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A POSSIBLE BROWN DWARF COMPANION TO GLIESE 569

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ABSTRACT

A faint, cool companion to Gliese 569 discovered during an infrared imaging survey of nearby stars may be the lowest mass stellar object yet found. The companion is somewhat cooler in its 1.65–3.75 μm energy distribution than the coolest known main-sequence stars, indicating a low mass. Despite its lower temperature, it is more luminous than similar extremely low-mass stars, suggesting that it is either a young low-mass star evolving toward the main sequence or a cooling substellar brown dwarf. The primary star has emission lines, a low space velocity, and exhibits flaring, all of which imply youth for this system. Observations of Gliese 569 and its companion over a period of 2 yr confirm the common proper motion expected of a true binary. The 5″ apparent separation (50 AU) implies an orbital period of roughly 500 yr which will permit an eventual direct determination of the mass of the companion.

Subject headings: infrared: sources — stars: late-type

I. INTRODUCTION

The lowest mass stars, despite being the most numerous constituents of the Galactic disk, are among the most elusive and poorly understood objects (see Liebert and Probst 1987 for a review). Because of their low temperatures, <3000 K, they are intrinsically dim and emit most of their energy in the infrared ($\lambda > 1$ μm). Particular interest surrounds the lowest mass stars, which can burn hydrogen and stabilize on the main sequence, and the less massive brown dwarfs, which subsist on gravitational energy and cool eternally. The minimum mass necessary for hydrogen ignition is not known precisely, but it is probably in the range 0.075–0.09 $M_{\odot}$ (cf. D'Antona and Mazzitelli 1985). The physics of the interiors and atmospheres of these low-mass objects is quite different than their higher mass counterparts and presents a challenge to both theoreticians and observers. The appearance of these objects depends critically on their atmospheres, which are fairly complex owing to molecular and grain opacity. The lowest mass stars and brown dwarfs could provide a solution to the Galactic disk missing mass problem if they are numerous enough.

To date only a handful of extremely low-mass stars have been observed and there are no confirmed brown dwarfs. It is crucial for further progress in this field to identify and scrutinize a large number of candidates, particularly those at or below the hydrogen-burning mass limit. Consequently Skrutskie *et al.* (1986) conducted a near-infrared imaging survey of 60 nearby stars to search for cool, dim companions. This *Letter* describes the successful detection of a dim red companion to Gliese 569 (=BD +16°2708, Vyssotsky/McCormick 157, Giclas 136–28, Yale 3372, hereafter Gl 569). The companion is either a very low mass star or else a cooling brown dwarf. The interpretation of the nature of Gliese 569B depends strongly on the age of the binary pair; if the age is less than 200 million years, the companion is most likely a brown dwarf.

II. OBSERVATIONS

Infrared observations of Gl 569 (dM2e) were made at the NASA 3.0 m Infrared Telescope Facility on Mauna Kea on the night of 1985 July 28–29 using the Rochester 32 × 32 InSb infrared CCD camera (Forrest *et al.* 1985). After the initial *K*-band (2.23 μm) images showed a possible companion about 5″ north of the primary, images at *H* (1.65 μm) and *L*′ (3.75 μm) were obtained. The calibration of these images followed the procedures outlined by Forrest *et al.* (1985) and Forrest, Pipher, and Stein (1986). Various candidate flat fields were evaluated according to the consistency of a given stellar source imaged at six distinct positions on the array. For the *H* and *K* bands, an out-of-focus image of a lunar mare through a narrow band 3.26 μm filter gave the best photometry. For the *L*′ exposures, the interior of the dome at 4.67 μm gave the best photometry. Observations of standard stars before and after observing Gl 569 were used to calibrate the system responsivity.

The photometric accuracy was tested further through observations of VB 8 obtained 40 minutes after the Gl 569 observations (Skrutskie, Forrest, and Shure 1987). Using the same calibration techniques, we obtained $K = 8.76$ and $L' = 8.27$ mag for VB 8. These are in good agreement with other observers' values as shown in Table 1. They also emphasize the redness of Gl 569B ($K - L' = 0.63$) compared to VB 8 ($K - L' = 0.49$).

