A&A 464, 635–640 (2007)
DOI: 10.1051/0004-6361:20066224

Astronomy & Astrophysics

Accurate masses of low mass stars GJ 765.2AB (0.83 $\mathcal{M}_\odot$+ 0.76 $\mathcal{M}_\odot$)*,**

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Received 10 August 2006 / Accepted 8 November 2006

ABSTRACT

Context. Because of the lack of precise masses, the coverage of the main-sequence empirical mass-luminosity relation for stars in the mass range from 0.6 $\mathcal{M}_\odot$ to 0.9 $\mathcal{M}_\odot$ is incomplete. The nearby K-type visual and spectroscopic binary GJ 765.2 = MLR 224 is a good candidate for new reliable points in this significant part of the relation.

Aims. We have found a combined orbital solution for the pair and derived physical properties of the components using interferometric and spectroscopic data.

Methods. The diffraction-limited speckle observations were mostly collected at the 6 m BTA telescope, and the velocities of the components were obtained using the CORAVEL radial velocity scanner on the Swiss 1 m telescope.

Results. In a combined solution, the orbital period is found to be 11.919 yr. The masses of the GJ 765.2 components are $\mathcal{M}_A = 0.831 \pm 0.020$ $\mathcal{M}_\odot$ and $\mathcal{M}_B = 0.763 \pm 0.019$ $\mathcal{M}_\odot$. The obtained orbital parallax of the system, $\pi_{\rm orb} = 31.0 \pm 0.5$ mas, is 7 percent lower than the Hipparcos value. The absolute V magnitudes of the stars, derived from the measured speckle magnitude differences, are: $M_V^A = 5.99 \pm 0.04$ and $M_V^B = 6.64 \pm 0.05$. The effective temperatures of the components, $T_{\rm eff}^A = 5060 \pm 130$ K and $T_{\rm eff}^B = 4690 \pm 160$ K, follow from the $V - K$ and $J - K$ color indices. The star metallicity value, estimated from the 6 m telescope spectrum, is [M/H] = -0.35 ± 0.15 dex.

Conclusions. The presented individual masses have 2.4% and 2.5% relative accuracies. Therefore, the components of GJ 765.2 rank among a dozen stars with masses accurate to within a few percent in the mass range 0.6–0.9 $\mathcal{M}_\odot$. The existing data on the kinematics of GJ 765.2 and its chromospheric activity indicate that the binary belongs to the middle age (3–4×10^9 yr) thin disk population of the galaxy.

Key words. stars: binaries: visual – stars: fundamental parameters – stars: late-type

1. Introduction

The coverage of the main-sequence (MS) mass-luminosity relation (MLR) is complete for intermediate-mass stars from the late-B through the middle G-type, corresponding to the mass range of 0.9–3.0 $\mathcal{M}_\odot$. From about 50 stars with accurately (better than 2–3%) known masses, 35 belong to eclipsing binary components with masses above 1 $\mathcal{M}_\odot$. At the end of the 90 s, a burst of very accurate masses at the bottom of the MS (masses below ~0.5 $\mathcal{M}_\odot$) came from the combination of very precise radial velocities of double-lined binary systems with adaptive optics and speckle interferometry (Ségransan et al. 2000; Delfosse et al. 2000). Masses accurate to within 2–10% for very low-mass stars were also provided by precise astrometric measurements using the Fine Guidance Sensors on board of the HST (Torres et al. 1999; Benedict et al. 2000). A series of accurate mass determinations allowed the improvement of the empirical MLR in its lower part. However, for the mass range of 0.6–0.9 $\mathcal{M}_\odot$, corresponding to late-G to late-K dwarfs, the need for precise masses remains important. This is a large region of the MS with very few known eclipsing systems. Andersen's (1991) critical compilation includes only one binary in this mass range; namely, HS Aur with masses of 0.900 and 0.879 $\mathcal{M}_\odot$. The reason for this deficiency is selection effects: eclipses of these small stars are rare, they have low luminosities, and short-period pairs have high rotation velocities and, therefore, blended spectral lines.

A second reason for a more thorough study of this mass range is the discrepancy between the measured properties of components of binary systems with masses 0.7–1.0 $\mathcal{M}_\odot$ and stellar evolution models (Lastennet et al. 2003). By fixing the accurately determined masses and luminosities for the pairs of this type, it is easier to operate with other model parameters (metallicity, age and mixing length parameter) to be able to fit the basic properties of the models. A larger sample of binaries covering just that region of masses would therefore be required.

Fifteen years after Andersen's compilation list, the development of correlation techniques for radial velocity measurements, accurate photometry and precise astrometry, now

* Based on observations made with the 6 m BTA telescope, which is operated by the Special Astrophysical Observatory, Russia, and the Observatoire de Haute-Provence, operated by the Centre National de la Recherche Scientifique de France.

** Tables 1 and 2 are only available in electronic form at http://www.aanda.org achievable using interferometric techniques, have led to new suitable late-G to late-K systems with accurate masses. These include an old and somewhat evolved secondary component in the eclipsing double-lined spectroscopic binary (eSB2) RS Cvn type system UV Psc (Popper 1997), the secondary in the interferometric SB2 binary Iota Peg (Boden et al. 1999), the secondary early-K dwarf star in the Hyades eSB2 system vB22 (Torres & Ribas 2002), the secondary in the old metal-poor interferometric SB2 system HD 195987 (Torres et al. 2002), both components of the isolated eSB2 system GU Boo (Lopez-Morales & Ribas 2005), the secondary component in the old interferometric SB2 HD 9939 (Boden et al. 2006), and a few others.

