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ASTRONOMY AND ASTROPHYSICS

The discovery of a new massive O-type close binary: τ CMa (HD 57061), based on Hipparcos and Walraven photometry*

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Abstract. We present an interpretation of Hipparcos Hp and Walraven $VBLUW$ photometry of the brightest star in the open cluster NGC 2362 (although not necessarily associated with this cluster), HD 57061 (30τ CMa, HR 2782, HIP 35415). In this multiple system the central component consist of a visual double star, two O-type stars separated by 0.″151, which is also known to be a 154.^{d}9 period single lined spectroscopic binary. It is now shown that this system also contains a massive close binary with a period of 1.^{d}282122, most probably as the main component of the spectroscopic binary. This system therefore contains both the longest period spectroscopic binary and the shortest period eclipsing binary known for O-type stars. The shape of the light curve is characteristic for heavily distorted double star components. An estimate has been made for various physical parameters of the system. The system seems to be typical for some binary interaction results obtained in N-body simulations for open clusters. Improved ephemeris are provided for two similar stars that were observed around the same time as HD 57061: HD 57060 and HD 167971.

Key words: technique: photometric – stars: individual: HD 57061 = 30 τ CMa = HR 2782 = HIP 35415, HD 57060 = UW CMa = HIP 35412, HD167971 = MY Ser = HIP 89681 – (stars) binaries: close

1. Introduction

Only few massive O-type close binaries are known. These stars are interesting in various respects: for deriving basic stellar parameters of massive stars, providing input parameters for stellar evolution and stellar structure models; for physics of wind collisions (sometimes leading to X-ray variability, see for example Berghöfer & Schmitt 1995); and for mass transfer during stellar evolution. Well-known cases are shown in Table 1. In the present paper we present and discuss Hipparcos and $VBLUW$ photometry (Walraven system) of a new member of this class, τ CMa (other identifiers for this star are: HD 57061, HR 2782, HIP 35415).

Binary stars are of great importance for the dynamical evolution of a star cluster. They can serve as an energy exchange mechanism, leading to the creation of very tight binaries and escaping cluster members, as well as temporary and usually very unstable three to four star configurations (see e.g. Terlevich 1987). A massive binary star in a cluster can lead to a wide range of accidental consequences for the cluster as well as the binary system (see for example Pols & Marinus 1994).

2. Previous work on τ CMa

τ CMa is a probable member of the open cluster NGC 2362 (=Mel 65), although its radial velocity differs by 9.9 km s^{-1} from those of other cluster members (see Trumpler, 1935, Struve & Kraft, 1954). Using a more recent determination of the radial velocity of the cluster by Conti et al. (1977), a difference between the radial velocity of the cluster and the γ velocity of the system of 8.0 km s^{-1} is found. Trumpler explained this difference as the result of redshift caused by the large masses of the stars involved. The mass required (300 M$_\odot$) seems, however, not to to be confirmed by more recent data on O type stars, and it is still well possible that this star is not (or no longer) a member of NGC 2632. The Trumpler effect for an O9 star is, according to Conti et al. (1977), around 1.5 km s^{-1}.

The central component, consisting of a bright visual binary, has been listed as a suspected variable by Kukarkin et al. (1982) with identifier NSV 3528. Finsen (1951) discovered this star as a visual double star. The separation and orientation angle for the two components as given by him, 0.″158 and 110.°2, are remarkably close to the Hipparcos values: 0.″151 and 299°(except for the choice of the brighter component, which causes the near 180°difference between the orientation angles). The Hipparcos catalogue gives for the magnitudes of these two components Hp = 4.887 and Hp = 5.329. The Catalogue of the Com-

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* Based on observations made with the ESA Hipparcos satellite, and on observations collected at the European Southern Observatory, La Silla, Chile

Table 1. Examples of massive O-type binary systems

HD	HIP	V_J	Name	Period	Variab.	Spectr.type	Note
1337	1415	4.41	AO Cas	$3^{\mathrm{d}}.52$	phot.	O9.5III + O8V	1
47129	31646	6.06	V640 Mon	$14^{\mathrm{d}}.4$	spect.	O7.5I + O6I	2
57060	35412	5.09	UW CMa	$4^{\mathrm{d}}.39$	phot.	O7.5Iabf + O9.7Ib	3
93205		7.74		$6^{\mathrm{d}}.08$	spect.	O3V + O8V	4
167971	89681	7.45	MY Ser	$3^{\mathrm{d}}.32$	phot.	O5V + [O8V + O8 Ib]	5

Notes to Table 1:
[1] Bagnuolo & Gies, 1991
[2] Plaskett's star, Bagnuolo et al., 1992
[3] Bagnuolo et al., 1994
[4] Conti & Walborn, 1976
[5] Leitherer et al., 1987

Table 2. Orbital parameters and derived quantities for the spectroscopic binary in τ CMa.