The plate scale and orientation of the infrared focal plane was determined by observing four star pairs as discussed in Forrest, Pipher, and Stein (1986). The plate scale at K was

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TABLE 1

STELLAR MAGNITUDES AND OTHER DATA

Parameter	VB 8	VB 10	LHS 2924	Gl 569B[a]
I	...	...	...	(13.88) ± 0.2
H	...	...	...	10.16 ± 0.1
K	8.82[b]	8.82[b]	10.68[b]	9.56 ± 0.1
L'	...	...	...	8.93 ± 0.1
$I - K$	3.46[b]	4.07[b]	4.62[b]	(4.32) ± 0.2
$H - K$	0.36[b]	0.44[b]	0.49[b]	0.60 ± 0.05[c]
$K - L$	0.34[d]	0.30[d]	...	...
$K - L'$	0.51[e]	...	...	0.63 ± 0.1
T_c(K)[f]	3250	3000	2750	2475 ± 100
$m - M$	−1.0[g]	−1.2[g]	0.1[h]	0.1 ± 0.24
M_H	10.2	10.5	11.1	10.1 ± 0.26
M_K	9.8	10.0	10.6	9.5 ± 0.26
Sp	M7 V[d]	M8 V[d]	M9[h]	...

[a] Data from this *Letter*; see text.

[b] Data from Probst and Liebert 1983 and McCarthy *et al.* 1985

[c] The uncertainty in the $H - K$ color (±0.05 mag) is smaller than the individual magnitudes (±0.1 mag) because many of the systematic effects which dominate the latter tend to cancel out in the former. Uncertainties due to the flat-field are reduced because the star was imaged on the same region of the array. Photometric uncertainties caused by the bright companion are substantially reduced because the same aperture sizes were used and the H and K images were very similar in quality. Finally, we have found that variations in system sensitivity due to the sky, telescope, or detector are highly correlated between H and K and will therefore tend to cancel in the $H - K$ color.

[d] Data from McCarthy *et al.* 1985.

[e] Data from Berriman and Reid 1987.

[f] T_c is the infrared color temperature derived from the J, H, and K fluxes by Probst and Liebert 1983 and the infrared fluxes for Gl 569B here assuming 1047, 641, and 256 Jy for a zero-magnitude star (i.e., α Lyr) at 1.65 (H), 2.23 (K), and 3.75 (L') μm, respectively.

[g] Data from Probst and Liebert 1983.

[h] Data from Giampapa and Liebert 1986.

0".437 ± 0".006 pixel^{-1} and the columns of the array were oriented at a position angle of 0°.7 ± 0°.4 E of N. A contour map of the K image is shown in Figure 1, and the brightness of the companion in stellar magnitudes is given in Table 1. The separation of 569B from 569A was 5".07 at 17°.5 P.A. (Table 2).

The very red colors of the companion($H - K = 0.6$ mag) make it a very interesting object, either a very low-mass star or a brown dwarf, if it is a true companion to Gl 569. A key test of this is common proper motion. Therefore a second epoch image of this system was obtained, to check for common proper motion and extend the spectral coverage. I-band images ("KPNO Mould System," $\lambda_0 = 0.830$ μm, 0.193 μm FWHM) were obtained by Alan Stockton using a 800 × 800 CCD and the University of Hawaii 2.2 m telescope on Mauna Kea on 1987 September 18 UT. There was thick and variable cloud cover, so only the difference in I magnitude between the primary and companion could be estimated. This difference, combined with the estimate of $I = 8.08$ for the primary Eggen 1968, 1987) gives the I magnitude of Table 1.

The position of the secondary relative to the primary was determined from two independent I-band images as follows. Because the Gleise star field is so devoid of stars, the scale and orientation of the CCD pixels were determined from seven stars in the field of the galaxy Markarian 509, imaged shortly afterward. The corresponding Palomar Sky Survey print was used to calculate the calibration star coordinates using SAO stars on the same print. The resulting plate scale was 0".139 ± 0".001 pixel^{-1} and the columns of the CCD were oriented at a position angle of 2°.4 ± 0°.5 E of N. Table 2 gives the derived separation. The K (1985.6) and I (1987.7) positions are shown

TABLE 2

SEPARATIONS OF GLIESE 569A TO 569B

Image	R.A. × cos (decl.)	Decl.
K-band, 1985.6	1".52 ± 0".15	4".84 ± 0".15
I-band, 1987.7	1.49 ± 0.15	4.78 ± 0.15
Change A to B, 2.1 yr	0.03 ± 0.21	0.06 ± 0.21
Proper motion, 2.1 yr	0.65[a]	−0.29[a]
Orbit motion, 2.1 yr	±0.13[b]	...