The high proper-motion star GJ 765.2 = HD 186922 = HIP 96656 [$\alpha = 19^{h}39^{m}06.4^{s}, \delta = +76°25'19''$ (2000), K1V, $m_V = 8.08$] has attracted attention over the past two decades as an additional good candidate for a comparison with detailed evolutionary calculations in the discussed mass range. The star is listed in the Third Version of the Nearby Star Catalogue (Gliese & Jahreiss 1991) with a trigonometric parallax $\pi_{\rm trg} = 43.9 \pm 11.2$ mas taken from the preliminary version of the General Catalog of Trigonometric Stellar Parallaxes, Fourth Edition (Van Altena et al. 1995). The trigonometric parallax catalogues, compiled at the Yale University Observatory, included GJ 765.2 with parallax values in the range of 19–52 mas. It is obvious that such inconsistency cannot be explained simply by the errors of astrometry. In 1971, the star was first recognized as a visual binary by Muller (1973), who used an eyepiece micrometer at the Nice Observatory 20-inch refractor. The binary, designated as MLR 224, has been observed regularly by the discoverer (see Table 1), often giving discrepant relative positions and remaining unresolved in many cases. Twenty years after Muller's first visual observations, the system was included in the list of Hipparcos targets. The astrometric satellite gave the first reliable relative positions and magnitude differences for the binary: PA = 116.0°, sep = 159 mas (epoch 1991.25), and ΔHp = 0.68 ± 0.28 (ESA 1997). In addition, it provided the precise parallax value, $\pi_{\rm hip} = 33.28 \pm 0.69$ mas, which placed the star significantly farther from the sun than derived from the ground-based astrometry.

GJ 765.2 was first observed by speckle interferometry at the 6 m BTA telescope in 1993, as a rapidly moving binary with an angular separation of $\lesssim 0.2''$. Shortly thereafter, Tokovinin (1994) calculated a preliminary orbit for the pair with a period of 11.76 yr and a semi-major axis of 225 mas using his measurements of radial velocities in combination with a few visual and speckle observations. Since then the pair has been measured repeatedly using speckle techniques, and the phase coverage of its orbit is now satisfactorily uniform. Radial velocities of GJ 765.2 have been monitored since 1983 with the CORAVEL spectrovelocimeter at the Haute-Provence Observatory, France. Based on these data, we present a new combined orbital solution and report the main physical properties of GJ 765.2 in this paper.

2. Observations

A short description of the instrumentation and observing techniques for speckle interferometry (Labeyrie 1970) with the 6 m BTA telescope at visible wavelengths can be found in Balega I. et al. (2002). We have accumulated 16 speckle measurements of GJ 765.2 over a period of 13.1 years, including 7 unpublished points. The binary is usually well-resolved by the diffraction limit of the 6 m telescope; the separation between the components always remains larger than ~25 mas. The measurements were performed at 12 epochs, uniformly distributed on the orbit. Three of the speckle observations were obtained in 1997 and 2001 in the infrared *J* and *K* spectral windows using the PICNIC and HAWAII-I array detectors of the Max-Planck-Institut für Radioastronomie, Bonn. The bispectrum speckle interferometry reconstruction procedure (Weigelt 1977; Lohmann et al. 1983) provides true images of an object and thus enables one to avoid the 180° ambiguity in the speckle position angles. Based on our experience in binary star measurements, we can adopt $\sigma_\theta = 0.50°$ and $\sigma_\rho = 1.5$ mas for the uncertainties in the BTA 1994–2006 observations. Exceptions are the 2002 measurements, which were obtained with four different filters under poor seeing conditions; therefore, they are given the weight 0.75 in the subsequent analysis. This is also why the magnitude differences are not presented for this date. For the two earlier measurements in 1993, the uncertainties are higher: $\sigma_\theta = 3.0°$ and $\sigma_\rho = 4.0$ mas. In that period, the old generation television photon-counting detector with higher instability and field aberrations was used for data recording. Unfortunately, these points are the most important for determining the shape of the orbit because of their closeness to the periastron.

The complete collection of interferometric observations is given in Table 1, together with 13 visual observations performed by Muller, one point from Hipparcos, and one speckle measurement made by Mason et al. in 2001.499. The visual data, as well as speckle observations published before 2006, were extracted from the Washington Double Star Catalog (`http://ad.usno.navy.mil/wds`). For completeness, in the table we provide the 6 epochs when the pair was not resolved by experienced visual observers. New speckle measurements with the 6 m BTA telescope in the period 2001.8–2006.4 are incorporated into our analysis of the orbital motion. Data in Table 1 include: the epoch of observation expressed as the fractional Besselian year; the position angle θ in degrees; the angular separation ρ in milli-arcseconds; the residuals to the calculated orbit; magnitude difference Δm together with the error of the measurement; filter specifications; the code of the observer or original reference.

A total of 50 radial velocity measurements for GJ 765.2 A and B were obtained between 1983 and 1998 with the CORAVEL radial velocity scanner (Baranne et al. 1979) on the Swiss 1 m telescope at the Observatoire de Haute Provence, spanning 15.1 years and 1.3 system periods. They are listed in Table 2, which also gives the heliocentric Julian date, the orbital phase, and velocity residuals. For an 8-mag K0 star, the velocities are measured with a typical precision of 500–650 m s^{-1}. Due to the comparatively long period of the system, the velocity amplitudes are small. Consequently, for a significant part of the orbit, the spectral lines of the components are severely blended.

