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GJ 900: A New Hierarchical System with Low-Mass Components

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Abstract—Speckle interferometric observations made with the 6 m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences in 2000 revealed the triple nature of the nearby ($\pi_{Hip} = 51.80 \pm 1.74$ mas) low-mass young (≈ 200 Myr) star GJ 900. The configuration of the triple system allowed it to be dynamically unstable. Differential photometry performed from 2000 through 2004 yielded I- and K-band absolute magnitudes and spectral types for the components to be I_A=6.66±0.08, I_B=9.15±0.11, I_C=10.08±0.26, K_A=4.84±0.08, K_B=6.76±0.20, K_C=7.39±0.31, Sp_A≈K5–K7, Sp_B≈M3–M4, Sp_C≈M5–M6. The "mass–luminosity" relation is used to estimate the individual masses of the components: $\mathcal{M}_A \approx 0.64\mathcal{M}_\odot$, $\mathcal{M}_B \approx 0.21\mathcal{M}_\odot$, $\mathcal{M}_C \approx 0.13\mathcal{M}_\odot$. From the observations of the components' relative motion in the period 2000–2006, we conclude that GJ 900 is a hierarchical triple star with the possible orbital periods P_{A-BC}≈80 yrs and P_{BC}≈20 yrs. An analysis of the 2MASS images of the region around GJ 900 leads us to suggest that the system can include other very-low-mass components.

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1. INTRODUCTION

In the solar neighborhood M-type dwarfs make up about 70% and no less than 40% of all population in terms of the number of stars and mass, respectively. The lifetime of the lowest-luminosity main-sequence stars exceeds the age of the Universe, making them good candidate objects for the study of the properties of the Galactic disk including the history of star formation in the local volume.

The study of young M-type field dwarfs may lead to the discovery of systems with brown dwarfs. The interest toward the discovery and study of multiple systems with substellar components has been growing progressively since the discovery of the first brown dwarf GJ 229 B [1]. It is evident that such objects can be found only at small distances from the Sun. An example of such objects is the group of brown dwarfs GJ 569 B, which had its first orbit and dynamical masses estimated from the results of observations made with three major telescopes: the 6 m Bolshoi Azimuthal Telescope (BTA) of the Special Astrophysical Observatory of the Russian Academy of Sciences, Keck II, and MMT [2].

Until recently, the review by Henry and McCarthy [3] remained the most representative summary of empirical data on the masses and luminosities of cool dwarfs obtained using various observational techniques. In recent years, new data on the principal parameters of low-mass stars in binary and multiple systems have been published. These data were obtained by combining different observational methods: adaptive optics imaging combined with accurate radial-velocity measurements [4], speckle and long-baseline interferometry with radial velocities measurements [5, 6], and space astrometry performed with fine guidance sensors of the Hubble Space Telescope [7, 8]. These studies allowed the main empirical relations to be substantially refined [9]. This concerns, in particular, the "mass–luminosity" relation, which is of great importance for the investigation of parameters of individual stars and of the entire population of our Galaxy.

In 1998, a speckle interferometric survey of low-mass binaries and suspected binaries discovered by *Hipparcos* [10] astrometric satellite was started at the BTA 6 m telescope [11]. Observations were performed at visual and infrared wavelengths with the aim to identify pairs with fast relative motion of components, which allow model-independent masses to be determined over a short time interval. In addition to measuring relative component positions with an accuracy of about 1–2 milliarcseconds (mas), we also measured the magnitude differences in the V, R, I, J, H, and K bands for most of the binaries. Objects of this program include the red star GJ 900=Hip 116384 with the *Hipparcos* [10] parallax of π_{Hip}=51.80±1.74

mas. The results of astrometric measurements of this star allowed it to be suspected as a binary based on a number of indicators (the object has flag ‘S’ in the *Hipparcos* catalog; see [12]), and that is why we included it into our program list.

The very first interferometric observations performed in November 2000 with BTA showed GJ 900 to be a triple system [13]. On the reconstructed image two fainter components are located 0.5″ and 0.7″ from the main star. The compact configuration of the GJ 900 system may indicate that it belongs to the class of dynamically unstable multiple stars. One must, however, bear in mind that the components of this system may appear to be located at comparable distances from the main star only in the sky-plane projection. To verify these assumptions, we included this system into the program of monitoring of the relative motion of the components.

