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ORBIT, MASSES AND SPECTRAL ANALYSIS OF THE VISUAL BINARY A 2329

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RESUMEN

Se presenta una órbita revisada de la binaria A 2329, calculada a partir de un conjunto de medidas interferométricas distribuidas a lo largo de un período orbital. En base a estos nuevos elementos orbitales y a la paralaje de Hipparcos se obtiene una masa dinámica para el sistema de $1.25 \pm 0.14\ \mathcal{M}_\odot$. También se confirma, considerando nuevos datos espectrales, que el tipo espectral MK es K7V.

ABSTRACT

A revised orbit for the visual binary A 2329, calculated taking into account a set of interferometric measures distributed over one orbital revolution, is presented. On the basis of new orbital elements and the Hipparcos parallax, a dynamical mass of the system of $1.25 \pm 0.14\ \mathcal{M}_\odot$ is obtained. By considering new spectral data, we confirm its MK spectral type as K7V.

Key Words: **ASTROMETRY — BINARIES: VISUAL — STARS: FUNDAMENTAL PARAMETERS — STARS: INDIVIDUAL (A 2329)**

1. INTRODUCTION

The visual binary A 2329 AB (WDS 02278+0426 = Gl 98 AB = HD 15285 = HIP 11452) was discovered in 1911 by Aitken (Aitken 1911) with the Lick 36-inch refractor. Both components are classified as K7V (Christy & Walker 1969) and their visual magnitudes are similar, 9.36 and 9.50, respectively (Gliese & Jahreiss 1991), although $\Delta m = 0.40$ with a 648-nm filter was measured by Horch, Meyer, & van Altena (2004) in 1999. The Hipparcos parallax 60.22 ± 1.75 mas places this system at a distance of 16.6 pc, being one of the nearby K stars.

The first orbit for ADS 1865 was calculated by Finsen (1937). Since then, seven more orbits have been calculated. Wierzbiński (1956, 1958) calculated two orbits in the 1950's taking into account new measurements. In the next decade van den Bos (1962) and Eggen (1967) reported new sets of orbital elements. Then, Starikova (1981) calculated a new orbit and ten years later, Heintz (1991) corrected it. Lastly, a new orbit was computed by Söderhjelm (1999).

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An early estimation of masses for both components was made by Wanner (1969), who gave $\mathcal{M}_A = 0.39 \pm 0.20\ \mathcal{M}_\odot$ and $\mathcal{M}_B = 0.47 \pm 0.20\ \mathcal{M}_\odot$ by using a parallax of $0''.066 \pm 0''.007$ and the orbital elements calculated by van den Bos (1962).

Thus, with the aim both to obtain more accurate orbital elements that are essential for the mass computation and to minimize observational residuals, we have recalculated the orbit (Andrade 2001).

Moreover, in view of differing spectral classifications, from K5 (Canon & Pickering 1918) to M2 (Vyssotsky & Mateer 1952), we have also analyzed its spectrum by using the 2.6-m telescope of the V. Ambartsumian Byurakan Astrophysical Observatory (BAO, Armenia). We confirm that its spectrum corresponds to a K7 dwarf.

2. MK CLASSIFICATION

Several spectra for A 2329 were obtained at the 2.6-m telescope of the V. Ambartsumian Byurakan Astrophysical Observatory on 2004 September with the spectral camera SCORPIO (Afanasiev et al. 2005), which is a multi-regime, prime focus focal reducer for observing both starlike and extended objects. In the spectroscopy mode, a grism with 600 lines mm^{-1} grating (with a resulting linear dispersion of 1.7Å, per element and a resolution of

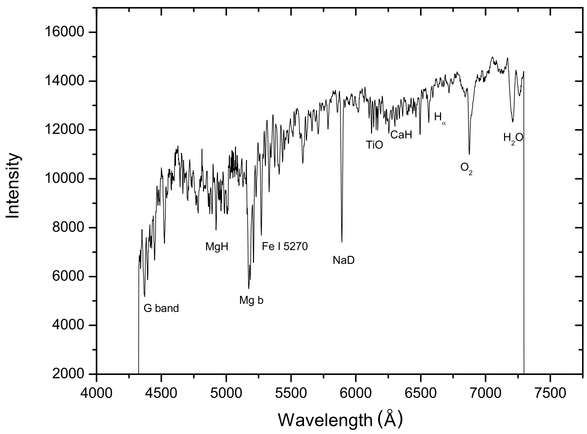

Fig. 1. Spectrum of A 2329. Several representative spectral lines are marked, and the intensity is given in arbitrary units.