Radial velocities of GJ 765.2 were also measured by Tokovinin (1994) on the 0.7 m telescope at Moscow University with another correlation scanner, RVM, leading to the first orbit calculation and now covering the period from 1986 to 2004. However, the accuracy of this data is somewhat inferior to CORAVEL, so we decided to use only CORAVEL velocities in our final orbital solution. For completeness, the RVM velocities are nevertheless given in Table 2 (marked with double asterisks).

3. Orbital solution, masses of the components and the parallax

The combined orbit was determined using the ORBIT code of Tokovinin (see Forveille et al. 1999, for comments). The program performs a least-squares adjustment to all available radial velocity and relative astrometry observations, with weights inversely proportional to the square of their standard errors. The solution is found simultaneously for the 10 elements of the astrometric-spectroscopic orbit, where the first seven are the usual elements in a visual orbit, and the other three are the radial velocity amplitudes and the centre-of-mass velocity of the system. All position angles have been transformed to the equinox 2000.0 to correct for precession. The speckle data were collected in the period 1993–2006, which corresponds to one revolution of the pair.

In total, the astrometric data sets cover almost 3 cycles of the system. The combination of the old visual observations and the new speckle data improves the orbital solution because they provide an extended time coverage. However, all but two eyepiece micrometer data points for GJ 765.2 show residuals more than 3 times their estimated errors. In addition, a systematic bias in the visual measurements of θ was found compared to the speckle data. We do not know the origin of these errors, but it is extreme difficulty to obtain visual observations at the resolution limit of the telescope. Therefore, we exclude all visual measurements in the orbit calculation – they are included here only to complete the list.

Our orbital solution uses only speckle measurements together with the radial velocities from CORAVEL. The radial velocities near conjunctions, affected by line blending, were excluded from the analysis. The remaining velocities were carefully analyzed to reveal systematic errors or highly deviating measurements. As a consequence, only 49 velocities of the brighter component and 43 of the fainter one were used in the following analysis. Figure 1 depicts the radial velocity orbit of GJ 765.2. We show all our measurements in the figure, including those which were not used in the orbital solution. Rejected observations are marked with an asterisk in Table 2.

A combined speckle-spectroscopic solution is given in Table 3. The last four positions in the table show the rms residuals of the measurements from the orbit. A graphical representation of the newly determined orbital ellipse and the observations are shown in Fig. 2, with the primary component at the origin. The motion of the secondary is direct (counter-clockwise), and the plane of the true orbit lies close to the line of sight. The position angle Ω of the ascending node is defined taking into consideration the radial velocity of the secondary with respect to the primary.

The visual measurements of Muller are given in the figure for illustrative purposes only. To make angles consistent with the 11.919 yr period of the system, we have reversed the quadrants of two visual observations: 1979.58 and 1991.60. Four erroneous points of Muller (1976.77, 1980.62, 1981.53, and 1989.75) are not presented. Unusual trends are seen in the θ residuals of visual observations displayed in the figure: all of Muller's visual points are shifted, on average, by 10° clockwise. It appears likely that his position angles include a systematic error, which can probably be explained by the high declination of this star.

The orbital parameters in Table 3 and the measured magnitude differences allow us to determine the main physical properties of GJ 765.2. The total mass of the system, resulting from the combined orbital solution, is $1.594 \pm 0.053\ \mathcal{M}_\odot$. The mass ratio is $q = 0.92 \pm 0.03$. The masses of the primary and secondary components are $\mathcal{M}_A = 0.831 \pm 0.020\ \mathcal{M}_\odot$ and $\mathcal{M}_B = 0.763 \pm 0.019\ \mathcal{M}_\odot$, respectively. Mass errors result from the errors of the orbital elements. The relative errors of the primary's and secondary's component mass estimates are 2.4% and 2.5%, respectively.

The distance determined to GJ 765.2, based on our orbital solution, is 32.23 ± 0.52 pc, corresponding to an orbital

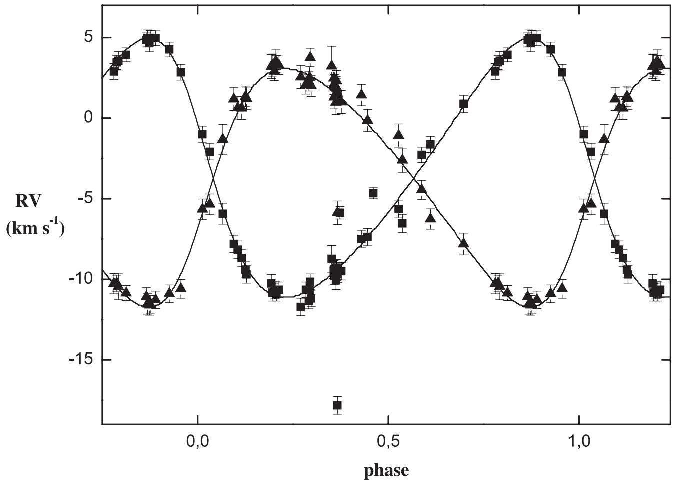

Fig. 1. CORAVEL radial velocity orbit of the GJ 765.2 AB system. Filled triangles represent measurements of the primary star; the filled squares correspond to the secondary.