[a] Proper motion of Gl 569A (W. van Altena 1987).

[b] The possible orbital motion is for a nominal 500 yr circular orbit seen pole-on and a negligible companion mass.

in Figure 2 compared to the proper motion of Gl 569A in 2.1 yr.

III. DISCUSSION

a) True Binary Companion

From Table 2 and Figure 2, it can be seen that during the 2.1 yr of observation in which Gl 569 traveled approximately 0".71 on the sky, the companion precisely followed it within our observational uncertainty of 0".21. This common proper motion is strong evidence that the pair represents a true physical system. The statistical significance of this result is greater than 3 σ, so a chance alignment with a foreground or background object is extremely unlikely. Nevertheless, we consider further if the red companion could be aligned with Gl 569 by chance.

The probability of a chance alignment with any known type of object is extremely small. At the high Galactic latitude

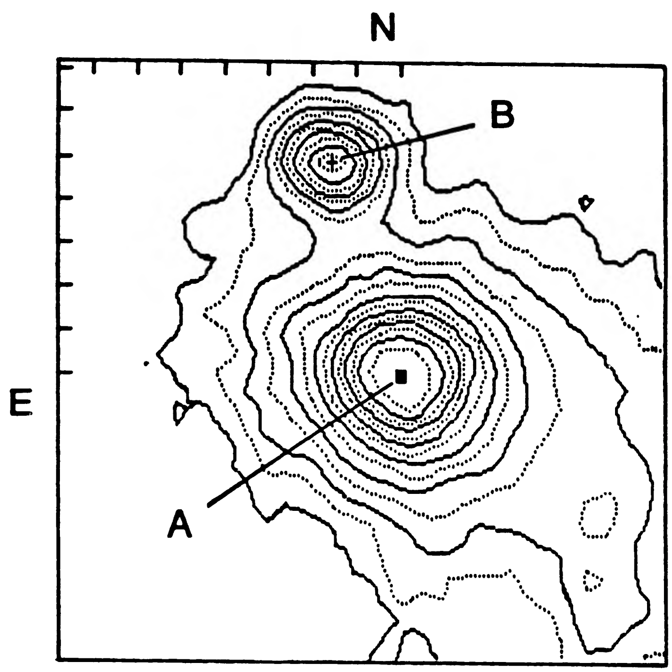

FIG. 1.—K-band (2.23 μm) image of Gliese 569A (14^{h}52^{m}08^s + 16°18'.3 [1950]) and 596B. Equal surface brightness contours are shown at 0.5 mag intervals from 16.25 to 9.75 mag pixel^{-1} with every other contour dotted. The Gl 569B peak brightness is 11.50 mag pixel^{-1}, and its integrated K magnitude is 9.56. The center of the Gl 569A image is saturated. Tick marks every 1" N and E of Gl 569A are shown on the border. Stellar images were approximately 0.95" × 0.98" FWHM in the NS × EW directions. The diffuse emission to the SW of 569A is due to scattered light from 569A.

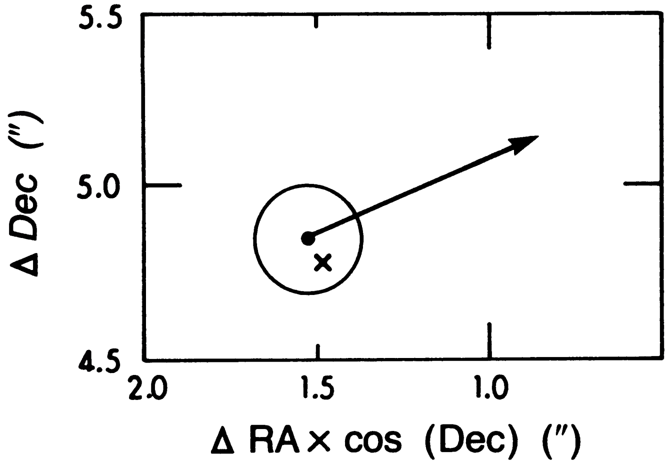

FIG. 2.—Positions of Gliese 569B relative to 569A compared to the proper motion of 569A in 2.1 yr. The solid dot marks the 1985.6 relative position. The circle is its uncertainty (±0″.15). The arrow shows minus the proper motion. If Gl 569B had negligible proper motion, its 1987.7 relative position (marked with an X) would have been at the tip of the arrowhead. Thus Gl 569A and 569B clearly share common proper motion.