In 2002–2003, Martin [14] observed GJ 900 with the CIAO adaptive optics system of the 8.2 m Subaru Telescope and confirmed the two faint companions of the central object. The results of two observations in the infrared bands H and K separated only by a five-month interval led him to conclude that the system is dynamically bound.

In this paper we report the results of the interferometric measurements of positional parameters and magnitude differences of the components of GJ 900 made during the period from November, 2000 through December, 2006, determine the absolute magnitudes and estimate the masses of the stars. We analyze the possible dynamical stability of the system based on the observations performed.

2. OBSERVATIONS AND DATA ANALYSIS

Speckle interferometric observations of GJ 900 were made with the BTA 6 m telescope in the V ($\lambda/\Delta\lambda$=550/30 nm), I ($\lambda/\Delta\lambda$=800/100 nm), and K($\lambda/\Delta\lambda$=2115/214 nm) bands, where λ is the central wavelength, $\Delta\lambda$ is the half-width of the band. A fast 512×512 Sony ICX085 CCD combined with a three-stage image intensifier was used as a detector from 2000 through 2004. During our 2006 observations we employed a new EMCCD (Electron Multiplying Charge Coupled Device) system with higher quantum efficiency and linearity. The image scale was equal to 4.1 and 6.7 mas/pixel for the first and second facilities, respectively. The exposure time of speckle interferograms varied from 5 to 20 msec depending on brightness of an object and seeing conditions. Infrared observations were made with HAWAII infrared detector of the Max-Planck-Institute for Radio Astronomy. Table1 gives a log of observations. This table gives the following data for each measurement: date as a fraction of Besselian year, seeing β in arcseconds, the number of speckle interferograms in each series.

Table 1. Log of observations

Date	β arcsec	N	Filter
2000.8754	1.5	900	I
2003.7880	1	1000	K
2003.9248	1.5	2000	I
2004.8208	1	2000	I
2006.9465	1	2000	V
2006.9465	1	2000	I

The angular distances ρ, position angles θ, and magnitude differences between the components Δm from speckle interferometric observation with the BTA telescope are given in Table 2. Due to the low signal-to-noise ratio in the 2006.9465 measurements in the V-band, the relative positions for this data are not presented in the table. A description of the technique of the determination of relative positions and component magnitude differences inferred from the averaged over a series of power spectra of speckle interferograms can be found in the paper by Balega et al. [11]. The resolution diffraction limit was equal to 0.022″, 0.033″, and 0.088″ in the V, I, and K bands, respectively. The accuracy of the measurement of position parameters is equal to 0.3–1.0° and 3–8 mas in position angle θ and angular separation ρ, respectively. The errors of measured θ and ρ depend on a number of parameters: component separation, magnitude differences, and seeing β. The accuracy of the determination of magnitude differences between components from the reconstructed power spectra is also a function of the same parameters. This accuracy varies from 0.05 to 0.2 for objects with m_V=8–10. The modulus of the Fourier transform of the object (visibility) was obtained from the series of speckle interferograms with the classical speckle interferometry method. For image reconstruction we used the bispectrum speckle interferometry method [15, 16]. Fig. 1 shows the reconstructed infrared and visual images of GJ 900 based on the observations made in 2003 and 2006.

To specify the spectral type of the object, the 3600–6200 Å spectrum of the object was taken in October 2006 with the UAGS spectrograph of the Zeiss-1000 telescope with a dispersion of 1.35 Å/pixel (Fig. 2).