Table 3. Speckle-spectroscopic orbital solution for GJ 765.2.

P(yr)	11.919 ± 0.003	K_A(km s^{-1})	7.40 ± 0.09
T	1993.150 ± 0.004	K_B(km s^{-1})	8.05 ± 0.08
e	0.240 ± 0.003	V_0(km s^{-1})	-3.73 ± 0.05
a(mas)	189 ± 2	σ_θ(°)	2.0
i(°)	80.2 ± 0.2	σ_ρ (mas)	2.0
$\Omega_{\rm asc}$(°)	293.0 ± 0.6	σ_{RVA}(km s^{-1})	0.40
ω(°)	250.0 ± 0.1	σ_{RVB}(km s^{-1})	0.32

parallax $\pi_{\rm orb} = 31.0 \pm 0.5$ mas. This value is approximately 7% smaller than the Hipparcos parallax, $\pi_{\rm hip} = 33.28 \pm 0.69$ mas. The nonlinear relative motion of the components during the Hipparcos mission was not properly taken into account in the data reduction and could affect the measured parallax. The error of the Hipparcos parallax value in the case of GJ 765.2 is probably underestimated and should be increased by a factor of 2 or 3. Similar discrepancies for other Hipparcos binaries were also mentioned by Shatskii & Tokovinin (1998), Tokovinin et al. (2000) and Balega Y. et al. (2002). At the distance of the system, the semi-major axis of the orbit is 6.1 AU.

4. Luminosities, metallicity and $T_{\rm eff}$

The mean speckle magnitude difference at 545 nm is $\Delta m = 0.65 \pm 0.03$, but because the components are similar in brightness, there is no significant difference in Δm between our spectral window and the V band. To derive the system's V magnitude, we have used the Hipparcos Hp and the Tycho $B_{\rm T}$ and $V_{\rm T}$ photometry (ESA 1997) as the most uniform and accurate collection of photometric measurements of the star. The Hp and Tycho magnitudes from the catalog were transformed to the Johnson's system using the relations $({\rm Hp}-V_{\rm Johnson})$ versus $(V-I_{\rm Cousins})$ and $V_{\rm Johnson}$ versus $V_{\rm Tycho}$ for K-type stars. The average from the Hipparcos and Tycho photometry value, $m_V = 8.059$, was used in combination with the orbital parallax to derive absolute component magnitudes, $M_V^A = 5.99 \pm 0.04$ and $M_V^B = 6.64 \pm 0.05$, where the uncertainties include the contribution from the distance error.

The metallicity of GJ 765.2 is not well constrained at this point. Based on the GJ 765.2 proximity to the Sun and since its space motion indicates a disk population, one can expect that GJ 765.2 has elemental abundances near solar values. The only

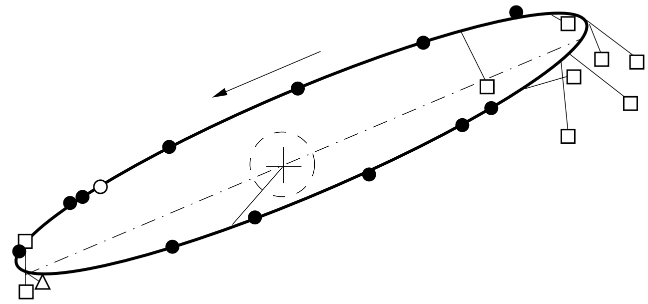

Fig. 2. Apparent ellipse representing the orbital elements for GJ 765.2. The BTA speckle interferometric data are indicated by filled circles, the speckle interferometric measurement performed by Mason et al. in 2001.499 is shown by an open circle, data from visual observers are given by open squares, and the Hipparcos measurement is shown as an open triangle. Residual vectors for all measurements are plotted, but in the case of speckle observations they are smaller than the points themselves. The orbital motion direction is indicated by an arrow. The solid line shows the periastron position, while the dot-dashed line represents the line of nodes. The dashed circle around the position of the primary has an angular radius of 0.02″ corresponding to the diffraction limit of the 6 m telescope in the V band.

published value can be found in the catalog of stellar metallicities (Zakhozhaj & Shaparenko 1996). They used the relation between the metallicity and UV excess for the late-type stars of the MS (Suchkov et al. 1987), together with the UBV photometry from the Catalogue of Nearby Stars (Gliese & Jahreiss 1991), to find [Fe/H] = −0.20. However, this method is only suitable for survey purposes, not for astrophysical analysis. To specify the [M/H] value, we placed the GJ 765.2 AB system on the observing program at the moderate resolution Main Stellar Spectrograph mounted on the 6 m telescope. The CCD spectrum was obtained in 2005.64 at the orbital phase 0.0472 using the resolution $\lambda/\Delta\lambda$ = 18 000 with the S/N ratio about 300 in the spectral region 4380−4630 Å. At the given phase the radial velocity difference between the components was about 0.9 km s^{-1}, which is below the resolution limit of the spectrograph. We used Kurucz's model atmospheres (Kurucz 1992), $T_{\rm eff}$ = 5000 K, and $\log g$ = 4.5 to estimate the metallicity from the comparison with the synthetic spectra. The adapted value, [M/H] = −0.35 ± 0.15 dex, is in agreement with the above-mentioned photometric estimate. Low accuracy of the metallicity estimate is explained by the short length of the spectrum used and the complexity of the spectrum modelling due to line blending.

