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ORBIT, DYNAMICAL MASS, AND MK TYPE OF VISUAL BINARY WOR 2

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ABSTRACT

On the basis of new speckle measurements with the 6 m telescope of the Special Astrophysical Observatory (Russia) and *Hipparcos* astrometry, an improved orbital solution with a period of $P = 24.1$ yr for the visual binary WOR 2 is obtained. The dynamical mass of the system is $1.40 \pm 0.25\ M_{\odot}$. Differential photometry ($\Delta m = 0.55$ mag) allowed us to estimate the luminosity of individual components ($M = +8.0$ and +8.6 mag), which in turn led to individual masses of 0.65 and 0.61 $M_{\odot}$, in good agreement with the systemic mass. The slit spectra obtained with the 2.6 m telescope of the Byurakan Astrophysical Observatory (Armenia) show that in the combined light WOR 2 is a K6 dwarf, whereas individually the components according to their luminosities are likely to be K6–K7 and M0 dwarfs. The equivalent width of the Hα absorption line (0.9 Å) is concordant with previous data, indicating the overall stability of this system.

Key words: astrometry — binaries: visual — stars: individual (WOR 2)

1. INTRODUCTION

The duplicity of WOR 2 (WDS 02288 + 3215 = HIP 11542 = Gl 99), with a separation between components of 0.″26 and a magnitude difference of 0.6 mag, was discovered in 1959 by Worley (1960). Three years earlier, WOR 2 was spectroscopically found to be an M0p dwarf by Vyssotsky (1956; Vys 393). The same dM0p type was reported by Bidelman & Lee (1975), but Reid et al. (1995) have recently classified it as a K7 dwarf. Its brightness, $V = 9.57$, was recently measured by Salim & Gould (2003), and the Washington Double Star Catalog (Mason et al. 2003) assigns $V = 10.2$ and 10.5 to the individual components. The *Hipparcos* parallax, $\pi = 38.71 \pm 2.17$ mas, places this star at a distance of 25.8 pc.

In spite of its brightness and convenient position on the northern sky ($\delta = +31^{\circ}$), this star was unevenly observed astrometrically. There are no reported observations between 1968 and 1974, or from 1991 until our recent observation in 2004.

The first orbit, with a period of 18.9 yr, was calculated by Baize (1986), who promptly changed it to an orbit of 23 yr (Baize 1991) due to a discrepancy with the first ever speckle measurement of this star (Balega et al. 1989) with the 6 m telescope of the Special Astrophysical Observatory (SAO; Russia). Since then, a new speckle observation by Balega et al. (1994) and *Hipparcos* astrometry (Perryman et al. 1997) data have been published. In addition, a new speckle measurement and differential photometry obtained with the 6 m telescope are reported in this paper. These additional high-precision data allow us to calculate an improved orbit.

Apart from the orbit calculation, in view of somewhat discrepant spectral classification several slit spectra were obtained with the 2.6 m telescope of the V. Ambartsumian Byurakan Astrophysical Observatory (BAO; Armenia) in order to verify the combined spectral type of WOR 2.

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2. ASTROMETRIC OBSERVATIONS AND ORBIT

2.1. *New Speckle Measurement, Differential Photometry, and Data Set*

The speckle measurement of WOR 2 was carried out on 2004 December 28 with the 6 m telescope of SAO with the speckle camera and an intensified 1280×1024 pixel CCD coupled with the S-25 photocathode. The image motion-compensated seeing (FWHM) during the observations was 1.″0–1.″5, and a filter with center wavelength and bandwidth of 800 and 110 nm, respectively, was used. Usually, this system allows us to observe binary components as faint as 15.0 mag in optical wavelengths with a dynamic range of about 4.0–5.0 mag. The diffraction-limited resolution is about 22 mas.

The relative position and the magnitude difference Δm are derived from the ensemble-averaged power spectrum. A double-slit pupil mask and interferometric binaries with slow orbital motion are used for calibration. More details regarding the observation and reduction procedure can be found in Balega et al. (2002) and remain essentially unchanged.

In total, astrometric observations of WOR 2 cover a timespan of about 50 yr and comprise 17 visual and speckle interferometric measurements and differential photometry data taken from the Washington Double Star Observations Catalog (Mason et al. 2001), the Fourth Catalog of Interferometric Measurements of Binary Stars (Hartkopf et al. 2004), the Second Photometric Magnitude Difference Catalog (Mason & Wycoff 2003), and elsewhere in the literature.