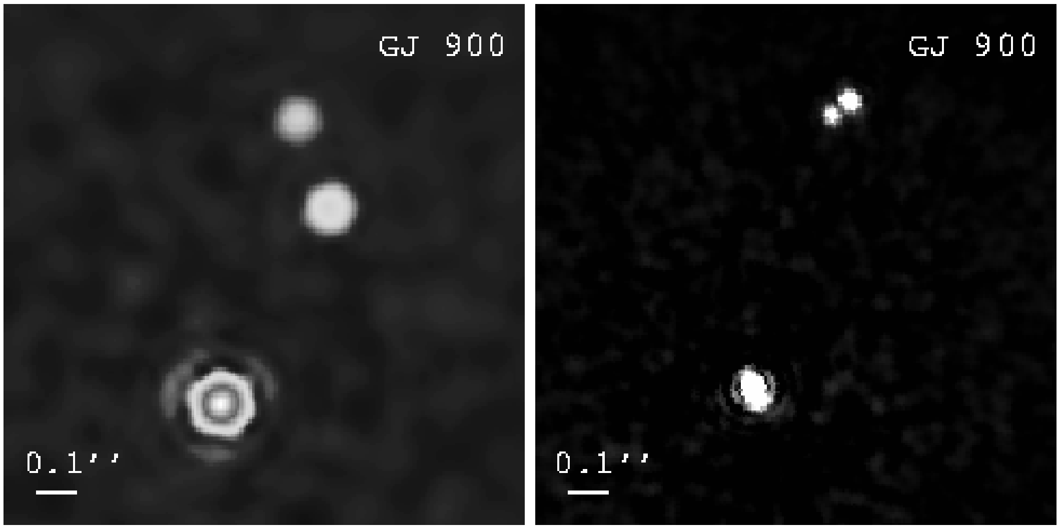

Fig. 1. Images of GJ 900 reconstructed from the 2115/214-nm filter observations with the BTA 6 m telescope in August 2003 (left) and from the 800/100-nm in December 2006 (right). North is at the top and East on the left.

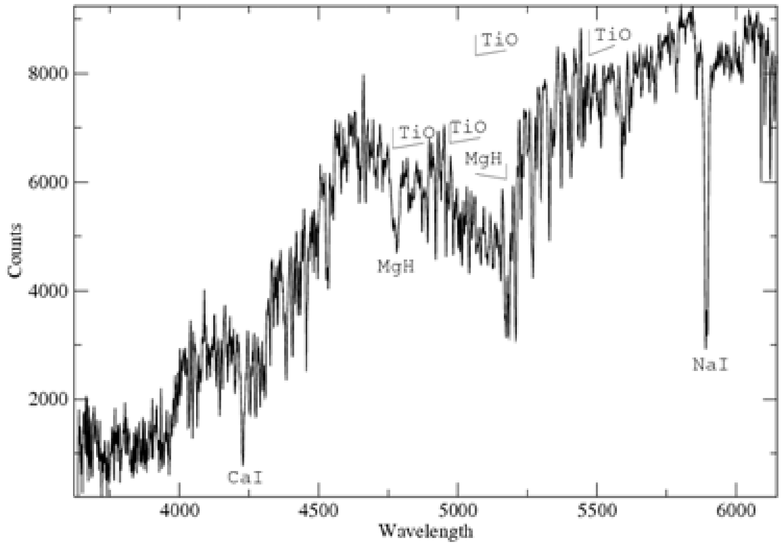

Fig. 2. Spectrum of GJ 900 in the 3600 − 6200 Å wavelength interval taken with the UAGS spectrograph of Zeiss-1000 telescope in October 2006. The strongest absorption lines and bands — those of TiO, MgH, CaI, and NaI — are indicated.

3. ABSOLUTE MAGNITUDES, MASSES AND SPECTRAL TYPES OF THE COMPONENTS

To compute the I- and K-band absolute magnitudes of the components of GJ 900, we used the results of differential speckle photometry performed with the BTA telescope (Table 2) and published integrated magnitudes of the system in these bands. For the sake of completeness, this table also includes the photometric data from [14]. The component magnitude differences determined using the results of speckle interferometry performed with BTA agree, on the whole, with those inferred from observations performed with the Subaru Telescope adaptive optics. At the same time, the results of differential photometry