Period	154.900 days
T(per)	2425203.63
ω	$98^{\circ}.10$
e	0.312
K	48.45 km s^{-1}
a sin i	0.655 AU
$(M_1+M_2)(\sin i)^3$	1.58 $M_{\odot}$
γ	42.5 km s^{-1}

ponents of Double and Multiple Stars (CCDM, Dommanget & Nys, 1994) lists this system as CCDM07192−2457, and gives 5 visual components, two of which form the bright central system, referred to as Aa. Of the three other, fainter components that are generally associated with this system, only one (component B) is of some relevance to the present study and can be found in the Tycho Catalogue: TYC 6541 4233 1 at $8''.30$, V_T = 9.77.

The central components Aa are known to contain a single lined spectroscopic binary with a period of $154^{\mathrm{d}}.9$ (Struve & Pogo, 1928, Struve & Kraft, 1954). This period is based on three sets of observations, obtained in 1906–1909, 1927–1928 and 1951–1952. A re-examination of the data as presented in those two papers was done (using representations given by Pecker & Schatzman 1959 and Bond & Allman 1996), giving the slightly modified orbital parameters shown in Table 2. The main reason for this reinvestigation was to allow for the residual velocities to be investigated with respect to the parameters of the newly discovered eclipsing binary in the system. All original measurements and the curve based on the fitted orbital parameters are shown in Fig. 1.

Although the system was reported to be a single line system, in one of the spectra a second set of lines seemed visible. This spectrum was subsequently down-weighted in the solutions. It seems most likely that the spectroscopic binary is the brighter one of the two visual components Aa. One would expected the spectral lines of brightest component to be most easily visible. $154^{\mathrm{d}}.9$ is one of the longest periods known for an O-type spectroscopic binary. It appears that the discovery by Finsen (1951) of this system as a visual double star was not known to Struve and Kraft at the time of their publication.

The combined magnitude for the visual binary is V_J = 4.41. The CCDM catalogue puts the fainter companion as the southern most star, while in the Hipparcos catalogue it is the brighter component. We will assume that the Hipparcos result (obtained independently by the two reduction consortia and indicated in the catalogue as a good, reliable solution) represents the actual configuration of this system.

Various spectral type determinations of the bright triple system were made, lying in the range O8 - O9, and luminosity class I - III (for further details see Kennedy & Buscombe, 1974). More recent ones were obtained from the Ultraviolet Bright Star Catalogue, ESA (1976) (O9I), and from the IUE Atlas, ESA (1984) (O9.5III). A spectrum of τ CMa can also be found in Walborn & Bohlin (1996) and a comparison with P Cygni profiles was presented by Prinja & Howarth (1986). The spectrum of this star is referred to in "The New Washington Double Star Catalogue" (Worley & Douglass 1994) as typical for a β Lyrae star, the proto-type of a class of very close eclipsing binaries with deformed components. The spectral lines were referred to by Struve & Kraft (1954) as very fuzzy, leading to three times larger than expected errors on the velocity estimates.

The distance modulus and the reddening for the cluster NGC 2362 were estimated by Humphreys (1978) as amounting to $M - m$ = 9.77 (r = 900 pc) and $E_{(B-V)_J}$ = 0.12. Later estimates by Mermilliod & Maeder (1986) and by Brown et al. (1986) give distance moduli of $M - m$ = 11.05 (r = 1620 pc) and $M - m$ = 10.76 (r = 1420 pc) respectively, with reddening values of $E_{(B-V)_J}$ = 0.11 and $E_{(B-V)_J}$ = 0.09. $VBLUW$ photometry of the triple system provided $E_{(B-V)_J}$ = 0.16. It should be realized, however, that any photometric reddening determination for a multiple system such as this one is uncertain due to way colour coefficients of the components "add up". There is also considerable (15 to 20 per cent at least) uncertainty in photometric distance calibrations as was shown for