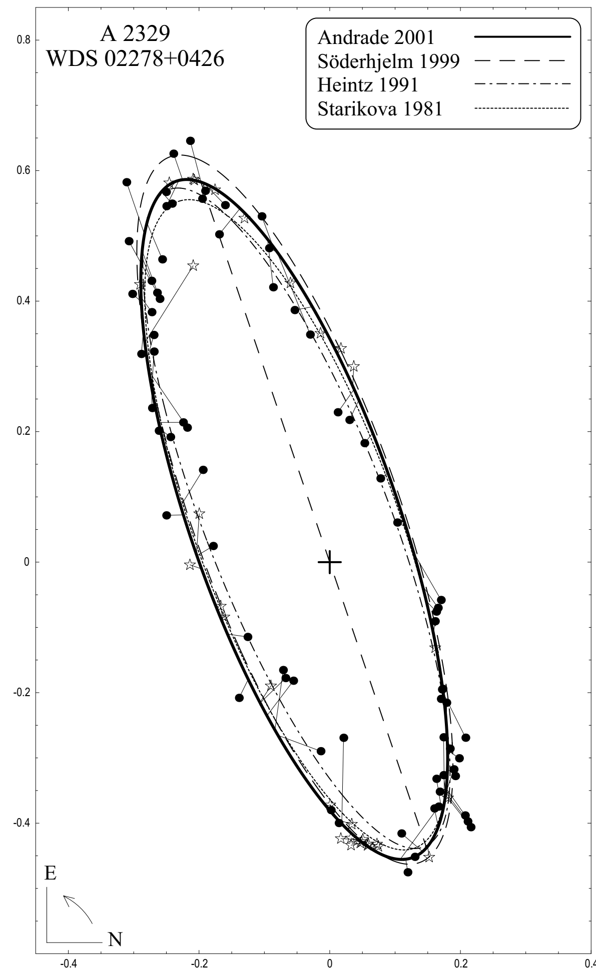

Fig. 2. Improved apparent orbit of A 2329 (solid line) compared to the recently derived orbits. The points and stars represent visual and speckle measurements respectively, the arrow shows direction of the motion. The scale on both axes is arcseconds, and each measurement is connected to its predicted position by an O−C line. The dashed line passing through the primary star is the line of nodes.

3.5−4.0Å) covering a spectral range ∼ 4250−7250Å, was used. The components' separation was less than $1\farcs0$ and the spectrometer slit of size $2\farcs0 \times 6\farcm0$ included both stars.

The standard criteria and indications given by Keenan (1987), Jaschek & Jaschek (1987), Keenan & McNeil (1989), Kirkpatrick, Henry, & McCarthy (1991), Gray (1994, 2000), Garrison (1994) and Malyuto, Oestreicher, & Schmidt-Kaler (1997) were followed for classification purposes. A grid of MK standards, mainly taken from Keenan & Yorka (1988) was observed simultaneously with A 2329, whose MK type was obtained through direct comparison with these standards. A more extended description of instrumentation as well as classification procedure can be found in Tamazian et al. (2006).

The spectrum of A 2329 is shown in Figure 1. A large number of absorption lines typical for late K dwarfs were identified, but only strong representative lines were used for classification purposes. As seen in Figure 1, the main features in the spectrum are the G band, Fe I λ5270, Mgb triplet, MgH λ4780 and λ5210, NaD λ5890 and several representative TiO bands. The G band is weak and almost dissolved into separate lines, while MgH λ4780 is well seen. The TiO bands are visible but not yet strong. In general, metallic lines are rather strong, Mgb and NaD being the strongest spectral features. All these features led us to assign a K7V type to A 2329.

3. ORBIT AND DYNAMICAL MASS

Since 1911, the system has been measured 108 times covering almost four orbital periods. From this set, 33 are interferometric measurements performed since 1978. At present, we have at our disposal a broad set of accurate measurements spanned over one orbital period. With these measurements and by applying the analytical method of Docobo (1985), a new improved orbit has been calculated (Andrade 2001). In fact, the last available measurement (Docobo et al. 2006), performed with the SAO 6-m telescope in 2004, has confirmed it.