Both astrometry and differential photometry data are given in Table 1. The first six columns list (1) observation epoch, (2) type of measurement (visual or interferometric), (3) magnitude difference Δm, (4) position angle, (5) separation, and (6) the reference from which the astrometric data were taken. Columns (7)–(10) list $(O - C)$ residuals in θ and ρ relative to our orbit and that of Baize (1991). Position angles are corrected for precession to refer them to the J2000.0 equinox. The last row gives the rms of residuals in θ and ρ, which are the indicators used to compare the orbits. The measurements' accuracy is presented if given in the original paper.

2.2. *Orbit and Dynamical Mass Calculation*

The method elaborated by Docobo (1985) was used to get the orbital solution. It is briefly summarized in Docobo et al. (2000) and Tamazian et al. (2002).

TABLE 1
MEASUREMENTS, $(O-C)$ RESIDUALS, AND rms VALUES

						THIS PAPER		BAIZE (1991)	
DATE (1)	V/I[a] (2)	Δm (3)	$\theta \pm \sigma$ (4)	$\rho \pm \sigma$ (mas) (5)	REFERENCE (6)	$(O-C)_\theta$ (deg) (7)	$(O-C)_\rho$ (mas) (8)	$(O-C)_\theta$ (deg) (9)	$(O-C)_\rho$ (mas) (10)
1959.72.....	Vis	0.6	105.5	260	1	−0.3	0	−1.7	−7
1960.84.....	Vis		115.6	150	2	+3.5	−5	+2.7	−39
1964.696.....	Vis	0.2	275.8	260	3	−2.5	+5	+7.3	+91
1966.509.....	Vis	0.2	283.1	280	3	−0.4	−10	4.3	+29
1966.909.....	Vis	0.3	281.6[b]	220	4	−3.1	−63	1.2	−34
1967.81.....	Vis		287.8	240	5	+0.3	−12	3.6	+1
1968.308.....	Vis	0.1	287.2	260	3	−2.3	+31	+0.5	+40
1968.95.....	Vis		287.6	200	6	−5.2	+6	−3.1	+13
1974.867.....	Vis		91.7	240	7	+3.8	+10	2.5	−21
1976.86.....	Vis		97.6	300	8	+3.9	−34	2.9	−50
1977.659.....	Vis	0.4	94.6	330	9	−0.6	−35	−1.7	−41
1980.864.....	Vis	0.3	100.0	380	9	0	−21	−2.2	+26
1983.97.....	Vis		101.8	270	10	−4.7	+24	−12.1	+92
1986.6464.....	Int		251.2 ± 2.0[b]	63 ± 2	11	0	0	1.1	−24
1989.8075.....	Int		281.4 ± 1.0	290 ± 3	12	0	0	+1.4	+36
1991.25.....	HIP		282.0 ± 0.5	271 ± 1	13	−3.5	−4	−4.4	+48
2004.9903.....	Int	0.55	100.0 ± 0.4	399 ± 2	14	0	0	−4.9	+91
rms.....						2.1	22.0	3.8	48.9

[a] Type of measurement: Vis, visual; Int, interferometric; HIP, from *Hipparcos*.
[b] Quadrant changed.

REFERENCES.—(1) Worley 1960; (2) Worley 1971; (3) Worley 1972; (4) Walker 1971; (5) Couteau 1968; (6) Couteau 1970; (7) Worley 1978; (8) Heintz 1978; (9) Worley 1989; (10) Couteau 1985; (11) Balega et al. 1989; (12) Balega et al. 1994; (13) Perryman et al. 1997; (14) this paper.

Initially, each measurement is weighted according to observational criteria such as telescope aperture, technique, and number of combined measurements (Docobo & Ling 2003). A family of Keplerian orbits are then generated whose apparent orbits pass through three base points that are assumed to be either the most reliable measurements or positions belonging to the areas with maximum observational likelihood. Simultaneously, $O-C$ residuals in both ρ and θ are determined for these orbits. Then the orbit with the smallest weighted rms values for both observed parameters (θ and ρ) is selected. Usually, the orbit with the smallest rms values in θ is not exactly the same as the orbit with the smallest rms values in ρ. Therefore, a number of orbital solutions between these two minimal solutions are determined.