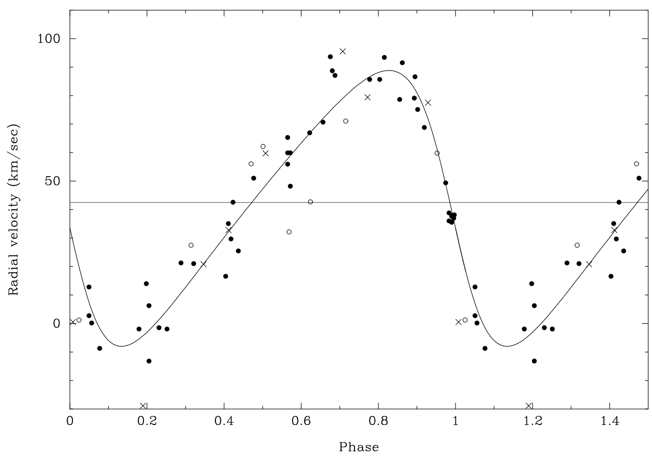

Fig. 1. The spectroscopic data for τ CMa. Full dots, open dots and crosses indicate data of good, average and low quality respectively. The curve represents the modelled radial velocities as based on the orbital parameters given in Table 2. The γ velocity is indicated by the dotted line.

the Pleiades cluster when the Hipparcos parallax determination became available (van Leeuwen & Hansen Ruiz, 1997). In addition, the Hipparcos distance determinations for OB-associations show a clear tendency for photometric distance calibrations for such early-type stars to give over estimates of their distances (see de Zeeuw et al. 1997).

A light variation with a total range of $\approx$ 0.05 mag was established (see Sect. 3.2 and van Genderen et al., 1985, 1989, van Genderen, 1989). The search for a period in these light variations met with difficulties. Two possible periods were found: $0\overset{\mathrm{d}}{.}39$ and $1\overset{\mathrm{d}}{.}76$ as well as a third one of slightly less significance at $0\overset{\mathrm{d}}{.}64$ (half the final period for the eclipsing binary system). The light curves were supposed to be more or less sinusoidal like most variable super- and hypergiants, the α Cyg variables. There was no suspicion that the light variation should be due to binarity, in which case the genuine period should be twice as long as the one found by the period search program.

3. Observations and reductions

3.1. Hipparcos photometry

The Hipparcos main-mission photometry has been described by van Leeuwen et al. (1997), van Leeuwen (1997) and in Volumes 1 and 3 of the Hipparcos and Tycho Catalogues, ESA (1997). The Hipparcos main mission photometry was derived from the same signal as the astrometric measurements. To accommodate the needs of the astrometric measurements, a broad passband was used, referred to as Hp. The specification of this passband can be found in ESA (1997), Volume 1, Table 1.3.1. The effective wavelength of this passband was very close to the V_J band. We use here only the dc-component of the Hp photometry, which is the most accurate and is not disturbed by the duplicity of the object.

The ecliptic coordinates of HIP 35415 are λ = $116\overset{\circ}{.}4$ and β = $-46\overset{\circ}{.}6$. Due to the Hipparcos scanning law characteristics, stars with ecliptic latitude near $\beta = \pm 47^\circ$ are among the most frequently observed objects in the Hipparcos catalogue. As a result, there were 227 photometric observations obtained for HIP 35415 over a 3.5 year period (compared with an average of 110 observations per star over the entire Hipparcos catalogue). This was one of the main reasons that the binary nature of this object could be discovered from the Hipparcos data.

The 9.77 mag companion was visible in the instantaneous field of view of the Hipparcos main detector. It was situated on the sensitivity slope and slight variations in pointing may have contributed a few milli-magnitudes of apparent variation. It was too faint relative to the main component to be taken into account in the double star solution, but could be seen separately in the processing of the Hipparcos star mapper data in the Tycho reductions.