All known observations and their residuals with regard to this orbit are listed in Table 1. In its first three columns observation epoch (in fraction of Besselian year), position angle (in degrees) and sep-

TABLE 1

MEASUREMENTS AND O−C RESIDUALS

Epoch	$\theta(^\circ)$	$\rho('')$	$\Delta\theta(^\circ)$	$\Delta\rho('')$	N° nights	Observers
1911.38	300.4	0.38	0.8	0.015	2	A
1919.33	108.5	0.60	0.0	−0.012	2	A
1921.22	113.7	0.60	−0.7	−0.023	4	A
1929.91	236.3	0.25	1.1	0.031	2	A
1934.987	284.8	0.43	−3.0	−0.036	2	B
1936.008	296.2	0.37	2.1	−0.052	1	B
1936.940	303.4	0.36	1.4	0.020	4	B
1936.982	302.8	0.34	0.3	0.004	4	Fin
1937.594	307.7	0.34	−3.2	0.075	4	Vou
1937.927	311.4	0.26	−6.6	0.037	3	B
1938.636	337.1	0.18	−8.6	0.033	5	Vou
1938.950*	341.2	0.18	−25.2	0.051	1	B
1940.003*	0.6	0.15	−67.6	−0.045	1	B
1942.72	101.6	0.43	0.7	−0.074	2	Vou
1945.631	114.6	0.60	3.1	−0.029	3	B
1945.74	113.8	0.62	1.9	−0.009	5	VBs
1947.700	118.9	0.53	0.6	−0.060	...	Jef
1948.72	122.0	0.58	−0.2	0.039	3	VBs
1948.730	122.6	0.49	0.3	−0.050	4	B
1950.02	132.1	0.43	3.4	−0.026	1	B
1950.711	136.6	0.30	3.2	−0.103	2	Wrh
1950.960	139.0	0.36	3.6	−0.023	2	Mrz
1950.99	129.8	0.42	−5.8	0.039	2	VBs
1951.96	142.4	0.33	−3.7	0.027	1	B
1952.870	164.0	0.26	1.9	0.025	1	Mrz
1952.98*	180.0	0.18	15.4	−0.048	1	B
1955.79	253.0	0.19	5.2	−0.064	4	B
1956.02	246.7	0.18	−5.2	−0.091	1	B
1957.732	270.3	0.38	−1.4	−0.014	3	B
1957.85	274.5	0.27	1.9	−0.131	2	VBs
1959.70	284.1	0.49	−0.2	0.020	4	Wor
1959.92	286.1	0.47	0.5	−0.000	2	B
1961.644	298.0	0.46	1.6	0.062	2	VBs
1961.667	298.1	0.37	1.5	−0.026	4	B
1961.68	298.0	0.45	1.3	0.055	3	VBs
1961.738	295.6	0.39	−1.6	−0.000	4	Wor
1961.743	298.1	0.44	0.9	0.050	1	VBs
1962.847	311.7	0.26	1.9	−0.013	4	Wor
1962.87	309.1	0.27	−1.1	0.000	2	Knp
1963.815	335.1	0.18	−2.9	0.021	4	Wor
1965.031	58.8	0.15	1.9	−0.013	1	Wor
1965.779	82.1	0.22	2.3	−0.033	1	Wor
1965.896	86.9	0.23	4.9	−0.038	5	Wor
1966.912	97.9	0.39	4.0	−0.002	4	Wor
1967.783	100.9	0.49	1.3	0.009	1	Wak
1967.799	94.9	0.35	−4.8	−0.133	1	Wak
1967.900	101.1	0.54	0.9	0.048	4	Wor
1968.80	108.6	0.53	4.4	−0.029	4	VBs
1969.949	106.3	0.57	−2.0	−0.042	1	Wak
1969.960	109.3	0.59	0.9	−0.022	1	Nbg
1970.053	108.3	0.68	−0.4	0.065	2	Wor
1970.785	110.9	0.67	−0.1	0.042	3	Wor
1972.068*	114.2	0.99	−0.9	0.371	1	Wak
1973.333	118.1	0.66	−1.3	0.083	2	Wor
1973.750	122.8	0.48	1.8	−0.077	2	Hln
1973.88	122.3	0.51	0.7	−0.040	4	Hei
1974.735	125.4	0.47	−0.0	−0.028	1	Wak
1974.816	126.3	0.51	0.5	0.018	4	Wor
1975.834	127.7	0.44	−4.2	0.022	2	Wor
1976.837	136.3	0.31	−4.4	−0.028	4	Wor
1976.94	141.8	0.31	−0.0	−0.020	3	Hei
1978.064	143.9	0.24	−15.5	−0.004	1	Wor
1978.7512	159.6	0.213	−17.1	0.009	1	Bnu
1978.77	172.1	0.18	−5.1	−0.024	3	Hei
1978.956	181.1	0.214	−1.9	0.018	1	Ebe
1979.754	202.0	0.18	−8.7	−0.009	3	Tok
1979.885	222.4	0.17	7.2	−0.021	1	Wor
1980.904	244.6	0.210	1.0	−0.030	1	Tok
1980.91	249.2	0.19	5.5	−0.051	3	Hei
1981.428	267.3	0.29	13.9	0.013	2	Wor
1982.7577	270.1	0.372	0.9	−0.003	1	McA
1982.82	272.0	0.40	2.2	0.021	3	Hei
1983.0663	274.8	0.403	3.0	0.008	1	McA
1983.6340	272.3	0.424	−3.7	−0.004	1	McA
1983.6367	276.8	0.428	0.8	0.000	1	McA
1983.7131	276.5	0.431	0.0	−0.000	1	McA
1983.7377	276.2	0.433	−0.5	0.000	1	McA
1983.7405	274.3	0.435	−2.4	0.002	1	McA
1983.8032	277.8	0.436	0.7	0.000	2	McA
1983.8059	274.4	0.424	−2.7	−0.012	2	McA
1983.8087	277.6	0.438	0.5	0.002	1	McA
1983.9644	279.5	0.438	1.4	−0.005	1	McA
1984.0272	279.7	0.442	1.2	−0.004	1	McA
1984.84	294.0	0.41	10.7	−0.058	3	Hei
1985.8375	288.6	0.477	−0.4	0.016	1	McA
1986.377	293.0	0.41	0.7	−0.028	5	Wor
1986.84	303.0	0.32	7.5	−0.088	3	Hei
1986.8915	296.6	0.404	0.7	0.000	1	Hrt
1986.99	300.9	0.37	4.3	−0.026	4	Lbu
1987.85	309.7	0.28	4.5	−0.030	2	Hei
1988.6608	320.9	0.208	0.5	−0.004	1	McA
1988.827	330.7	0.185	5.3	−0.008	1	Cou
1988.8620*	55.3	0.176	88.7	−0.013	1	Ism
1989.83	30.4	0.12	5.8	−0.009	3	Hei
1989.9385*	65.3	0.250	32.8	0.118	1	Hrt
1990.75	73.7	0.19	2.1	−0.018	2	Hei
1991.25	83.0	0.302	0.4	0.030	1	Hip
1991.7157	87.0	0.328	−2.0	−0.003	1	Hrt
1991.8937	92.3	0.351	1.4	−0.002	1	Hrt
1992.6779	98.0	0.432	0.9	−0.008	1	Bag
1993.9252	103.9	0.543	0.5	−0.004	1	Hrt
1994.7032	107.1	0.597	0.7	0.007	1	Hrt
1995.7600	109.6	0.623	−0.3	−0.000	1	Hrt
1995.9264	109.5	0.621	−1.0	−0.005	1	Hrt
1996.6965	112.9	0.631	0.0	0.002	1	Hrt
1999.8830	124.3	0.515	−0.3	0.006	1	Hor
2000.877	114.7	0.50	−15.4	0.061	1	WSI
2004.990	207.5	0.182	−0.2	−0.006	1	Doc