Individual luminosities of the components in the infrared can be determined from measured intensity ratios in the J and K bands and the combined m_J and m_K magnitudes for GJ 765.2, available from the 2 MASS Catalog (Skrutskie et al. 1997). These, combined with the orbital parallax value, yield absolute J and K magnitudes of the components, which are given in the generalized Table 4 together with the $(V-K)$ and $(J-K)$ color indices. The infrared color indices for the components allow for an estimate of the effective temperatures, which is nearly independent from the adapted [Fe/H] value. Using the color-temperature calibration by Alonso et al. (1996) and the metallicity value [Fe/H] = −0.35, we adopt the following values of the temperatures for the GJ 765.2 components: $T^A_{\rm eff} = 5000\pm120$ K, $T^B_{\rm eff} = 4770\pm150$ K and $T^A_{\rm eff} = 5120\pm160$ K, $T^B_{\rm eff} = 4615\pm190$ K, correspondingly from the $(V-K)$ and $(J-K)$ color indices. The error of these estimates comes from the speckle photometry errors and temperature calibration errors (∼2%). In the following analysis, we will use the average estimates of the temperature, namely, $T^A_{\rm eff} = 5060 \pm 130$ K, $T^B_{\rm eff} = 4690 \pm 160$ K.

Table 4. Summary of the main physical parameters of GJ 765.2.

Parameter	Primary	Secondary
Mass ($\mathcal{M}_\odot$)	0.831 ± 0.020	0.763 ± 0.019
log ($\mathcal{M}/\mathcal{M}_\odot$)	−0.0804 ± 0.0104	−0.1175 ± 0.0108
m_V	8.54 ± 0.02	9.19 ± 0.04
M_V	5.99 ± 0.04	6.64 ± 0.05
$L/L_\odot$	0.40 ± 0.02	0.26 ± 0.02
$M_{\rm bol}$	5.71 ± 0.05	6.17 ± 0.06
J magnitude	4.40 ± 0.09	4.94 ± 0.22
K magnitude	3.92 ± 0.09	4.34 ± 0.22
$(V-K)$	2.07 ± 0.10	2.30 ± 0.23
$(J-K)$	0.48 ± 0.13	0.60 ± 0.32
$T_{\rm eff}$ (K)	5060 ± 130	4690 ± 160
log $T_{\rm eff}$	3.702 ± 0.011	3.670 ± 0.015
Spectral type	K1V	K3V
[M/H]	−0.35 ± 0.15	

The inferred bolometric luminosities of each star are L^A = 0.40 ± 0.02 $L_\odot$ and L^B = 0.26 ± 0.02 $L_\odot$. Bolometric magnitudes, $M^A_{\rm bol}$ = 5.71 ± 0.05 and $M^B_{\rm bol}$ = 6.17 ± 0.06, are determined using the average estimates of the temperatures and the bolometric corrections from Flower (1996). We summarize the astrophysical parameters for the GJ 765.2 system in Table 4.

5. Age and MLR

To compare the inferred parameters of the GJ 765.2 components with evolutionary tracks, it is necessary to know the age of the system. Three indicators, kinematics, chromospheric activity and metallicity, can be used to estimate the ages of K dwarfs. The existing data lead to contradictory age values for GJ 765.2. Montes et al. (2001) identified GJ 765.2 as one of 34 possible members of the Castor moving group with an age of 200 Myr. They found that the position of the star in the velocity space, (U, V, W) = (−23.5, −10.2, −16.6) km s^{-1} (corrected due to the solar motion the value is (U, V, W) = (−13.5, −5.0, −9.4) km s^{-1}), corresponds to the location of this young group in the (U, V) and (W, V) planes. However, the authors did not account for the presence of the secondary star and used an inexact value of its center of mass velocity. With our velocity value, V_0 = −3.73 km s^{-1}, and the orbital parallax value, $\pi_{\rm orb}$ = 31.0 ± 0.5 mas, the Galactic space-velocity components become:

(U, V, W) = (−17.83 ± 0.58, −0.99 ± 0.18, −8.74 ± 0.31), total velocity $V_{\rm Total}$ = 19.9 km s^{-1}.

With these new (U, V, W) values, GJ 765.2 no longer fits the position of the Castor moving group, (−10.7, −8.0, −9.7) km s^{-1}, $V_{\rm T}$ = 16.5 km s^{-1}, in the (U, V) plane (Barrado y Navascues 1998), while for its position in the (W, V) plane it can be associated with the Ursa Major supercluster. Therefore, following the specified space velocity components, GJ 765.2 must be discarded as a possible member of the Castor young moving group.