Table 2. Speckle interferometric and adaptive optics measurements of GJ 900

Date, BY	Component vector	ρ mas	σ_ρ mas	$\theta°$	σ_θ	Δm	$\sigma_{\Delta m}$	Filter	Reference
2000.8754	AB	417	3	316.4	0.4	2.42	0.15	I	[13]
	AC	716	5	344.3	0.4	3.65	0.22		
	BC	399	6	13.6	0.6				
2002.5990	AB	510	10	324.5	0.1	1.78	0.02	H	[14]
	AC	760	10	344.0	0.1	2.55	0.03		
2002.5990	AB	510	10	324.5	0.1	1.61	0.03	K	[14]
	AC	760	10	344.0	0.1	2.38	0.04		
2003.0480	AB	520	20	327.4	0.1	1.70	0.04	H	[14]
	AC	740	20	343.9	0.1	2.31	0.06		
2003.7880	AB	557	5	331.3	0.6	1.92	0.18	K	This paper
	AC	733	6	345.1	0.6	2.55	0.30		
	BC	234	4	19.9	1.0	0.63	0.35		
2003.9248	AB	559	4	331.7	0.4			I	This paper
	AC	726	5	345.1	0.4				
	BC	224	6	20.4	0.6				
2004.8208	AB	606	3	335.8	0.3	2.56	0.06	I	This paper
	AC	714	4	345.5	0.4	3.18	0.22		
	BC	155	5	26.7	0.5				
2006.9465	AB	751	3	342.5	0.3			I	This paper
	AC	708	8	344.7	0.7				
	BC	51	9	130.3	0.8				

do not rule out the variability of one or several components of the system. The integrated I-band magnitude determined from the color index of the system, $V - I = 1.65$ [17], and the visual magnitude adopted from [18], is equal to m_I=7.94. The integrated K-band magnitude is equal to m_K=6.01±0.01 [19]. We combine these data with the *Hipparcos* parallax and magnitude differences from Table 2 to infer the following estimates for the absolute magnitudes of the components of GJ 900:

I_A=6.66±0.08, K_A=4.84±0.08,

I_B=9.15±0.11, K_B=6.76±0.20,

I_C=10.08±0.26, K_C=7.39±0.31,

where for the I band we used the mean result averaged over two observations made with the BTA 6 m telescope: $\Delta m_I^{AB} = 2.49\pm0.07$, and $\Delta m_I^{AC} = 3.42 \pm 0.24$. The H-band component magnitude differences measured using the adaptive optics [14] yield the following absolute magnitudes for the components:

H_A=5.11±0.08,

H_B=6.85±0.09,

H_C=7.54±0.15.

The luminosities of the components allow their masses to be estimated from the "mass—luminosity" relation, however, to do this, we must know the age and metallicity of the system.

Gizis et al. [20] compared the activity of a large sample of nearby M-type field dwarfs with the activity of M-type dwarfs in open clusters and calibrated the "age—activity" relation. We use the $V - I = -6.91 + 1.05 log(\tau)$ relation to infer an age of 10^8 Myr for the adopted distance modulus of m—M=1.43. X-ray luminosity of late-type stars is yet another indicator of their activity. According to *ROSAT* observations, the X-ray luminosity of GJ 900 is $L_x = 108.8\times10^{27}$ erg/s

[21]. This value corresponds to an M-dwarf age of 100–200 Myr.

The fluxes in the CaII H and K and MgII h and k lines are good indicators of stellar activity and hence of stellar age [22, 23]. However, no relations for age as a function of these indicators have been derived for stars of spectral types later than K. The only solution is to compare GJ 900 with stars having similar spectra with the age determined using other methods. For GJ 900 Giampapa et al. [24] report CaII H and K line flux measurements: $log(F_{CaII}) = 5.18$ erg/s×cm^2. We adopted the MgII-line flux $log(F_{MgII}) = 5.83$ erg/s×cm^2 from [25]. For comparison, we selected two stars of similar spectral types: GJ 212 and GJ 879. The CaII H and K line fluxes of these stars are equal to $log(F_{CaII}) = 5.49$ erg/s×cm^2 [26, 27] and $log(F_{CaII}) = 5.97$erg/s×cm^2 [28, 29], respectively. The MgII h and k line fluxes are equal to $log(F_{MgII}) = 5.36$ erg/s×cm^2 [25] and $log(F_{MgII}) = 5.98$erg/s×cm^2 [25], respectively. The ages of these stars were inferred from kinematics, isochrones, and lithium abundance and vary from 100 to 200 Myr.