aration (in arcseconds) are given, followed by the observed minus calculated (O-C) residuals in position angle ($\Delta\theta$) and separation ($\Delta\rho$) given in the next two columns. The number of nights and the observer code (as it appears in WDS) are given in the last two columns. An asterisk in the first column indicates that the corresponding measurement has relatively high residuals ($\Delta\theta > 15^\circ\!.0$ and/or $\Delta\rho > 0''\!.150$) regarding the two last orbits.

In Table 2 are given the orbital elements and dynamical mass, along with their corresponding errors, the correction for precession to make the position angle refer to the epoch 2000.0, and previously available orbital elements. The uncertainties of the orbital elements have been determined taking into account the range of orbits with the smallest weighted root mean squares (RMS) deviations in position angle and separation. Calculation of the

TABLE 2

ORBITAL ELEMENTS AND SYSTEM MASS

Element	Andrade (2001)	Söderhjelm (1999)	Heintz (1991)	Starikova (1981)
P (yr)	25.32 ± 0.40	25.3	25.21	25.198
T	1988.16 ± 1.20	1987.7	1987.89	1937.837
e	0.237 ± 0.002	0.22	0.225	0.230
a ($''$)	0.559 ± 0.012	0.58	0.548	0.537
i (°)	73.3 ± 3.5	74	75.0	73.1
Ω (°)	108.7 ± 2.0	109	110.8	109.6
ω (°)	233.2 ±10.0	223	228.9	234.8
$\mathcal{M}$ ($\mathcal{M}_\odot$)	1.25 ± 0.14	1.40	1.19	1.12
Precession (°)	+0.0034			