(+59°) of Gl 569, stars are rare, and stars as red as the companion are very rare. Essentially all known stars this red at high Galactic latitudes are red giants, which are very luminous. To appear at an apparent K magnitude of 9.6, a red giant would have to be 18–27 kpc distant or 10–23 kpc above the Galactic plane. Since the scale height for these stars is less than 1 kpc, this is very unlikely. A background galaxy is also implausible. The object is stellar, $< 1''$ diameter, and too red for typical galaxies. We conclude that the faint, red, common proper motion object is a true binary companion to Gl 569.

b) Cool Energy Distribution and Luminosity

As shown in Table 1, the 1.65–3.75 μm broad-band spectrum, which includes the peak of its energy distribution, is cooler than the reddest dwarf stars previously known, LHS 2924 and VB 10. The less well-determined I-band magnitude also indicates a very red $I - K$ color, though not as red as LHS 2924. The infrared measurements can be nicely fitted by a 2475 ± 100 K blackbody curve, significantly cooler than the 2750–3000 K shape of the VB 10 and LHS 2924 broad-band distributions (Probst and Liebert 1983). Taken at face value, this indicates a cooler photosphere, a later spectral type, and a lower mass for this object.

W. van Altena (1987) has reviewed the data on Gl 569A and concludes that the trigonometric parallax is 0″.0956 ± 0″.0114 (standard error) corresponding to a distance of 10.5 pc. This gives absolute magnitudes of 10.1 at H and 9.5 at K for Gl 569B, which are 0.5–1 mag brighter than VB 10 and LHS 2924 (Table 1). Since these wavelengths monitor the peak of the energy distribution for stars of these temperatures, this implies Gl 569B is 0.5–1 mag more luminous. This is quite important since redder and cooler main-sequence stars are invariably *less* luminous. The parallaxes for both Gl 569 and LHS 2924 should be determined more accurately to confirm this result. The present data on the luminosity and color of Gl 569B indicate a position *above* the main sequence on the observational Hertzsprung-Russell diagram.

c) Type of Object

There are several possible identifications for the red companion. First, it could be red because of unusual abundances in the atmosphere and actually be a star as hot as the luminosity indicates. This seems unlikely because all of the colors $I - K$, $H - K$, and $K - L'$ (see Table 1) indicate approximately the same degree of redness compared to the coolest stars previously observed. Further, the primary is classified as dM2e by Joy and Abt (1974), with no indications of unusual abundances. The high-resolution spectra of Marcy (1987) confirm the normal metal abundances of the primary. Since we have concluded that the red object is a true companion, it should have the same abundances as the primary.

Next, the red object could actually be a close binary. If the components were *identical*, each would be 0.75 mag dimmer than is listed in Table 1. This would make each of the components similar to VB10 and LHS 2924 in brightness and redness. The image of Gl 569B (Fig. 1) shows no hint of any significant elongation which implies less than 0″.5 (5 AU) for the apparent separation. Therefore we consider this to be somewhat improbable.

The most interesting possibility for the red object is that it is a very low-mass star, or perhaps a brown dwarf, which is still in the process of contraction and cooling. The theoretical evolution of these objects has been studied by D'Antona and Mazzitelli (1985), Stringfellow (1986), and Nelson, Rappaport, and Joss (1986). They find that brown dwarfs with masses 0.04–0.06 $M_\odot$ will traverse the H-R diagram just above the positions of the lowest mass stars (0.08–0.09 $M_\odot$) at an age between 10^8 and 10^9 yr. The age to reach a given luminosity is a strong function of the mass. For the approximate luminosity of Gl 569B ($10^{-3.2}$ $L_\odot$), this ranges from <2–3×10^8 yr for $M < 0.075$ $M_\odot$ (i.e., probably a brown dwarf) to >4–10×10^8 yr for $M > 0.09$ $M_\odot$ (i.e., probably a star). Thus if Gl 569B is young ($<2 \times 10^8$ yr), it is probably a brown dwarf, and if it is old ($>10^9$ yr), it is more likely to be a low-mass star. Between these ages, it could be either type of object, given the current uncertainties in the theoretical evolution of such objects. To distinguish between the possibilities, the age of Gl 569B is needed. Fortunately, the age of the primary, Gl 569A, will give a very good estimate of this, since they undoubtedly formed at the same time. Therefore we consider indications of the age of Gl 569A.

d) The Age of the System

There are several physical parameters of stars in the solar vicinity which indicate age. These include the space velocities, rotational velocity, chromospheric activity, lithium abundance, and luminosity and color compared to the zero-age main sequence. As discussed below, the age indicators for Gl 569A are consistent with a relatively young age.

