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GLIESE 569B: A YOUNG MULTIPLE BROWN DWARF SYSTEM?[1]

Matthew Kenworthy,[2] Karl-Heinz Hofmann,[3] Laird Close,[2] Phil Hinz,[2] Eric Mamajek,[2] Dieter Schertl,[3] Gerd Weigelt,[3] Roger Angel,[2] Yuri Y. Balega,[4] Joannah Hinz,[2] and George Rieke[2]

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ABSTRACT

The nearby late M star Gliese 569B was recently found by adaptive optics imaging to be a double with separation ∼1 AU. To explore the orbital motion and masses, we have undertaken a high-resolution (∼0″.05) astrometric study. Images were obtained over 1.5 yr with bispectrum speckle interferometry at the 6.5 m Multiple Mirror Telescope (MMT) and 6 m Special Astrophysical Observatory telescope. Our data show motion corresponding to more than half the orbital period and constrain the total mass to be greater than 0.115 $M_{\odot}$, with a most probable value of 0.145 $M_{\odot}$. Higher masses cannot be excluded without more extended observations, but from statistical analysis we find an 80% probability that the total mass is less than 0.21 $M_{\odot}$.

An infrared spectrum of the blended B double obtained with the MMT has been modeled as a blend of two different spectral types, chosen to be consistent with the measured *J*- and *K*-band brightness difference of a factor of ∼2. The blended fit is not nearly as good as that to a pure M8.5+ template. Therefore, we hypothesize that the brighter component likely has two unresolved components with near equal masses, each the same as the fainter component.

If Gl 569B is a triple, our dynamical limits suggest each component has a mass of 50^{+23}_{-4} $M_{\rm Jup}$. We infer an age for the system of 300 Myr from its kinematic motion, which places it as a member of the Ursa Major moving group. All the above parameters are consistent with the latest DUSTY evolution models for brown dwarfs.

Subject headings: binaries: general — stars: evolution — stars: formation — stars: individual (Gl 569) — stars: low-mass, brown dwarfs

1. INTRODUCTION

Gliese 569 has been known for some time as a binary star 9.8 pc distant, with two M stars at a projected separation of 50 AU. The low-mass secondary (subsequently designated 569B) was found through infrared imaging (Forrest, Skrutskie, & Shure 1988). Visible imaging and low-resolution spectroscopy of this component suggested it to be an M8.5 dwarf (Henry & Kirkpatrick 1990) although rather luminous for its age when compared to other cool field dwarfs (Forrest et al. 1988). In 1999, Martín et al. (2000, hereafter M00) imaged the fainter B component with the Keck II adaptive optics system and found it to be a binary with projected separation of 1 AU and ∼0.5 mag brightness difference. A determination of the mass of the system from orbital motion is thus possible and of particular interest, since it is thought (from stellar activity indicators) to be young, between 0.1 and 1.0 Gyr (M00). At this age, the components of Gl 569B are good brown dwarf candidates. There has been little chance to test brown dwarf models against objects of known mass from direct dynamic measurement, although a lower mass limit was obtained by Basri & Martín (1999) for the spectroscopic brown dwarf binary PPl 15.

2. ASTROMETRIC IMAGING BY BISPECTRUM SPECKLE INTERFEROMETRY

We imaged the Gl 569 system with the Bonn IR speckle camera on 2000 July 4 at the new 6.5 m Multiple Mirror Telescope (MMT), 10 months after the original discovery image (M00), and again on 2001 March 9 and 10 at the Special Astrophysical Observatory (SAO) 6 m telescope in Russia. In both cases, reimaging optics were used so as to properly sample diffraction-limited speckles. At the MMT, the images were recorded in the *H* and *K* bands with pixel sizes of 18.70 ± 0.19 and 24.68 ± 0.25 mas, and at the 6 m telescope, images were recorded in both the *J* and *H* bands, with 13.33 ± 0.13 and 20.11 ± 0.20 mas, respectively. The seeing was typically 1″.0–1″.5 over all nights.

