	(O-C)$_\theta$	(O-C)$_\rho$
1988.1704	12.9	0.057	−0.6	0.002	−2.1	0.000	0.0	0.000
1993.0925	35.4	0.039	0.3	−0.002	1.5	0.001	−0.3	−0.001
1993.1967	36.7	0.041	1.0	0.000	2.2	0.004	0.3	0.001
2001.0197	232.3	0.055	−74.5	0.030	−108.9	0.016	0.0	0.000

The orbital elements (equinox J2000) are listed in Table 1 together with the orbital elements following from the two earlier solutions: first orbit (Gies et al. 1993) and second orbit (Gies et al. 1997).

Fig. 1 gives the apparent orbit where the solid curve refers to our orbit and the dashed one to that published earlier. The solid straight line is the nodal line. The arrow in the corner below indicates the sense of the companion's revolution around the primary.

Table 2 contains the observational data used and their residuals for all three calculated orbits.

3. SPECTROSCOPIC DATA

Some high resolution spectroscopic observations (S/N≈400), indicate the presence of some spectral features in the wings of rather sharp and deep primary line profiles that could be formed by spectral lines which belong to the secondary component (Gies et al. 1993). These very shallow and broad features, blended by strong spectral lines of the primary star, are not suitable for precise radial velocity measurements of the secondary component. Therefore, practically 15 Mon is a single-lined binary system. Consequently, from radial velocity measurements, in addition to the eccentricity and the periastron longitude, the mass function and the projected semimajor axis of the primary star can be derived only. Spectroscopic observations of 15 Mon are unequally spaced in time with large gaps (the longest gap is 46 years). Because of this the orbital elements of this binary determined from radial velocities are rather uncertain.

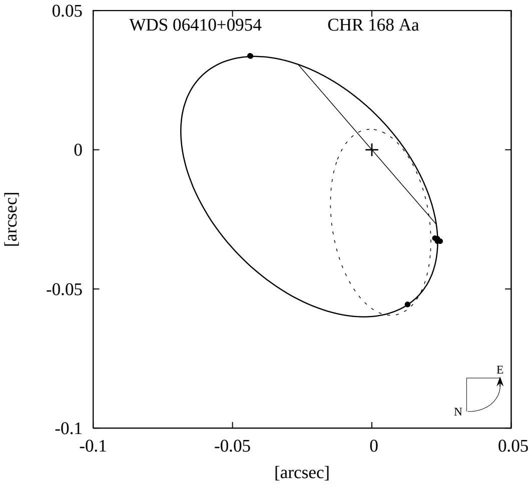

Figure 1: Apparent orbit for 15 Monocerotis: the solid curve refers to our orbit and the dashed one to that published earlier (second orbit); details see in the main text.

Combining our orbital period, eccentricity and inclination of the orbit, and the new value of the semiamplitude in the velocity curve given by Gies et al. (1997) we obtain 3.81 for the mass function. We estimate the mass of the primary to be $29.1\mathcal{M}_{\odot}$, based on its position in the HR diagram according to spectral type O7V (Lang 1992) and derive the mass of the secondary $21.3\mathcal{M}_{\odot}$. This leads to a mass ratio of 0.73. The obtained mass ratio is consistent with the expected mass ratio derived from the spectral type of the components. Thus the total mass is $50.4\mathcal{M}_{\odot}$. Combined with our orbital elements by means of Kepler's third law it yields a dynamical distance of 736 pc which is within the distance interval mentioned in Introduction. Therefore, there is no need to assume the unrealistic distance of 950 pc (Gies et al. 1993).

With our orbital elements we calculate the radial velocity in order to see its agreement with the measured values. This is presented in Fig. 2. The best agreement is found when values of about 28-30 km s^{-1} are assumed for the motion of the mass center along the line of sight. Independently we find 28.4 km/s in two catalogs (Barbier-Brossat and Figon 2000, Kharchenko et al. 2007). Therefore, this value is assumed as the radial velocity of the mass center in the fitting procedure. The fit in the radial velocity helped us to assume the values given for our orbital elements in Table 1 as final ones since we had several good solutions as said above. In this case the residuals between the values of radial velocity following from our assumed orbit and the measured values are the smallest.