Stellar age can be estimated from its space velocities using Grenon's (1987) kinematic age parameter,

$$f = \frac{1}{300}\sqrt{U^2 + 2.5V^2 + 3.5W^2}.$$

It is based on the assumption that all stars sharing the same f value should have the same age. For GJ 765.2, Grenon's parameter value is 0.08, which means that the star belongs to the

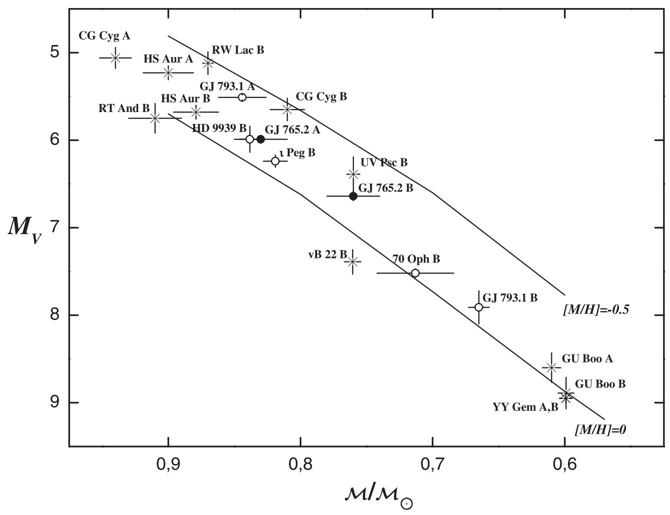

Fig. 3. The mass-magnitude relation in the *V* band for the mass range 0.6−0.9 $\mathcal{M}_\odot$. The filled circles are the components of GJ 765.2. The asterisks represent the components of eclipsing double-lined spectroscopic binaries; the open circles show the components of astrometric double-lined spectroscopic binaries. The two curves are 5 Gyr theoretical isochrones from Baraffe et al. (1998) for metallicities [M/H] = 0.0 and [M/H] = −0.5.

young-to-intermediate age group of the thin disk population (age less than 3−4 Gyr).

The slightly enhanced CaII chromospheric emission of GJ 765.2 also counts in favour of its young age. The star was included in the Young et al. (1989) compilation of the measured Ca II H and K fluxes with the empirical $\langle S \rangle$ index equal to 0.32. This value is slightly higher than the typical value for most late-type MS stars ($\langle S \rangle = 0.25$). It should be noted, however, that a small increase of the $\langle S \rangle$ emission can be caused by the binary nature of the star.

On the other hand, in his survey of the chromospheric emission and rotation among solar-type stars in the solar neighborhood, Soderblom (1985) gives the following ratio of the CaII H and K flux to the stellar bolometric flux for GJ 765.2: $\log R_{\rm HK} = -4.59$. It corresponds to relatively low chromospheric activity of a typical late-type MS star. The chromospheric CaII emission flux in G and K stars is proportional to their rotation rates. It follows from the same paper that GJ 765.2 rotates ~50% faster than most stars at $(B-V) = 0.88$; namely, $\Omega/\Omega_\odot = 0.91$. At the same time, this value is about 3 times lower than for Hyades late-type members. Following the "activity-age" relation, $R_{\rm HK} \propto t^{1/2}$, the age of GJ 765.2 should be close to 4 Gyr. A low X-ray luminosity of 8.4×10^{27} erg s^{-1} (Hünsch et al. 1999), which is attributed to magnetically heated coronae of the components, also gives evidence of its considerable age. We therefore conclude that GJ 765.2 is a middle-age system of the thin disk.

The location of the GJ 765.2 components in the mass-magnitude diagram is shown in Fig. 3. Added in the figure are two theoretical isochrones for the age 5 Gyr from Baraffe et al. (1998) for two metallicity values, [M/H] = 0.0 and [M/H] = −0.5. The location of the GL 765.2 components in the "mass-M_V" diagram can be compared with other well-studied binaries of the same mass regime. The components of binaries display a broad spectrum of ages, chemical compositions, and evolutionary stages.

In a search for possible faint physical or common proper-motion companions associated with the GJ 765.2 binary system, we extracted all stars from the 2MASS Point Source Catalog within a 5 arcmin radius of the star and plotted them on the $(J, J-K)$ color−magnitude diagram. None fall close to the main sequence corresponding to the distance to the star, so we are confident that GJ 765.2 is a binary, not a triple.

6. Summary

The overall goal of this study is to improve our knowledge about the lower MS MLR where eclipsing binaries are missing; more precisely, in the mass region of 0.6−0.9 $\mathcal{M}_\odot$. CORAVEL radial velocities were combined with 17 speckle interferometric observations and one Hipparcos measurement to obtain an astrometric-spectroscopic solution for the system, yielding direct mass determinations and an orbital parallax. The resulting masses are $\mathcal{M}_A = 0.831 \pm 0.020\ \mathcal{M}_\odot$ and $\mathcal{M}_B = 0.763 \pm 0.019\ \mathcal{M}_\odot$. The formal errors of 2.4 and 2.5% put this result into a category of only 12 systems (17 components) in the mass range of 0.6−0.9 $\mathcal{M}_\odot$ that have mass uncertainties similar to or better than ours. The components of GJ 765.2 are sufficiently different in mass to provide a good test of models.

Our orbital parallax is 7% lower and ~50% more precise than the direct Hipparcos trigonometric parallax. Together with the differential speckle magnitudes, this implies absolute *V* magnitudes of the stars, $M_V^A = 5.99 \pm 0.04$ and $M_V^B = 6.64 \pm 0.05$. The result illustrates the accuracy attainable from a speckle-spectroscopic orbit when the parallax measurement error is included.

The temperatures of the components, resulting from the *V*, *J* and *K* speckle magnitude differences, are: $T_{\rm eff}^A = 5060 \pm 130$ K, $T_{\rm eff}^B = 4690 \pm 160$ K. Correspondingly, they belong to spectral types K1 and K3. The metallicity of the system was roughly estimated from the 6 m telescope moderate resolution spectrum: [M/H] = −0.35 ± 0.15 dex. Available age indicators, chromospheric activity, and metallicity classification suggest that the system is 3−4 Gyr old. Recent evolutionary models show good agreement with the location of the GJ 765.2 components in the mass-luminosity diagram in the *V* band.