A re-examination of the Hipparcos data by Staffan Söderhjelm of Lund Observatory provided marginal evidence that the brighter component of Aa is in fact the eclipsing binary. The experiment made use of the fact that this star was very well observed. The data were roughly split into two batches, one associated with the minima of the light curve, and one associated with the maxima of the light curve. For each batch a separate double star solution was made. For the data at maximum light the component magnitudes were found to be $Hp(prim)$ = 4.91 $\pm$ 0.04 and $Hp(sec)$ = 5.34 $\pm$ 0.10. For data at minimum light the equivalent values were $Hp(prim)$ = 4.96 $\pm$ 0.04 and $Hp(sec)$ = 5.30 $\pm$ 0.10. Given the averages over the phases that were taken, a magnitude difference of a few hundreds of a magnitude were expected. The observation that the brighter star is the eclipsing binary appears to be confirmed by reports concerning the spectral lines of HIP 35415, which also would indicate that the spectrum of the eclipsing binary was dominating. This leaves component “a” of the Aa system (for the time being) as a single star, while component “A” is most probably a triple system.

3.2. $VBLUW$ photometry

The central system of O stars, the components Aa to which we shall refer as τ CMa, was included in a long-lasting, high-precision photometric program, with the purpose of investigating possible micro variations of luminous massive stars. The observations were made from 1980 till 1986 with the 90-cm Dutch telescope on La Silla, ESO, equipped with the Walraven $VBLUW$ photometer. Details of the photometric system and the observing procedure can be found in Lub & Pel (1977) and van Genderen et al (1985). The triple system was always centered in such a way that the 9.77 magnitude companion “B” at $8\overset{\prime\prime}{.}3$ was outside the $16\overset{\prime\prime}{.}5$ diaphragm. The influence of this companion could have amounted to a maximum of 0.0065 mag if it had been visible within the diaphragm.

All measurements were made relative to one comparison star, HD 58612 (= HIP 36024). The average values for both stars are shown in Table 3. All data are given according to the final calibration of the Walraven system (Pel & Lub, in prep.) and differ slightly from values presented earlier by van Genderen et al. (1985).

Two other massive binaries of similar type were observed during the same period, viz. HD 57060 and HD 167971 (see Table 1). They were described by van Genderen et al. (1988). Improved ephemeris for the timing of the primary minimum for these two stars, using Hipparcos and Walraven photometry, are as follows. For HD 57060:

$$Hp(min) = 2448500.074 + 4.393378 \times E, \quad (1)$$

and for HD 167971:

$$Hp(min) = 2448501.259 + 3.321634 \times E. \quad (2)$$

The individual measurements in the Walraven V_W channel were presented by van Genderen et al. (1985, 1989). The colour index variations were observed to be very small, and only average values were given. In the Walraven photometric system observations are presented as the logarithm of the intensities. Multiplication by -2.5 gives an equivalent scale in magnitudes. Transformation equations between V_J of the Johnson UBV system and the Walraven V_W as well as between $(V-B)_W$ and $(B-V)_J$ can be found in Pel (1987) and van Genderen et al. (1989). A comparison between the Hipparcos Hp measurements and V_W was presented in Chapter 21 of Volume 3 of ESA (1997).

4. The period determination

The statistical aspects of the use of the Hipparcos photometric data in variability research have been described by van Leeuwen et al. (1997) and in Volume 3 of ESA (1997). The distribution of gaps and the lengths of data stretches is far from optimal for periods between a few days and 40 to 70 days, and aliasing is often impossible to distinguish: the window functions resulting from the distribution of data were generally very poor. Periods of less than 2 days were, on the other hand, generally very well detectable, in particular for well observed stars.

The methods used in the period search at the Royal Greenwich Observatory were the discrete fourier transform (Scargle, 1982, 1989) and the analysis of variance (Schwarzenberg-Czerny, 1989). The methods were used in parallel (detections were required to be significant for both methods), and independent determinations were done at Geneva Observatory, using a Fourier analysis as described by Deeming (1975) and Ferraz-Mello (1981). In addition, a references data base was created, against which any apparently new determination was checked. In the case of HIP 35415 the period as given in the literature was different (van Genderen, 1985), but the original ground-based data confirmed and refined the new period.

The Hipparcos data identified this star as a short period eclipsing binary, with the following photometric ephemeris for the timing of the primary minimum ($Hp(min)$) in HJD:

$$Hp(min) = 2448501.089 + 1.28212 \times E, \quad (3)$$

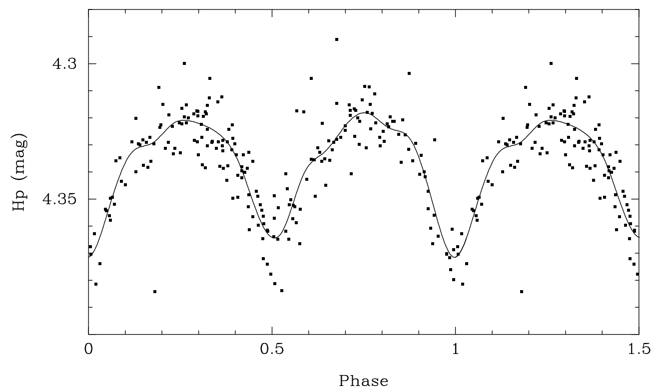

Fig. 2. The Hp observations folded with the 1.282122 day period.