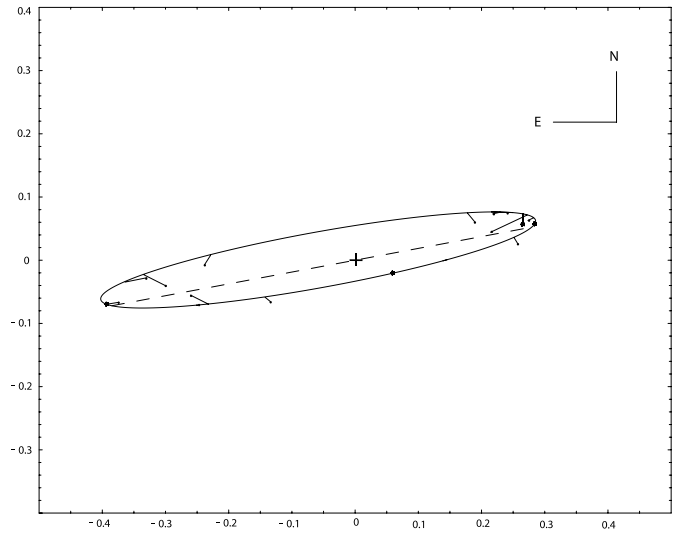

FIG. 1.—Apparent orbit of WOR 2 (the scales on both axes are in arcseconds). Each measurement is connected to its predicted position by an $O-C$ line. The dashed line passing through the primary star is the line of nodes. The points and stars represent visual and speckle measurements, respectively.

The orbital solution with the smallest $O-C$ residuals is selected as the best fit, and the range of orbits is used to characterize the uncertainties in the orbital elements. Over this range of orbital solutions, all orbital elements are computed simultaneously and independently to ensure a proper error estimation for each (Tamazian et al. 2002). The range of orbital solutions typically corresponds to $O-C$ residuals at $\pm(1-2)\,\sigma$.

Our orbit was initially announced in Docobo & Tamazian (2005) and is graphically represented in Figure 1. Table 2 lists the orbital elements with their corresponding standard errors (and system mass) both for our orbit and for that of Baize (1991), and Table 3 contains ephemerides up to 2016.0. For the reader's convenience, the ephemerides for 2009, 2010, and 2011 are given with 0.25 yr intervals to better describe the rapidly changing separation.

3. MK CLASSIFICATION

A well-defined homogeneous set of spectral types in the revised MK system (Keenan 1987) is a key element in the determination

TABLE 2
ORBITAL ELEMENTS AND SYSTEM MASS

Element	This Paper	Baize (1991)
P (yr).....	24.07 ± 0.5	23.0
T.....	1987.35 ± 3	1988.8
e.....	0.296 ± 0.02	0.22
a (arcsec).....	0.361 ± 0.005	0.32
i (deg).....	82.9 ± 4	80.4
Ω (deg).....	100.6 ± 7	99.5
ω (deg)	122.5 ± 10	158.0
System mass ($M_\odot$).....	1.40 ± 0.25	1.07

TABLE 3
EPHEMERIDES

	This Paper		Baize (1991)	
Epoch	θ (deg)	ρ (mas)	θ (deg)	ρ (mas)
2006.00.....	101.6	372	108.3	249
2007.00.....	103.5	323	114.2	176
2008.00.....	106.3	249	129.8	95
2009.00.....	112.2	153	206.7	49
2009.25.....	115.2	126	229.9	59
2009.50.....	119.9	98	244.4	76
2009.75.....	128.1	71	253.4	95
2010.00.....	145.9	46	259.3	115
2010.25.....	187.3	33	263.4	135
2010.50.....	232.8	43	266.6	155
2010.75.....	253.1	67	269.0	173
2011.00.....	262.2	94	271.0	190
2011.25.....	267.3	121	272.6	205
2011.50.....	270.5	147	274.1	218
2011.75.....	272.8	172	275.4	230
2012.00.....	274.5	195	276.6	239
2013.00.....	278.8	263	280.8	253
2014.00.....	281.8	291	285.1	233
2015.00.....	284.5	284	291.1	184
2016.00.....	287.7	250	302.8	120

of the fundamental stellar properties, the luminosity function, and the mass-luminosity relation, which are poorly known at the lower end of the H-R diagram. The MK types for many visual binaries, estimated on the basis of the prism surveys, are often subject to change after a more careful study of the slit spectra. Obtaining MK types on the basis of the slit spectra is a significant problem (Gray et al. 2003).