Zuckerman et al. [30] believe GJ 900 to be a possible member of the Carina-Near moving group with an estimated age of 200 ± 50 Myr. However, the star's membership in this group is doubtable. The radial velocity of GJ 900 is equal to −10 km/s and differs strongly from that of the core of the group (+20 km/s [30]). The center of the moving group is at a distance of 30–50 pc from us, whereas GJ 900 is located within mere 19 pc from the Sun. The equivalent width of the LiI λ6708 line [31] in the spectrum of GJ 900 is several factors of ten smaller than in that of the corresponding lines in the spectra of the main members of the group.

Martin [14] used the results of the kinematical survey of Montes et al. [32] to estimate the age of the star at 50–100 Myr.

Thus all the available observational data indicate that GJ 900 is a young system with the age of about 200±100 Myr.

Since GJ 900 is located in the immediate proximity to the Sun (d=19.3 pc) and belongs to the galactic disk population, we can suppose that its metal abundance is close to the Sun's value. This assumption is supported by the results of the spectroscopic study of the system performed by Zboril and Byrne [31]. They give the metallicity of the star [M/H]= -0.1 ± 0.2.

Zboril and Byrne [31] determined the effective temperature of GJ 900 from sensitive photospheric lines and molecular bands with the allowance for surface gravity and microturbulence. Their estimate, T_{eff}=4000 K, is lower by 200 K than the temperature inferred from the $B{-}V$ and $R{-}I$ color indices [33]. It is evident that this temperature and the corresponding spectral type K7 refer to the main component of the system.

Speckle interferometric measurements of the I-, K-band component magnitude differences and adaptive optics measurements in the H and K bands allow the effective temperature and hence the spectral type of the primary component to be estimated using the calibrated relation between temperature and $V{-}I$ and $V{-}K$ color indices [34]. To estimate the V-band luminosity of the primary component, we used the I-, H-, and K-band absolute magnitudes and theoretical isochrones for the age of 200 Myr [35]. The mean V_A inferred from three isochrones is equal to 8.35±0.07. In this case, given the distance modulus of $m - M = 1.43$, the color indices of the primary should be equal to $(V{-}I)_A$=1.70±0.08 and $(V{-}K)_A$=3.52±0.09. The calibration of temperature in terms of color index derived by Alonso et al. [34] depends only slightly on the metallicity of the star. We assume that the iron abundance is equal to the solar value to infer from the estimated $(V - I)_A$ and $(V - K)_A$ indices the temperature of the component GJ 900 A, T^A_{eff}=4079±180 K, which corresponds to a late K-type dwarf.

An analysis of the GJ 900 spectrum obtained with the UAGS spectrograph on the Zeiss-1000 telescope showed that the energy distribution and relative intensities of individual strong lines correspond to those of a K5–K7-type star (Fig. 2). The characteristic features of the spectrum include strong TiO and MgH absorption bands.

For the age of 100–200 Myr and solar chemical composition the $M_I - \mathcal{M}$ and $M_K - \mathcal{M}$ evolutionary tracks for low-mass stars computed by Baraffe et al. [35] imply a primary-component mass in the interval from 0.64 to 0.67 $\mathcal{M}_\odot$. This mass agrees best with the primary spectral type of K5 − K7. The masses of lower-mass components B and C inferred from the same tracks show a much greater scatter. The mass of GJ 900 B is estimated to range from 0.28 to 0.34 $\mathcal{M}_\odot$, and that of GJ 900 C, from 0.16 to 0.24 $\mathcal{M}_\odot$. Note the scatter of possible masses is even greater when estimated from the K-band photometry of the stars studied. The resulting mass estimates correspond to the spectral types of M3 − M4 and M5 − M6 for the second and third components, respectively.

4. RELATIVE MOTION OF COMPONENTS, LIKELY ORBITAL PERIODS, AND DYNAMICAL STABILITY OF THE SYSTEM

The proper motion of GJ 900 is equal to 344 mas/yr. If we were dealing with accidental projection, components B and C would have shifted by almost 2″