which already fitted very well with the earlier Walraven photometry. By combining the Hipparcos and the Walraven photometry the period was refined to $P = 1\overset{d}{.}282122 \pm 0\overset{d}{.}000004$. The accuracy estimate of the period is based on a total of around 3100 cycles between the first Walraven data and the Hipparcos data, and an estimated accuracy for the determination of the phase of minimum light of 0.01, equivalent to $0\overset{d}{.}013$. Figs. 2 and 3 show the two sets of data folded with the final period.

The accuracy on the individual Hp measurements is approximately 0.005 mag. For the Walraven data, with data-points representing averages of observations obtained over 20 minute intervals, the accuracy is equivalent to 0.001 mag.

It is clear from the light curves that the stars in this binary system are very much distorted, as one would expect for a period of $1\overset{d}{.}282$ (considering that binaries in this class with longer periods are already distorted). As this period is very different from the period of the spectroscopic binary, the conclusion has to be that the central component of τ CMa is a quadruple system, consisting of a wide visual binary, a spectroscopic binary and an eclipsing binary.

There is some indication that the eclipsing binary is cooler when observed at minimum than when observed at maximum. The observed difference is of the order of 0.002 mag. The size of the actual difference depends on the colour indices for the other two stars, information that is not available. No phase related variations were observed in the $(B-U)$ and $(U-W)$ colour indices due to the larger noise, amounting to ±0.007 and ±0.005 magnitudes respectively. The larger noise on the $(B-U)$ index points to some intrinsic variations in the Balmer lines. Variations over the Balmer continuum, given by the $(U-W)$ index, are either smaller or more correlated than variations across the Balmer jump. This appears to be normal behaviour among early type supergiants.

Some calculations can be done concerning the actual brightness variations of the eclipsing binary. If the eclipsing binary is contained in the brighter spectroscopic binary, then the amplitude variations for this triple system would be between Hp = 4.949 and Hp = 4.863. If the eclipsing binary is the fainter component, which appears less likely from both the Hipparcos data and the spectroscopic data, then the actual light

Table 3. Walraven photometry for τ CMa and its comparison star HD 58612.

Name	HIP	HD	Spect.	V	V-B	B-U	U-W	B-L
τ CMa	35415	57061	O9I	0.9910	-0.0520	-0.0760	0.0290	-0.0410
	36024	58612	B7III	0.4380	-0.0373	0.2385	0.0623	0.0503