TABLE 3

EPHEMERIDES

t	θ (°)	ρ ($''$)
2006.0	238.5	0.226
2007.0	257.2	0.296
2008.0	268.5	0.369
2009.0	276.3	0.430
2010.0	282.4	0.466
2011.0	288.1	0.465
2012.0	294.3	0.420
2013.0	303.1	0.329
2014.0	320.9	0.210
2015.0	13.2	0.128

RMS has been accomplished by using the criterion of Docobo & Ling (2003), which weights each measurement according to the telescope aperture, the number of nights and the observer.

Our orbit is shown in Figure 2, and the ephemerides are given in Table 3. It was announced earlier, in IAU Commission 26 Information Circular 144, and classified as grade 2 (good orbit) according to the orbit grading method of Hartkopf, Mason, & Worley (2001).

The obtained semi-major axis, period (see Table 2), Hipparcos parallax of 60.22 ± 1.75 mas, and Kepler's third law:

$$\mathcal{M} = \frac{a^3}{\pi^3}\frac{1}{P^2}$$

yield a total mass for the system of $1.25 \pm 0.14\ \mathcal{M}_\odot$. The contribution of the parallax to the overall error is 59.7%, and the remaining part is due to uncertainty in the semi-major axis (32.5%) and period (7.8%). With a more accurate parallax, we would be able to reduce the current accuracy from 14.4% to 7.2% (for the same orbit).

4. DISCUSSION

We summarize in Table 4 some statistical results concerning the orbits computed for this system, where the measurements with relatively large residuals (indicated by an asterisk in Table 1) have been removed from the statistics because of their low accuracy (see Section 3).

In order to compare the accuracy of the recent orbits we show in Figure 3 RMS-MA (Root Mean Square–Mean Average) diagrams for position angle and separation. A short line indicates that both visual and speckle (or interferometric) measurements have similar errors (given by position of extreme points) and, therefore, are fitted in a similar way. Instead of dealing with two types of measurements, we can use the total contribution, whose value is given by the central point in the polygonal line. In any case, if points over the line are located near the origin, it indicates that corresponding errors are close to zero. By applying this to the set of orbits for A 2329, we conclude that our orbit fits better the speckle measurements maintaining, at the same time, a very good fit to the visual ones.

The calculated mass, $1.25\ \mathcal{M}_\odot$, is lower than that obtained from Söderhjelm's orbit ($1.40\ \mathcal{M}_\odot$), which corresponds roughly to a pair of K3 dwarfs. However, according to Gray's calibration (Gray 1992), the mass for a K7V star is about $0.60\ \mathcal{M}_\odot$, which agrees well with the total mass obtained above.

TABLE 4

STATISTICAL RESULTS

Orbit	$\Delta\theta^{v+s}_{RMS}$ $\Delta\theta^{v+s}_{MA}$	$\Delta\rho^{v+s}_{RMS}$ $\Delta\rho^{v+s}_{MA}$	$\Delta\theta^{v}_{RMS}$ $\Delta\theta^{v}_{MA}$	$\Delta\rho^{v}_{RMS}$ $\Delta\rho^{v}_{MA}$	$\Delta\theta^{s}_{RMS}$ $\Delta\theta^{s}_{MA}$	$\Delta\rho^{s}_{RMS}$ $\Delta\rho^{s}_{MA}$
Andrade 2001 (this paper)	$4\overset{\circ}{.}4$	$0\overset{''}{.}022$	$4\overset{\circ}{.}1$	$0\overset{''}{.}044$	$4\overset{\circ}{.}4$	$0\overset{''}{.}011$
	$-0\overset{\circ}{.}7$	$-0\overset{''}{.}000$	$0\overset{\circ}{.}8$	$-0\overset{''}{.}010$	$-1\overset{\circ}{.}1$	$0\overset{''}{.}002$
Söderhjelm 1999	$4\overset{\circ}{.}9$	$0\overset{''}{.}029$	$5\overset{\circ}{.}6$	$0\overset{''}{.}055$	$4\overset{\circ}{.}7$	$0\overset{''}{.}017$
	$2\overset{\circ}{.}0$	$-0\overset{''}{.}011$	$3\overset{\circ}{.}5$	$-0\overset{''}{.}030$	$1\overset{\circ}{.}6$	$-0\overset{''}{.}006$
Heintz 1991	$4\overset{\circ}{.}4$	$0\overset{''}{.}025$	$3\overset{\circ}{.}2$	$0\overset{''}{.}041$	$4\overset{\circ}{.}6$	$0\overset{''}{.}018$
	$-2\overset{\circ}{.}5$	$0\overset{''}{.}011$	$0\overset{\circ}{.}5$	$-0\overset{''}{.}002$	$-3\overset{\circ}{.}2$	$0\overset{''}{.}015$
Starikova 1981	$5\overset{\circ}{.}5$	$0\overset{''}{.}027$	$4\overset{\circ}{.}1$	$0\overset{''}{.}041$	$5\overset{\circ}{.}8$	$0\overset{''}{.}022$
	$-2\overset{\circ}{.}0$	$0\overset{''}{.}013$	$0\overset{\circ}{.}9$	$0\overset{''}{.}002$	$-2\overset{\circ}{.}8$	$0\overset{''}{.}016$