3.1. *Spectral Observations*

Several spectra for WOR 2 were obtained at the 2.6 m telescope of the BAO on 2004 September 2 with SCORPIO, which is a multiregime, prime focus focal reducer for observing both starlike and extended objects. On the 2.6 m telescope, SCORPIO is used in combination with a $2K \times 2K$ Lick3 CCD based on a 2063×2058 Loral system, with elements of 15 μm^2 size and a readout noise of $\sim 5\ e^{-1}$. The resulting field of view is $14' \times 14'$, and the spatial resolution is $0''.42$ per element. In the spectroscopy mode, a grism with a 600 lines mm^{-1} grating (with a resulting linear dispersion of 1.7 Å per element and resolution of 3.5–4.0 Å) covering the spectral range ~4100–7500 Å was used. Since the components' separation in the WOR 2 system is less than $1''.0$, the spectrometer slit of size $2''.0 \times 6'.0$ contained both stars.

We observed at about the same zenithal distance spectrophotometric standards (Kharitonov et al. 1988) for both atmospheric extinction correction and spectrograph response fitting for different wavelengths. The spectra of some late-type MK standards from the list of Keenan & Yorka (1988) were also obtained for comparison purposes. All stars were observed at less than 1.5 air masses, and we estimate our relative fluxes to be calibrated on the order of 10% accuracy, well enough for classification purposes.

The standard ESO Munich Image Data Analysis System environments were used for data reduction, including the subtraction of bias, dark frames, and dome flats. The wavelength dependence of the instrument profile was determined from single

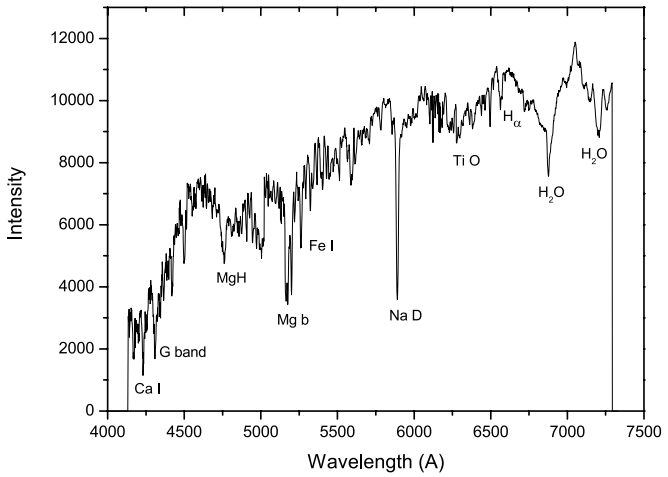

FIG. 2.—Spectrum of WOR 2. Several representative spectral lines are marked. The intensity is given in arbitrary units.

lines in the comparison spectra and taken into account when calculating the parameters of spectral lines.

3.2. *Line Identification and Classification*

The spectrum of WOR 2 is shown in Figure 2. A large number of absorption lines were identified, but strong representative lines (some are marked in Fig. 2) were only used for classification purposes. When identifying the spectral lines we took into consideration both wavelength coincidence and line intensity.

Different spectral atlases and libraries (Yamashita et al. 1977; Gunn & Stryker 1983; Jacoby et al. 1984; Kirkpatrick et al. 1991; Goy et al. 1995; Allen & Strom 1995; Montes et al. 1997; Pickles 1998) were used for line identification. The standard criteria and indications given by Keenan (1987), Jaschek & Jaschek (1987), Keenan & McNeil (1989), Gray (1992, p. 431; 1994), Garrison (1994), Malyuto et al. (1997), and Montes et al. (1997) were followed for classification purposes.

The main features in the spectrum are the absorption lines Ca I λ4226, the *G* band, Fe I λ5270, the Mg *b* triplet, MgH λ4780 and λ5210, and NaD λ5890 (typically the strongest feature for mid-K spectral type); several TiO bands (including a well-observed broad feature at 6100–6400 Å) were used to classify the spectrum.

As is seen from Figure 2, Ca I is rather strong, the *G* band begins to dissolve into separate lines, MgH λ4780 is still strong, and TiO bands are visible but not yet strong. Apart from this, metallic lines in general are rather strong, with Mg *b* and NaD being the strongest spectral features. These properties and the application of the above-mentioned criteria allow us to classify WOR 2 as K6 V, coinciding within the usual accuracy of one subclass with the classification as K7 V by Reid et al. (1995).