Stars of the young disk population, with ages less than that of the Hyades (about 6×10^8 yr), show generally low space motion with respect to the local standard of rest (Eggen 1969*b*). Gl 569A has a relatively low proper motion (Table 2) and a small radial velocity (-7.0 km s^{-1}; Marcy, Lindsay, and Wilson 1987). The resulting $U = -10$ km s^{-1}, $V = 4$ km s^{-1}, and $W = -15$ km s^{-1} space velocities put it firmly in the young disk region of the space motion groups as defined by Eggen (1969*a*, *b*). We use the Eggen (1969*b*) sign convention for U, i.e., directed away from the Galactic center.

An active chromosphere and rapid rotation indicate a youthful star, provided that it lacks a close binary companion which could tidally influence it. Evidently, stars when formed tend to rotate rather rapidly and as they age, the rotation rate decreases. As discussed by Stauffer and Hartmann (1986*b*), the $V \sin i$ rotation rate is statistically correlated with stellar age for single dwarf M stars. For stars later than dM0 in the Pleiades (age $\approx 70 \times 10^6$ yr), approximately one-third have $V \sin i \leq 10$ km s^{-1} while one-third have $V \sin i > 45$ km s^{-1}. In the Hyades (age $\approx 6 \times 10^8$ yr), two-thirds of the M dwarfs have $V \sin i \leq 10$ km s^{-1} while one-third are in the 15–25 km s^{-1} range. In contrast, dwarf M stars lacking Hα emission, which are typically much older, show no detectable rotation (<10 km s^{-1}). Marcy (1987) has made a preliminary analysis of his high-resolution visible spectra of Gl 569A and finds no evidence for rapid rotation. We estimate an upper bound of 3–10 km s^{-1} for $V \sin i$. Statistically, this result implies an age more akin to that of the Hyades or older, but many slow rotators are found in young clusters such as the Pleiades. In addition, a pole-on geometry would mask a rapid rotation of the star.

Active chromospheres, leading to line emission and flaring, are believed to be by-products of rapid rotation in conjunction with convection. Consequently the presence of emission lines in an isolated star indicates extreme youth. The radial velocity measurements of Gl 569A by Marcy, Lindsay, and Wilson (1987) rule out a companion close enough to tidally influence it. Therefore, the presence of Hα in emission in this dM2e star suggests an age less than 10^9 yr (Stauffer and Hartmann 1986*a*). A preliminary analysis of the spectra of Marcy (1987) indicate an Hα equivalent width around 1 Å. This is on the low side of the distribution of line strengths seen in the Pleiades for dM2 stars ($R - I = 0.8$–1.0) and appears to be more typical of Hyades age stars (Stauffer and Hartmann 1986*a*), though their data set for the Hyades is less complete.

A further sign of youth is flaring. Gl 569A has been observed to flare in the continuum by Eggen (1968, 1987). Marcy (1987) has also noted variability in the Hα emission line on time scales as short as a month.

IV. CONCLUSIONS

The red, pointlike object found approximately 5″ from the nearby star Gl 569 is almost certainly a true binary companion. Kepler's law gives an orbital period of order 500 yr, which would explain the lack of astrometric or radial velocity perturbations seen to date. The red colors in the infrared indicate a temperature somewhat lower than the benchmark reddest known dwarfs, VB 10 and LHS 2924. Therefore, it is probably a cooler and less massive object. Surprisingly, the intrinsic brightness in the 1.65 to 2.23 μm region (H and K bands), which monitors the total luminosity for stars of these temperatures, is 0.5–1.0 mag brighter than VB 10 and LHS 2924. From Planck's law this implies a larger size for Gl 569B, indicating that it is either a very low mass star or a brown dwarf which has been caught in the process of contraction and cooling. The age of the star should allow us to distinguish between these possibilities. An age less than 2×10^8 yr would favor the brown dwarf solution while an age greater than 10^9 yr indicates a low mass star to be. Since its age must be close to that of the primary, these hypotheses can be tested cleanly.

The primary is known to be isolated and exhibits many of the attributes of young stars. The low space velocities, the hydrogen and Ca II emission lines, and the flaring activity all suggest a young star. On the other hand, preliminary spectral analysis by Marcy (1987) shows no evidence for a high rotation rate or large lithium abundance. Based on the above, the most likely age range is between that of the Pleiades (70×10^6 yr) and Hyades (6×10^8 yr).