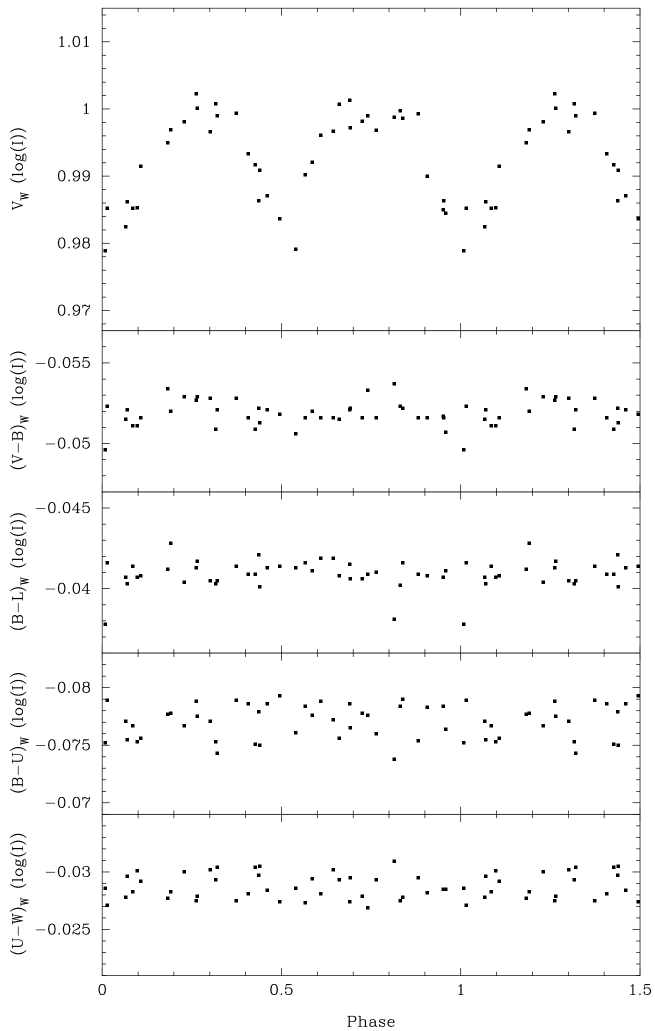

Fig. 3. The Walraven observations folded with the 1.282122 day period.

variations range from Hp = 5.424 to Hp = 5.296. In the first case, the actual amplitude for the eclipsing binary would still be larger. The near equal depth of the minima and the absence of clear colour variations indicates that the components of the binary are very similar in mass and evolutionary status. It should be noted, though, that the presence of the other two stars tends to diminish all variations, and actual differences will be larger than observed.

Both the Hipparcos and the Walraven light curves show some additional noise which may be due to any one of the four components in the system, and could reflect micro variations that are often observed for massive evolved O-type stars (van Genderen, 1989). The Hipparcos light curve seems to indicate a higher noise level for the secondary minimum than for the primary minimum, which would indicate that these secondary fluctuations originate mainly from the brighter component.

5. Physical parameter estimates

If we adopt a total mass for the eclipsing binary in the range of 30 to 60 $M_\odot$ then given the orbital period of $1^{\rm d}\!.282$, the separation of the centers of the two stars will range from 0.07 to 0.09 AU, equivalent to 15 to 19 $R_\odot$. Assuming, on the basis of the nearly equal minima, that the two stars are very similar, the radii of these stars would range from 7.5 to 9.5 $R_\odot$. Taking $T_{\rm eff}$ = 30 000 K, and applying the following equation:

$$M_{\rm bol} = 42.38 - 5\log(R/R_\odot) - 10\log T_{\rm eff}, \qquad (4)$$

gives an estimated bolometric magnitude for each companion of -6.8 to -7.3. Using a bolometric correction of -2.9 (Schmidt-Kaler 1982), an estimated absolute magnitude in V is obtained: $M_V = -3.9$ to $M_V = -4.4$, and for the combined magnitude of the two components: $M_V = -4.6$ to $M_V = -5.1$. Assuming that the brighter component of the visual double star contains the eclipsing binary, and that the third (spectroscopic) component of this system is relatively faint, we have an observed magnitude of m_V = 4.9. The reddening correction is approximately 0.3 mag, giving m_V = 4.6. This then gives an estimated distance modulus of $M-m$ = 9.2 to $M-m$ = 9.7. This is in good agreement with the determination by Humphreys (1978), but puts this system, and probably the cluster NGC 2362, much closer to the Sun than the values given by either Mermilliod & Maeder (1986) or Brown et al. (1986).

The same range in total mass for the eclipsing double star can be used in the parameters for the spectroscopic double star, adding some 5 to 10 $M_\odot$ for the unseen companion. For a mass range of 35 to 70 $M_\odot$, the inclination i of the orbit of the spectroscopic binary ranges from $i = 21°$ to $i = 16°$, giving for the semi-major axis a range from a = 1.8 AU to a = 2.4 AU. With these parameters, eclipses are not expected to be observed for the spectroscopic double star. Assuming a distance of 1 kpc, the orbital motion would reflect as an astrometric double with positional variations at the level of a few milli-arcseconds, too small to be detected with Hipparcos. The residuals for the 1951-1952 observations were plotted against a phase calculated using the ephemeris of the eclipsing binary. Fig. 4 shows a clear modulation at the right phase: the maxima and minima in the velocity coincide with the maxima in the light curve, and the brighter component moves away before the primary minimum. Also shown are the earliest measurements, while the 1927-1928