Diffraction-limited images of the triple system were reconstructed using the bispectrum speckle interferometry method described in Weigelt (1977), Lohmann, Weigelt, & Wirnitzer (1983), and Hofmann & Weigelt (1986). The bispectrum of each frame consisted of 113 million elements, and the object power spectrum was determined with the speckle interferometry method (Labeyrie 1970). The unresolved bright point source Gl 569A of the wide (5″.0) binary served as a reference star for the determination of the speckle transfer function, and the resulting images are diffraction-limited images (Fig. 1). The pixel scale was derived from measurements of several wide calibration binaries with well-known separation and position angle (with separation error ≲1% and position angle error ≲1°).

The position angles, radial separation, and associated measurement errors are given in Table 1. Also listed for completeness is the published discovery data from the Keck II telescope (M00).

3. ORBITAL SOLUTION FOR Ba/Bb

Solutions for the orbital elements of the close binary Ba/Bb were found from the three epochs of observation, using classical astrometric techniques (Aitken 1964). Although the data points are well placed to cover most of the orbit, a unique solution is not possible without more extended observations. Nevertheless, we are able to place analytically a strong lower

[1] Some of the observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

[2] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721; mak@as.arizona.edu.

[3] Max-Planck-Institut für Radioastronomie, Auf dem Huegel 69, D-53121 Bonn, Germany.

[4] Special Astrophysical Observatory, Nizhnij Arkhyz, Zelenchuk region, Karachai-Cherkesia 357147, Russia.

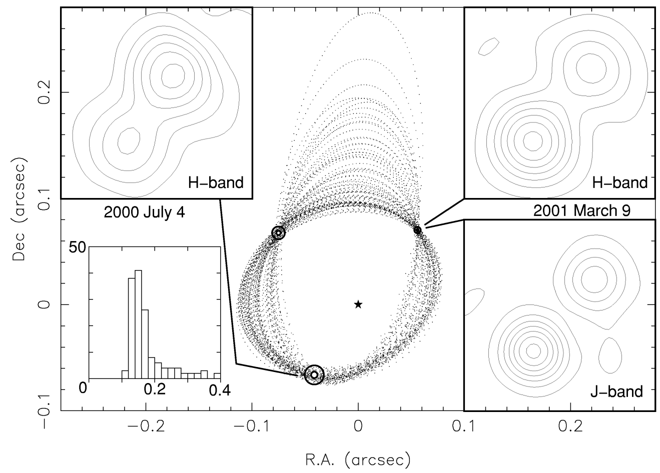

FIG. 1.—Orbital solutions found that all pass within 2 σ of each observed epoch. The inner circles are 1 σ error bars, and the outer circles are 3 σ. Ba is at the center of the frame with Bb orbiting it. The MMT and SAO bispectrum speckle images (*inset*) are shown with the highest contours at 95% of the peak value and decreasing in steps of 10%. The orbital solutions and the reconstructed images have the same scale. North is up and east is to the left for all images. The histogram in the lower left-hand corner shows the distribution of mass (in units of solar mass) for all accepted orbital solutions.

limit to the combined mass. Orbits that exactly fit the data are not possible for a combined mass of less than 0.136 $M_\odot$, and for a wide range of assumed eccentricity (0.3–0.5) the mass lies between 0.136 and 0.150 solar masses, with the corresponding periods from 2.3 to 3.5 yr and the semimajor axes lying between 0.93 and 1.25 AU.

In order to explore the effect of measurement errors and the possibility that we happened to catch a higher mass system with wider spacing at higher inclination, we constructed a Monte Carlo model. Many trial binaries were constructed with uniform distribution in total mass, ellipticity, and period. The epoch of periastron (t) was chosen randomly within the range $0 < t < P$, with P up to 10 yr, and viewing directions were modeled as from points uniformly distributed over a sphere. The ephemeris was calculated, and the calculated positions for the three observed epochs were compared with the observations. If the orbit matched the data to within 2 σ of each of the three observed data points, the orbital elements of that orbit were noted, along with the combined mass of the system.