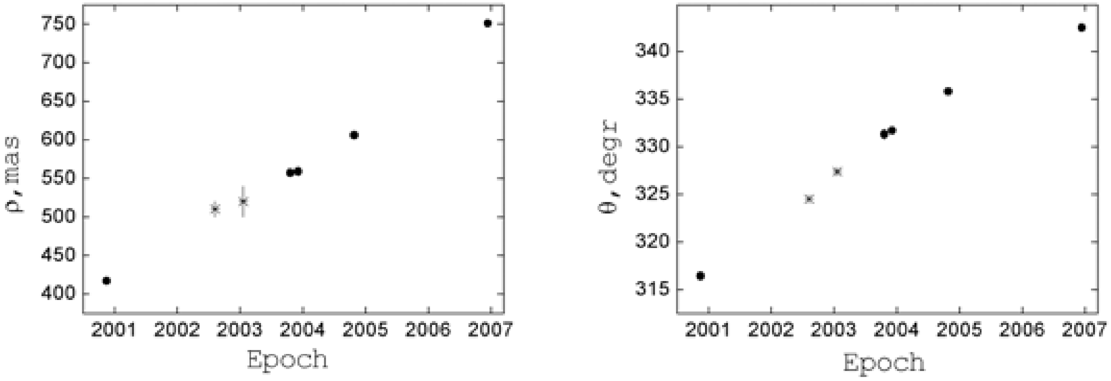

Fig. 3. Measurement of the angular separation and position angle of GJ 900 B relative of GJ 900 A. Circles and asterisks show the speckle interferometric measurements made with the BTA 6 m telescope and the measurements made with the Subaru Telescope [14] using adaptive optics, respectively. The bars show the measurement errors.

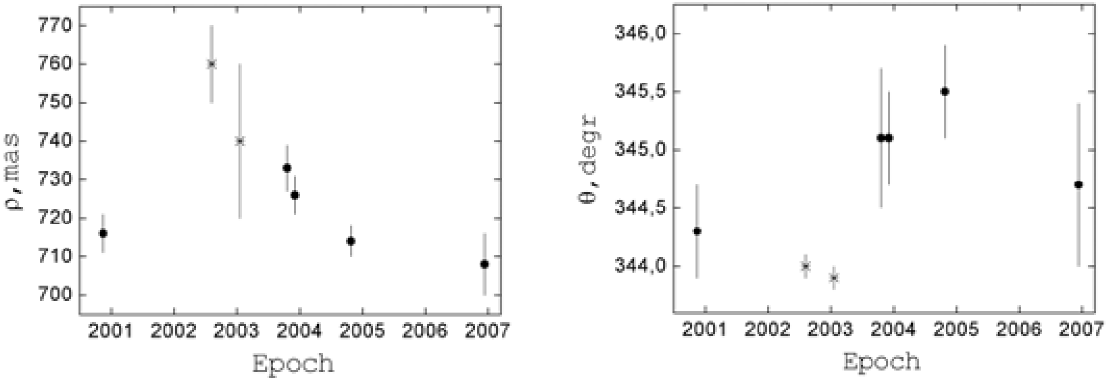

Fig. 4. Same as Fig. 3, but for GJ 900 C.

relative to component A during the observing period from 2000 to 2006. However, the mutual positions of these components changed insignificantly during our monitoring program (Fig. 3 and 4). The average annual variation in the positional parameters of component B relative to component A was equal to 4.3° and 55 mas in position angle and angular separation, respectively. The variation of the position of component C relative to component B is equal to 19.2°/yr and 57 mas/yr for θ and ρ, respectively. It follows from the relative position changes that the components B and C form an inner short-period subsystem, which moves with the component A around the GJ 900 mass center. The average annual variations of the positional parameters imply an orbital period of about 80 and 20 years for the subsystems A-BC and BC, respectively. Thus GJ 900 is a gravitationally bound hierarchical multiple system. The planes of the orbital motion of components in the subsystem BC and of component A are tilted most probably at a large angle to each other, resulting in the observed configuration.

5. THE PRESENCE OF EXTRA COMPONENTS IN THE SYSTEM

To find eventual faint components in the GJ 900 system, we analyzed the 2MASS images [36] taken in August, 2000. We found on the J, H, and K-band images a faint companion of ≈12–13 magnitude ≈ 12″ Northeast of the central object (Fig.5). The K-band image also shows another component, at ≈ 15″ South of the central source. The probability for a star to be located accidentally within the 30-arcsec field in the region studied is equal to about one percent. Hence GJ 900 is very likely to be a quadruple or even a quintuple system. From the intensity ratio it follows that the faint components are late M dwarfs.