4. PHOTOMETRIC DISTANCE

For 15 Mon the distance can be determined also photometrically. The data about the spectral type are available, especially for the primary (O7V) where they are very reliable, whereas for the other component we find O9.5V. Then the absolute magnitude M_v expected for such spectral type in the case of component A is equal to

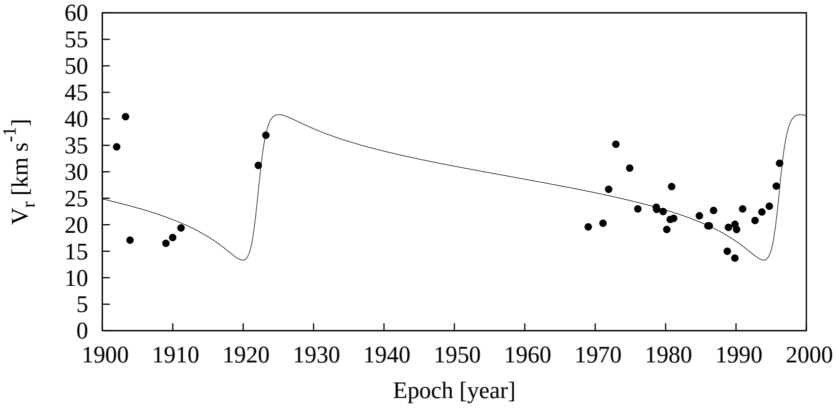

Figure 2: Radial velocity fit: the curve corresponds to our orbital elements and the points are the measured values.

-5.2 (e.g. Lang 1992 - p.137, Binney and Merrifield 1998 p. 110; both based on the same data source from 1982). Combined with the value for the corresponding apparent magnitude (4.66) this yields a distance modulus of 9.86. This value means that the binary would be at a distance of about 950 pc, but provided that the interstellar extinction is zero which, clearly, is not realistic.

However, for O stars in general we find physical parameters (Howarth and Prinja 1989) according to which an O7V star should have $M_v = -4.9$. This yields a distance modulus of 9.56, i.e. without extinction the distance would be about 815 pc.

For the interstellar extinction we find various values: from about 0.2 (Lang 1992, Dahm and Simon 2005) via 0.25 (Dahm et al. 2007) towards 0.41 (Ramírez et al. 2004).

With regard to the values for the distance modulus and extinction mentioned above, most likely the distance of the binary lies between 700 pc and 800 pc. This result agrees very well with the values cited above for cluster NGC 2264 as a whole.

5. DISCUSSION AND CONCLUSIONS

If accepted that the limits for the 15 Mon distance are 700 pc and 800 pc (more precisely the middle of 750 pc is assumed) and the orbital elements proposed by Gies et al. (1997) are used, then by applying Kepler's third law one obtains the corresponding total mass to be equal to $29.5\mathcal{M}_\odot$. If our orbital elements are used, by applying Kepler's third law the total mass of the system is found to be $53.4\mathcal{M}_\odot$ for the same distance.

Among the physical parameters of O stars determined by Howarth and Prinja (1989) is also the mass. According to them an O7V star should have a mass of $36\mathcal{M}_\odot$ and an O9.5V one $21\mathcal{M}_\odot$. In the particular case the primary of 15 Mon was found by these two authors to have a mass of $39\mathcal{M}_\odot$. Then the total mass of this binary is $60\mathcal{M}_\odot$. Our total mass of $53.4\mathcal{M}_\odot$ is very close to this value and the one following from the spectroscopy ($50.4\mathcal{M}_\odot$) is not too different. However, the value of $29.5\mathcal{M}_\odot$

following from the orbital elements by Gies et al. (1997) appears to be too low. In addition, the mass-luminosity relation for the main sequence stars (e.g. Lang 1992) yields for the total mass of such a pair about $50\mathcal{M}_{\odot}$.

From what has been said above we conclude that:

i) the distance of 950 pc for 15 Mon (open cluster NGC 2264) is too large, most likely the true one lies between 700 pc and 800 pc;

ii) our orbital elements obtained from speckle measurements only are in favor of a longer period and larger semimajor axis than found earlier.

New measurements both speckle and radial velocity ones are very desirable in order to throw more light on the case of binary 15 Mon.

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