4. DISCUSSION

Since its discovery, WOR 2 has practically covered two revolutions. In spite of the gaps in observations mentioned above, the measurements covered the most distant positions of the secondary. Due to the geometry of this system, these points correspond to the maximal curvature of the apparent orbit, thus contributing decisively to the orbit's quality. Taking into account the much larger weight of speckle measurements, these circumstances allow us to calculate a rather well defined orbit in spite of a relatively small number of measurements.

An overview of $(O - C)$ residuals both in position angle and separation shows that our orbit represents a substantial

improvement over the previous one. While the orbit's improvement is mostly due to accurate speckle observations, the method of calculation is also a key element. Data listed in Table 1 show that much greater weight is given to speckle data (see details on the weighting procedure in Docobo et al. 2000).

Quantitatively, the improvement is reflected in the quadratic means of residuals (rms), which are significantly smaller than those of the previous orbit (see Table 1). In particular, the rms values in ρ and θ for our orbit are equal to 2.1 and 22 mas, respectively, whereas the same values for Baize's orbits are 3.8 and 49 mas.

Our orbit can probably be graded 2 (good orbit) according to the scheme proposed by Hartkopf & Mason (2004). Usually, binaries that have covered two revolutions are the best candidates to get the maximal grade 1 (definitive orbit). However, the small number of observations and their uneven coverage of the orbital arc suggest that the definitive orbit for WOR 2 is yet to be determined.

From Table 3 one can see a rapid change in apparent separation between 2009.75 and 2010.75, which can be measured by the 6–8 class telescopes only. Should such measurements be performed, the definitive orbit can probably be calculated.

The dynamical mass of the system, $1.40 \pm 0.25\ M_{\odot}$, is $0.33\ M_{\odot}$ larger than that obtained from the Baize orbit. No significant variation in this value should be expected, since the limit is imposed by Kepler's third law. Moreover, when there are no discrepancies regarding the temperature and luminosity of the components, in principle, a small increase in the system's mass reflects correctly the change of the combined spectral type from M0 to K7.

It is worth noting, however, that the overall accuracy of the dynamical mass determination for this binary (and many others) is almost entirely conditioned by the low relative accuracy of the parallax determination. Although an accuracy of less than 1% in period and angular semimajor axis is obtained for a number of binaries (Mason et al. 1999), they are all strongly hindered by the 3%–5% accuracy of parallaxes, which translates to a 10%–15% error in mass determination. Such low accuracy is very far from the theory requirements, so *Hipparcos* parallaxes in many cases deteriorate the overall accuracy of the mass determination. For example, should the parallax error be equal to zero, the dynamical mass error is $0.082\ M_{\odot}$ (5.7%). At present, such a value can still be used to fit certain theoretical tracks. As regards further improvement of the orbit itself (and therefore the accuracy of the dynamical mass determination), more efforts should be applied to get high-resolution measurements in the second quadrant and, even more importantly, at the points of minimal separation between components. Evidently, new post-*Hipparcos* data (from *Gaia* and the *Space Interferometry Mission*) are needed to improve the situation, since the number of well-determined orbits is rapidly growing.

Taking into account the 0.55 mag difference, as well as the apparent brightness $V = 9.58$ (Salim & Gould 2003) in the combined light, we obtain 10.09 and 10.64 mag for the primary and secondary components, respectively. With a distance of 25.83 pc, these values lead to $M = +8.03$ and $+8.58$ mag as luminosity estimates for the primary and secondary components, respectively. The mass of each component can then be estimated using the formula given in Henry et al. (1999):

$$\log(\mu/\mu_{\odot}) = +0.002456M_V^2 - 0.09711M_V + 0.4365$$

where the mass is designated μ to distinguish it from luminosity.

The masses 0.65 and $0.61\ M_{\odot}$ are obtained for the components, and their sum, $1.26\ M_{\odot}$, is in a good agreement with the obtained dynamical mass. Apart from this, according to Schmidt-Kaler (1982) the obtained luminosity corresponds approximately to K7 and M0 dwarfs, concordant with our spectral classification.

Herbst & Miller (1989) measured the equivalent width of the Hα absorption in the spectra of WOR 2 as 0.85 Å. Although our spectra are not well suited to spectrophotometry, we estimated the roughly similar value of $\sim$0.9 Å, in a good agreement with the above result. This is an indication of the overall photometric stability of the system.

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