Acknowledgements. We are grateful to I. I. Romanyuk and E. A. Semenko for providing the original spectrum of GJ 765.2 and for their helpful comments, particularly their analysis of the star's metallicity. This project required extensive observations at the SAO 6 m BTA telescope and the Haute-Provence 1 m telescope, and we would like to thank the technical personnel of both observatories for their assistance. The speckle interferometry program at the 6 m telescope has been partly supported by the Russian Foundation for Basic Research through grant No. 04-02-17563a. The publication has made use of the SIMBAD database, operated at CDS in Strasbourg, France, and the Washington Double Star Catalog (`http://ad.usno.navy.mil/wds`).

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Online Material

Table 1. Astrometric measurements, their deviations from the ephemerides, and differential magnitudes for GJ 765.2.

Epoch	θ	ρ	$\Delta\theta$	$\Delta\rho$	Δm	$\lambda/\Delta\lambda$, nm	Reference
1971.570	275.6	0.170	–14.9	–0.007	0.7		Muller[a]
1971.670	280.0	0.210	–11.0	0.029	0.7		Muller[a]
1972.650	288.6	0.200	–7.1	0.000			Muller[a]
1973.580	296.6	0.190	–3.6	0.010			Muller[a]
1974.560	291.0	0.130	–16.3	–0.003			Muller[a]
1974.600							Heintz[a]
1975.530							Heintz[a]
1976.770	180.0	0.140	113.1	0.088	0.7		Muller[a]
1977.520							Muller[a]
1979.580	296.3	0.170	184.2	0.003	0.7		Muller[a]
1980.620	349.4	0.190	228.4	0.075	0.7		Muller[a]
1980.660							Muller[a]
1981.530	10.5	0.160	–164.7	0.132	0.7		Muller[a]
1983.070	287.0	0.180	–0.7	0.028			Muller[a]
1984.550	286.2	0.220	–9.4	0.020			Muller[a]
1989.750	189.8	0.180	91.6	0.063			Muller[a]
1991.250	116.0	0.159	5.4	–0.10	0.68 ± 0.28	$V_{\rm Hp}$	ESA[a]
1991.600	286.7	0.160	173.9	–0.005			Muller[a]
1993.351	151.7	0.035	–5.2	0.000			Balega et al.[a]
1993.844	264.7	0.052	5.7	0.008			Balega et al.[a]
1994.713	285.1	0.129	–0.2	–0.002	0.49 ± 0.07	656/30	Schöller et al.[a]
1997.789	303.0	0.166	0.6	0.001	0.42 ± 0.20	2165/328	Schöller et al.[a]
1997.789	303.3	0.166	0.9	0.001	0.47 ± 0.20	1238/276	Schöller et al.[a]
1998.777	311.3	0.111	–0.6	0.001	0.67 ± 0.03	545/30	Balega et al.[a]
1999.813	348.3	0.046	–0.6	–0.001	0.76 ± 0.08	610/20	Balega et al.[a]
2000.878	80.8	0.068	0.3	0.000	0.63 ± 0.03	545/30	Balega et al. (2006)
2001.499	96.9	0.110	1.1	0.003			Mason et al.[a]
2001.752	99.3	0.122	0.0	0.000	0.56 ± 0.03	750/35	Balega et al. (2006)
2001.837	100.2	0.128	–0.1	0.002	0.61 ± 0.05	1238/276	This paper
2002.801	108.3	0.165	0.0	0.000		545/30	This paper
2002.801	107.8	0.165	–0.5	0.000		600/20	This paper
2002.801	107.9	0.163	–0.4	–0.002		700/33	This paper
2002.801	107.8	0.163	–0.4	–0.002		850/75	This paper
2004.815	126.8	0.082	–0.9	0.001		600/20	This paper
2006.438	282.6	0.115	–0.4	0.001		545/30	This paper

[a] Data extracted from the Washington Double Star Catalog (`http://ad.usno.navy.mil/wds`).

Table 2. Radial velocities and residuals for GJ 765.2.