The mass distribution found in this way is non-Gaussian (see inset of Fig. 1), with 80% in the range 0.115–0.216 $M_\odot$ and the remaining highest 20% forming a high-mass tail. We conclude that the combined mass for Gl 569B is $0.144^{+0.059}_{-0.010}$ $M_\odot$ for 20%–80% limits, with a hard lower mass limit of 0.115 $M_\odot$, consistent with the analytically derived orbital fits. Our present astrometry cannot yield the division of mass between the individual components.

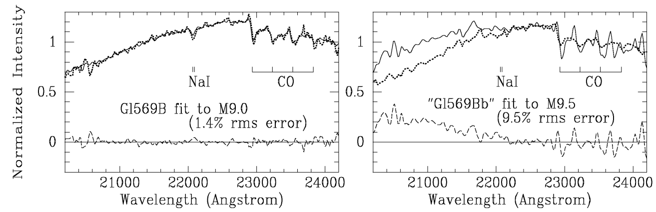

FIG. 2.—*Left*: Fit of the observed Gl 569B *K*-band spectrum (*solid line*) with our M9.0V template star (BRI 1222−1221; *dotted line*). The excellent match (residuals are plotted as the dashed line) shows that the blended light from Gl 569Ba and Bb appears consistent with just an M9.0 spectrum. *Right*: Similiar to the plot on the left except that the residual "Gl 569Bb" deblended spectrum is fitted to a M9.5 star. Even though this "Gl 569Bb" was our best deblended spectrum and M9.5 was the closest spectral match in the *K* band, it is shown to have a poor fit with a large residual error. Hence, our deblending efforts of Gl 569B's spectra into a hotter star and a cooler star are much less successful than just a pure M8.5–M9 spectrum.

4. SPECTRAL TYPES AND TEMPERATURES OF GL 569Ba AND GL 569Bb

We obtained *J*, *H*, *K* spectra of Gl 569A and the B-component blend on 2001 March 4 1230 UT at the 6.5 m MMT Observatory with the FSPEC IR spectrograph (Williams et al. 1993). FSPEC is a cryogenic long-slit near-IR (1–2.5 μm) spectrograph that we used at the low-resolution ($R \sim 700$) mode. The spectra were taken and reduced with standard IR beam-switching techniques. Terrestrial lines were removed by observing an F9 V star just before and after the Gl 569 science exposure and at a nearly identical air mass. Artifacts from the F9 V star were removed as described by Maiolino, Rieke, & Rieke (1996). The F9 and the Gl 569B spectra were extracted with standard IRAF routines and wavelength-calibrated with the OH night-sky emission lines. No contamination from Gl 569A was observed.

We have compared the observed *K*-band spectrum of Gl 569B (containing both Ba and Bb) to late M star dwarf standards taken during the same run and have modeled it as a sum of two spectra corresponding to the observed difference in *K* magnitude of 0.7. It appears that a minimization of the residuals occurs when "deblending" Gl 569Ba by 65.5% M8.0 and 34.5% M9.5. In Figure 2, we show the effective spectrum of "Gl 569Bb" assuming that 65% of Gl 569B's light is from Gl 569Ba being an M8.0 star. This "Gl 569Bb" spectrum appears in the *K* band to be closest to an M9.5 star. We also show a fit of "Gl 569Bb" to an M9.5 template and show 9.4% rms error in the fit. Even though this was our best blended fit, there are large residuals and a poor fit to the CO features. No mix of a cooler and hotter star weighted by $\Delta K = 0.7$ mag works well.