For each orbit (first column) RMS and MA for visual and speckle (or interferometric) measurements, as well as the total contribution, are given from second to seventh columns. Super-index v, s, and $v+s$ indicate visual, speckle, and total contribution, respectively.

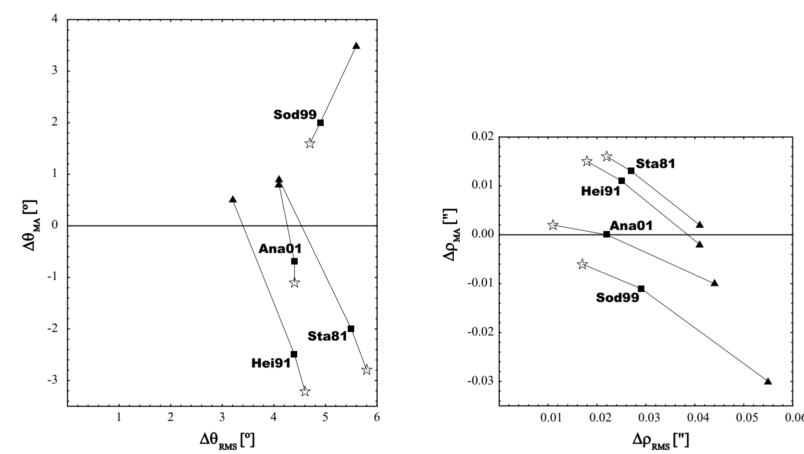

Fig. 3. RMS-MA diagrams for position angle and separation. Each polygonal line contains three RMS-MA points for a given orbit. Visual measurements are indicated by a filled triangle, while those for speckle (or interferometric) ones are indicated by empty stars. The central point (a filled square) indicates position for the contribution of both measurement types.

Recently, we have developed a calibration (obtained after a certain statistical procedure of mass data taken from Belikov [1995]) for estimating masses, as follows:

$$\mathcal{M}_V = a + \frac{b}{s^2}$$
$$s(\mathcal{M}_V) = \sqrt{s^2(a) + \frac{s^2(b)}{s^4}}$$

where $a = -0.117 \pm 0.090$, $b = 27.47 \pm 0.61$, and s is a continuous analytical variable defined by de Jager & Nieuwenhuijzen (1987) that represents the spectral class. Given a value of $s = 6.2$ for a K7V star, this yields an estimated mass of $0.60 \pm 0.09\ \mathcal{M}_\odot$.

On the other hand, with apparent magnitudes $m_A = 9.36$ and $m_B = 9.50$ and Hipparcos parallax of 60.22 ± 1.75 mas, we obtain luminosities $M = 8.26 \pm 0.06$ and $M = 8.40 \pm 0.06$, respectively. In these calculations the errors have been estimated by considering the parallax error only. Then, the mass of each component can be estimated according to Henry & McCarthy (1993) by:

$$\log\left(\frac{\mathcal{M}}{\mathcal{M}_\odot}\right) = +0.002456\ M_v^2 - 0.09711\ M_v + 0.4365$$

With this formula, masses of $0.63 \pm 0.01\ \mathcal{M}_{\odot}$ and $0.62 \pm 0.01\ \mathcal{M}_{\odot}$ are obtained for the primary and secondary components, respectively. It is worth noting that their sum is $1.25 \pm 0.01\ \mathcal{M}_{\odot}$, in perfect agreement with the total mass obtained by us.

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