HJD	Date	RV_A (km s^{-1})	RV_B (km s^{-1})	$(O–C)_A$ (km s^{-1})	$(O–C)_B$ (km s^{-1})	Orbital phase
45 533.464	1983.541	3.20	–10.26	0.32	0.66	0.1935
45 543.442	1983.569	3.29	–10.82	0.38	0.13	0.1958
45 584.358	1983.681	3.54	–10.68	0.56	0.35	0.2052
45 620.282	1983.779	3.28	–10.65	0.25	0.43	0.2134
45 868.576	1984.459	2.55	–11.71	–0.33	–0.79	0.2705
45 969.299	1984.735	2.53	–10.67	–0.11	–0.01	0.2937
45 976.299	1984.754	3.76	–10.15	1.14	0.49	0.2952 *
46 221.544	1985.425	3.23	–8.73	1.50	0.94	0.3515 *
46 245.572	1985.491	2.07	–9.47	0.45	0.08	0.3571
46 248.490	1985.499	2.48	–9.47	0.87	0.07	0.3577
46 249.499	1985.502	1.30	–9.38	–0.31	0.16	0.3580
46 253.481	1985.513	2.01	–9.80	0.42	–0.28	0.3589
46 270.524	1985.559	0.98	–10.07	–0.53	–0.64	0.3628
46 274.450	1985.570	1.90	–9.49	0.41	–0.08	0.3637
46 278.452	1985.581	2.31	–9.28	0.83	0.11	0.3646
46 279.484	1985.584	1.86	–9.54	0.39	–0.15	0.3649
46 280.448	1985.586	1.64	–9.62	0.17	–0.24	0.3650
46 332.329	1985.728	1.00	–9.50	–0.22	–0.38	0.3770
46 561.621	1986.356	1.43	–7.50	1.40	0.32	0.4297 *
46 632.431	1986.550	–0.14	–7.37	0.24	0.01	0.4459
46 632.364	1986.550	–0.20	–6.37	0.19	1.00	0.4459 **
46 645.375	1986.586	–0.98	–7.28	–0.52	0.01	0.4489 **
46 985.539	1987.517	–1.08	–5.64	1.49	–0.65	0.5271 *
47 012.343	1987.590	–4.26	–4.26	–1.51	0.54	0.5332 **
47 029.397	1987.637	–2.61	–6.53	0.25	–1.85	0.5371 *
47 248.652	1988.237	–4.45	–2.28	–0.09	0.76	0.5875 *
47 350.511	1988.516	–6.26	–1.63	–1.18	0.63	0.6109 *
47 728.543	1989.551	–7.81	0.89	0.02	0.16	0.6977
48 079.441	1990.512	–9.69	2.72	0.54	–0.63	0.7783 **
48 088.539	1990.537	–10.27	2.89	0.02	–0.51	0.7804
48 105.415	1990.583	–10.26	2.53	0.13	–0.99	0.7843 **
48 109.377	1990.594	–10.02	2.71	0.39	–0.84	0.7852 **
48 121.444	1990.627	–10.24	3.46	0.24	–0.15	0.7880
48 140.329	1990.679	–10.45	3.56	0.14	–0.17	0.7923
48 229.235	1990.922	–10.85	3.93	0.20	–0.30	0.8127
48 229.235	1990.922	–11.99	3.17	–0.94	–1.07	0.8127 **
48 166.274	1990.750	–10.54	3.60	0.19	–0.30	0.7983 **
48 458.426	1991.549	–10.79	4.39	0.94	–0.59	0.8653 **
48 459.563	1991.553	–11.08	4.85	0.64	–0.12	0.8657
48 473.374	1991.590	–11.54	4.97	0.19	0.00	0.8688

Table 2. continued.

HJD	Date	RV_A (km s^{-1})	RV_B (km s^{-1})	$(O-C)_A$ (km s^{-1})	$(O-C)_B$ (km s^{-1})	Orbital phase
48 495.385	1991.651	–11.60	4.65	0.13	–0.33	0.8739
48 505.365	1991.678	–11.56	4.98	0.17	0.01	0.8762
48 565.258	1991.842	–11.27	4.96	0.39	0.07	0.8899
48 721.658	1992.270	–10.89	4.26	0.05	0.15	0.9258
48 738.472	1992.316	–12.88	1.87	–2.07	–2.11	0.9297 **
48 843.483	1992.604	–12.09	1.50	–2.31	–1.36	0.9538 **
48 853.415	1992.631	–10.59	2.84	–0.92	0.11	0.9561
49 099.638	1993.305	–5.65	–1.00	0.26	0.35	0.0127 *
49 172.446	1993.504	–3.68	–3.68	0.94	–0.92	0.0293 **
49 184.498	1993.537	–5.34	–2.09	–0.92	0.89	0.0321 *
49 332.298	1993.942	–1.32	–5.93	0.63	–0.26	0.0661 *
49 457.571	1994.285	1.18	–7.80	1.36	–0.21	0.0949 *
49 504.568	1994.414	0.63	–8.16	0.25	0.04	0.1057
49 547.490	1994.531	0.62	–8.68	–0.22	0.02	0.1155
49 592.486	1994.654	1.35	–9.41	0.08	–0.24	0.1259
49 604.393	1994.687	1.23	–9.70	–0.15	–0.42	0.1286
49 917.511	1995.544		–7.20		3.80	0.2005 **
49 921.480	1995.555	2.91	–10.75	–0.05	0.25	0.2014
49 945.413	1995.621	3.35	–10.89	0.35	0.16	0.2070
49 975.327	1995.702		–7.23		3.86	0.2137 **
50 281.467	1996.541	2.09	–10.65	–0.66	0.13	0.2842
50 314.424	1996.631	2.28	–11.34	–0.39	–0.65	0.2917
50 324.388	1996.658		–6.57		4.09	0.2940 **
50 341.309	1996.704	2.00	–11.19	–0.59	–0.59	0.2978
50 635.507	1997.510		–6.24		3.13	0.3654 **
50 641.550	1997.526	–5.87	–17.82	–7.3	–8.47	0.3668 *
50 641.563	1997.527	1.52	–9.69	0.09	–0.34	0.3669
50 668.459	1997.600		–5.87		3.34	0.3730 *
51 050.419	1998.646		–4.66		2.31	0.4608 *
51 057.306	1998.665		–4.58		2.34	0.4623 **
51 519.163	1999.929		–3.34		0.33	0.5684 **
52 053.413	2001.392		–3.79		–4.30	0.6911 **
52 211.214	2001.824		–2.30		–4.04	0.7274 **

[*] CORAVEL measurements not included in the orbital solution. [**] RVM measurements not included in the orbital solution.