However, much to our surprise, we found that the IR (1–2.5 μm) spectrum from Gl 569B was very well fitted by a pure M9 template spectrum. The rms residual from just fitting Gl 569B to an M9 spectrum yielded a fit of only 1.4% rms error and excellent fits to the CO features. The slight residual in this

TABLE 1
MEASURED PROPERTIES OF THE GLIESE 569B SYSTEM

Epoch	Telescope	Position Angle (deg)	Separation (mas)	ΔJ	ΔH	ΔK	Resolution (mas)
1999.654	Keck 10 m[a]	48 ± 2	101.0 ± 2.0	0.5 ± 0.2	0.5 ± 0.1	0.5 ± 0.1	50
2000.501	MMT 6.5 m	148 ± 3	78.0 ± 3.0	...	0.7 ± 0.1	0.7 ± 0.1	53
2001.186	SAO 6.0 m	321 ± 1	89.6 ± 1.0	...	0.9 ± 0.1	...	57
2001.189	SAO 6.0 m	320 ± 1	89.9 ± 1.0	0.6 ± 0.1	...	0.75 ± 0.15	53

[a] Results from Martín et al. 2000 included for comparison.

TABLE 2
MEASURED EQUIVALENT WIDTHS FOR Gl 569B

Star	K I 11690 Å	K I 11770 Å	K I 12440 Å	K I 12530 Å	H_2 1.34/1.29 μm	*K*-Band Spectral Type 2.05–2.40 μm	Adopted Spectral Type	Adopted T_{eff}[a] (K)	Typical ($J-K$) for Adopted Spectral Type[b]
Gl 569B	5.48 (M8)	7.52 (M9)	9.93 (M9)	9.44 (M8.5)	0.76 (M9)	M8.5+	M8.5+	2150 ± 75	1.20
"Gl 569Bb"	10.13 (L3)	10.42 (L3)	13.00 (L3)	12.80 (L3)	0.68 (L1)	M9.5	M9.5–L3	1985 ± 120	1.45
M8 template[c]	5.29 (M8)	7.12 (M8.5)	8.72 (M8.0)	7.40 (M7.5)	0.81 (M7)	M8.0	M8.0	2225 ± 75	1.05

NOTE.—All spectral types fitted to the spectral type indices of Reid et al. 2001.
[a] Temperature scale from Leggett et al. 2001.
[b] Typical colors from Reid et al. 2001.
[c] Our M8 template star was 2MASSW J1444171+300214.

fit of the Na doublet might be due to low surface gravity (Luhman et al. 1998) or to low-level coronal activity.

We examined our *J* spectra and measured the equivalent widths for both the K I doublets and the steam feature at 1.34 μm (see Table 2). Based on these measurements and the best spectral type indices of Reid et al. (2001), we find that Gl 569B is easily and consistently classed as M8.5–M9 (M8.5+) with a T_{eff} of 2150 ± 75 K from the template scale of Leggett et al. (2001). These temperature errors do not take into account the ~300 K systematic offsets between different models; ±75 K is simply a relative temperature error. This choice of temperature scale is optimal since the same Ames dusty atmospheric features and opacities were used in the full DUSTY tracks (Chabrier et al. 2000, 2001) and so any systematic offsets in the stellar temperatures and the DUSTY model temperatures are minimized with this choice of temperature scale. Moreover, as discussed in Leggett et al. (2001), this temperature scale has a relative accuracy (±75 K) for the M7–L3 spectral type considered here, where dust opacity plays a large role.

Again, when we attempt a separation as two components of different brightness, the *J*-band residual spectrum "Gl 569Bb" extracted from the Gl 569B spectrum appears poorly fit by any template. However, we can classify this "Gl 569Bb" somewhere in the M9.5–L3 range with a T_{eff} of 1985 ± 120 K. The large error in this T_{eff} again suggests that this extracted "Gl 569Bb" spectrum is not physical and so does not match any spectral type well. Therefore, it appears both Bb and Ba are best fitted by an M8.5+ spectrum for both the bright and faint components.