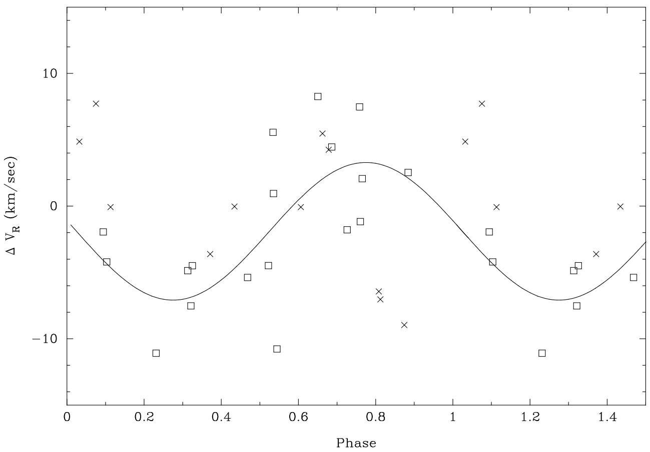

Fig. 4. Residuals in radial velocity for the 1951-1952 observations (open squares) and the 1906-1909 observations (crosses) plotted against the phase derived from the ephemeris of the eclipsing binary. The modulation has a 3σ significance and has the correct phase.

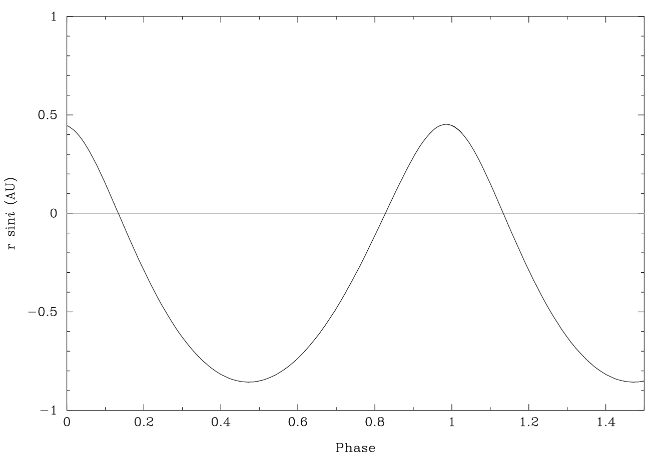

Fig. 5. The variation in the distance along the line of sight for the spectroscopic binary, plotted against the phase of the spectroscopic ephemeris. The projected distance variations result in phase shifts for the eclipsing binary of between -0.004 to +0.002, too small to be detected from the available data.

measurements are not shown because of their much higher noise levels. With the eclipsing binary system describing an orbit, phase shifts are expected for the observed light curve. These phase shifts are determined by the distance variations between the observer and the system, which can be derived directly from the orbital parameters given in Table 2, and shown in Fig. 5. These variations translate into +4 to -8 minutes shift, equivalent to a maximum phase shift of +0.002 to -0.004, which is not observable from the available data due to its relatively high intrinsic noise.

Finally, there is the visual double star and the apparent discrepancy in radial velocity between the cluster NGC 2362 and the γ velocity of the spectroscopic binary. The separation of the visual double is $0\farcs15$, equivalent to a minimum separation of 150 AU at a distance of 1 kpc. If we assume the visual double to describe a circular orbit, then the observed separation and radial velocity give an orbital period of about 250 yr. Assuming that the total mass of this system is around 50 to 90 $M_{\odot}$, this gives an estimate for the semi-major axis in the range a = 150 AU to a = 180 AU, which seem very reasonable values. We may therefore assume that the discrepant radial velocity is mainly the result of the orbital motion of the visual binary. Given the stability of the position angle of the visual binary, one would have to assume that the normal to the orbital plane of this system is almost perpendicular to the line of sight.

6. Conclusions

The presence of a connected system of a very tight and a very wide O-star binary as a quadruple system in the open cluster NGC 2362 is of great interest for studies of cluster dynamics as well as for studies of stellar evolution and the formation of binary stars. The most likely scenario (considering results from N-body simulations for star clusters) seems to be that this system was formed the way we see it today through an interaction between two binary systems. In the process, one binary system became much tighter, while the other system lost one component to the first system. These kind of component exchanges have been frequently observed in numerical simulations. This could explain why we observe both the shortest period eclipsing binary and the longest period spectroscopic binary for O-type stars together with one single star of similar spectral type in one and the same quadruple system.

A quadruple system such as this (effectively for stellar dynamics more like a triple system), is in general unstable and will often lead to the release of one of its members. Further observations are needed to provide more details for the physical parameters of this interesting multiple system.

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