A direct measurement of the mass of Gl 569B would most clearly discriminate between a brown dwarf and a low-mass star. This will be possible eventually through observation of the orbit of Gl 569B and Gl 569A around their center of mass. The orbital motion of Gl 569B might be detectable in a few years but observation of the orbital motion of Gl 569A, which is 5–10 times smaller than that of 569B owing to the difference in mass, will probably require decades. Determination of the mass of 569B will require observation of a significant fraction of the orbit of the pair over the next century. It is important to acquire accurate positional data for Gl 569A now so that the mass of Gl 569B can be determined.

A more accurate estimate of the age for this system is needed in order to compare the temperature and luminosity of Gl 569B to theoretical low-mass evolutionary tracks. Photometric studies might reveal the rotation rates of Gl 569A and, with difficulty, 569B. More accurate measurements of the parallax and metallicity of the primary are needed to assess whether it is slightly overluminous, and therefore probably quite young, as indicated by the photometric parallax of Eggen (1968).

As emphasized by Berriman and Reid (1987), spectra in the infrared are needed to estimate the effective temperatures and luminosities of the least massive stars due to their deep molecular absorption features. The effective temperatures are particularly uncertain because of the relatively low spectral resolution in the infrared attained to date and the lack of detailed theoretical spectral sequences for comparison. Higher resolution infrared spectra of Gl 569B and the other very red dwarfs are needed in order to place them accurately on the Hertzsprung-Russell diagram and compare them to the theoretical evolutionary models.

Finally, the theoretical evolutionary tracks need to be refined, to pin down ages versus mass and luminosity more precisely. Accurate theoretical stellar atmospheres for these objects are needed in order to determine their effective temperatures.

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REFERENCES

Berriman, G., and Reid, N. 1987, *M.N.R.A.S.*, **227**, 315.
D'Antona, F., and Mazzitelli, I. 1985, *Ap. J.*, **296**, 502.
Eggen, O. J. 1968, *Ap. J. Suppl.*, **16**, 49.
———. 1969*a*, *Ap. J.*, **155**, 701.
———. 1969*b*, *Pub. A.S.P.*, **81**, 553.
Eggen, O. J. 1987, private communication.
Forrest, W. J., Moneti, A., Woodward, C. E., Pipher, J. L., and Hoffman, A. 1985, *Pub. A.S.P.*, **97**, 183.
Forrest, W. J., Pipher, J. L., and Stein, W. A. 1986, *Ap. J. (Letters)*, **301**, L49.
Giampapa, M. S., and Liebert, J. 1986, *Ap. J.*, **305**, 784.

Joy, A. H., and Abt, H. A. 1974, *Ap. J. Suppl.*, **28**, 1.
Liebert, J., and Probst, R. G. 1987, *Ann. Rev. Astr. Ap.*, **25**, 473.
Marcy, G. W. 1987, personal communication.
Marcy, G. W., Lindsay, V., and Wilson, K. 1987, *Pub. A.S.P.*, **99**, 490.
McCarthy, D. W., Jr., Probst, R. G., and Low, F. J. 1985, *Ap. J. (Letters)*, **290**, L9.
Nelson, L. A., Rappaport, S. A., and Joss, P. C. 1986, *Ap. J.*, **311**, 226.
Probst, R. G., and Liebert, J. 1983, *Ap. J.*, **274**, 245.
Skrutskie, M. F., Forrest, W. J., and Shure, M. A. 1986, in *Astrophysics of Brown Dwarfs*, ed. M. C. Kafatos, R. S. Harrington, and S. P. Maran (Cambridge: Cambridge University Press), p. 82.
Skrutskie, M. F., Forrest, W. J., and Shure, M. A. 1987, *Ap. J. (Letters)*, **312**, L55.
Stauffer, J. R. 1987, private communication.
Stauffer, J. R., and Hartmann, L. W. 1986*a*, *Ap. J. Suppl.*, **61**, 531.
———. 1986*b*, *Pub. A.S.P.*, **98**, 1233.
Stringfellow, G. S. 1986, in *Astrophysics of Brown Dwarfs*, ed. M. C. Kafatos, R. S. Harrington, and S. P. Maran (Cambridge: Cambridge University Press), p. 190.
van Altena, W. F. 1987, private communication.

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