5. AGE OF THE GLIESE 569 SYSTEM

Since age is critical to expected luminosity for such late stars, we have examined the kinematic evidence, with a view to obtaining a more accurate estimate. We calculate the heliocentric *UVW* velocity for Gl 569A using the proper motion and parallax from *Hipparcos* (HIP 72444) and the radial velocity of Marcy, Lindsay, & Wilson (1987; $v_r = -7.17 \pm 0.28$ km s^{-1}) and employ a Galactic motion vector algorithm (J. Skuljan 2000, private communication). We find a *UVW* vector of (+7.8, +3.2, −13.3) km s^{-1}, with uncertainties of (0.2, 0.1, 0.3) km s^{-1}. Comparing this vector with the Soderblom (1990) scatter plots of the *UVW* motions of nearby active dwarfs, we noticed that it is very close to that of the Ursa Major (UMa) moving group (+12.6, +2.1, −8.0; Soderblom et al. 1993), with Gl 569 within 7.2 km s^{-1} of Soderblom's space motion for the UMa group.

The age of the UMa nucleus is ≃0.3 Gyr (Soderblom et al. 1993); however, there is a somewhat larger spread in age when one examines the early-type stellar content of the UMa moving group on larger scales (Asiain et al. 1999; Chen et al. 1997). From the correlation between the young age inferred from stellar activity indicators, and the kinematic similarity between Gl 569 and the UMa moving group, we suggest that it is a member of the moving group with an age of 0.3 ± 0.1 Gyr. We also note that the slightly subsolar metallicity of Gl 569A ([M/H] = −0.15; Zboril & Byrne 1998) is similar to the value for the UMa nucleus stars ([Fe/H] = −0.08 ± 0.09; Soderblom et al. 1993).

6. DISCUSSION

We have seen in § 4 that the blended spectrum of Ba/Bb matches that of a single M8.5+ star with much smaller residuals than a blend of an M8.0 and M9.5 star. We therefore postulate that all the light from Gl 569B (containing both Ba and Bb) is from an M8.5+ spectral type. Moreover, we have independently found that the $\Delta J-\Delta K$ differential colors of the Ba and Bb components are −0.10 ± 0.14 mag, in close agreement with the value of 0.0 ± 0.14 observed by M00. Therefore, we see no evidence of Bb being any redder than Ba while

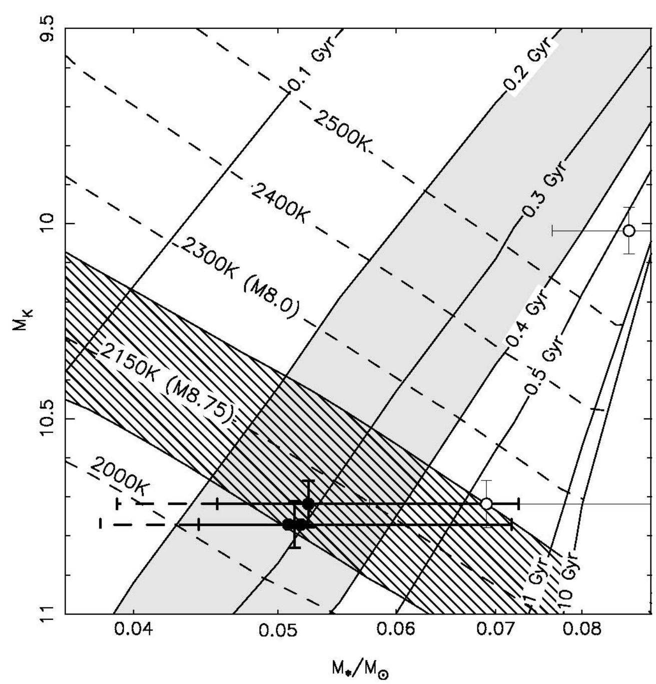

FIG. 3.—Mass-M_K diagram for Gl 569Ba/Bb for the cases where Ba is either a single or a double star. The shaded isochrones represent the estimated age range for the UMa stream. The open circles represent the positions of Ba and Bb if Ba is a single star. The filled circles represent Ba and Bb if Ba is treated as an equal mass binary. In both cases, mass error bars are for 1 σ confidence limits and the hard lower mass limit is represented as a dotted extension to the mass error bars. The isotherms have spectral types associated with them according to models from Chabrier et al. (2000) and Leggett et al. (2001).