To verify these hypotheses, I-band images of the GJ 900 vicinity were taken by A.V. Moiseev in February 2007 with the SCORPIO focal reducer on the

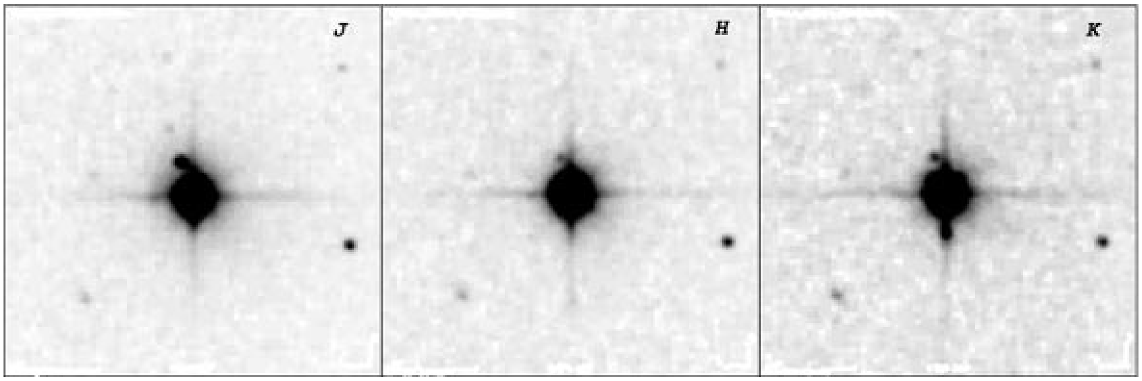

Fig. 5. J-, H-, and K-band 2MASS images of the $2.1' \times 2.1'$ region around GJ 900 [36]. North is at the top and East on the left.

BTA telescope. We took and then averaged 25 ten-second exposures. The limiting magnitude of the resulting image is 17^m, but we found no objects at the location of the northeastern component. This result suggests that either this component is too red to be seen in the I band — and this assumption is supported by the absence of the object on the I-band plate of the DSS2 survey — or that, because of the proper motion of the component or that of GJ 900, this object is now projected onto GJ 900. Hence infrared photometry is needed to make the final conclusion about the membership of components in the multiple system. If the components found do not belong to the multiple system GJ 900, they should shift considerably relative to GJ 900 since the time when the corresponding 2MASS images were taken. If the relative positions of these components remain unchanged, this object should be a unique low-mass multiple system, which is of interest for testing the theory of star formation and dynamical evolution of stars.

6. CONCLUSIONS

Speckle interferometric observations made with the BTA 6 m telescope during the period from 2000 to 2006 showed that GJ 900 is a gravitationally bound triple star. This system belongs to the population of the thin disk of the Galaxy and has an age of 200±100 Myr. The absolute magnitudes of the components are: I_A=6.66±0.08, I_B=9.15±0.11, I_C=10.08±0.26, K_A=4.84±0.08, K_B=6.76±0.20, and K_C=7.39±0.31, and their spectral types are: $Sp_A \approx$K5–K7, $Sp_B \approx$M3–M4, and $Sp_C \approx$M5–M6. We used the evolutionary tracks of Baraffe et al. [35] to compute the component masses for the solar metallicity and for the age of 200±100 Myr: $\mathcal{M}_A \approx 0.64$–$0.67\mathcal{M}_\odot$, $\mathcal{M}_B \approx 0.28$–$0.34\mathcal{M}_\odot$, $\mathcal{M}_C \approx 0.16$–$0.24\mathcal{M}_\odot$. The estimated masses and absolute magnitudes of the components agree with the results obtained in the H and K bands with the Subaru Telescope adaptive optics [14].

We estimated the orbital periods of the components, $P_{BC} \approx 20$ yr and $P_{A-BC} \approx 80$ yr, and concluded that GJ 900 is an hierarchical multiple star. We explain the comparable mutual angular separations between the components by the effect of sky-plane projection.

We examined the J-, H-, and K-band images of the 2MASS survey and found possible distant components of the GJ 900 system at $12''$ and $15''$. If these components are gravitationally bound to the triple star, GJ 900 should be a young quintuple system of red dwarfs.

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