appearing only half as bright! As Table 2 points out, the expected $\Delta J - \Delta K$ color for a binary composed of an M8.0 and a M9.5 star is $\Delta J - \Delta K = (J-K)_{\rm M9.5} - (J-K)_{\rm M8.0} = 0.30$ mag. Since 0.3 mag is inconsistent (at 3 σ) with the $\Delta J - \Delta K = -0.10 \pm 0.14$ observed, it is difficult to understand how Gl 569B can be composed of two stars of different spectral types.

It appears that both Gl 569Ba and Gl 569Bb have the same temperature. However, since Gl 569Ba is 1.9 ± 0.2 times as bright as Gl 569Bb, the most logical explanation for this overluminosity is that Gl 569Ba is itself a binary star (as first suggested by M00). Moreover, the lack of any blended spectral features cooler than M9 in the Gl 569B spectra argue that the Gl 569Ba binary is likely composed of two stars both close to M8.5–M9.0 in spectral type. Hence, we conclude that Gl 569Ba is most likely a close ($\lesssim$0.1 AU) binary with nearly equal magnitude components. Therefore, the Gl 569B system becomes a hierarchical triple with Gl 569Bb orbiting around a binary, Gl 569Baa and Gl 569Bab. All three of these stars should have nearly identical M8.5+ spectral types and therefore very similar masses.

We now examine the models of Chabrier et al. (2000, 2001) and see how treating Ba/Bb as a double system compares to a triple-system model. In order to do this, we adopt the photometry of the combined Gl 569B system from Forrest et al. (1988), who measured $K = 9.56 \pm 0.1$. The individual absolute magnitudes follow from our measured brightness ratios given in Table 1 and the parallax $d = 101.91 \pm 1.67$ mas from *Hipparcos* (Perryman et al. 1997). We take the values to be $M_K({\rm Ba}) = 10.02 \pm 0.12$ mag and $M_K({\rm Bb}) = 10.72 \pm 0.12$ mag.

Figure 3 shows Ba/Bb considered both as a double system (*open circles*) and as a triple system with Ba composed of two equal-mass objects (*filled circles*). For the binary case, it is clear that although Bb gives marginal agreement to its uncertain spectral type of M9–L3, it is Ba that stands out as an object much more luminous than spectral fitting and typing to an M8.0 would suggest. However, considering B to be a triple system results in all three components of nearly equal mass (the two Ba components are 0.049 $M_\odot$ each, and Bb is 0.057 $M_\odot$), a spectral type consistent with an M8.5+ star, $\Delta J - \Delta K \sim 0$ (as observed), and a model age in good agreement with a kinematically derived age of 0.3 ± 0.1 Gyr.

The astrometric and spectroscopic results presented here suggest that Gl 569B is a young hierarchical triple brown dwarf system with three nearly equal components of $\sim 50^{+23}_{-4}$ $M_{\rm Jup}$ each and a dynamically constrained lower mass sum of $M = 0.115$ $M_\odot$. The work reported here must therefore be regarded as simply a step to understanding what promises to be a key brown dwarf system. Continued high-accuracy astrometric measurements, as represented by our third epoch measure (± 1 mas), should yield an accurate and unambiguous total mass for the system. Furthermore, by careful calibration of plate scale, accurate measurement of the individual motions of the two stars should be possible, so individual masses can be derived with no recourse to theoretical models, and high-resolution spectroscopy is required to see if Ba is indeed a spectroscopic binary.

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