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THE SOLAR NEIGHBORHOOD. III. A NEAR-INFRARED SEARCH FOR WIDELY SEPARATED LOW-MASS BINARIES

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ABSTRACT

A near-infrared survey designed to detect widely separated, very low-mass companions to M dwarfs within 8 pc is described. This survey is unique in that it is sensitive to companions with separations of ~100–1400 AU from primaries and with masses down to the 0.03 $\mathscr{M}_\odot$ level, thereby sampling rarely explored parameter space. In Phase I of this program, described here, candidate stellar and brown dwarf companions are identified by creating color–magnitude plots of all detected point sources in the fields surrounding primaries and searching for objects that are bright enough to be stellar ($M_J \leqslant 11$) or that fall close to theoretical brown dwarf isochrones like GD 165B ($M_J \sim 13$). Common proper motion and spectroscopic checks are used to screen candidates. To date, all candidates for which we have made follow-up observations have been identified as background sources and no new low mass stellar or brown dwarf candidates have emerged from this survey. Phase II of this program will include a search for common proper motion between primaries and *all* field objects to $M_J \sim 17.5$, allowing identification of widely separated substellar components, including objects like GL 229B. © *1996 American Astronomical Society.*

1. INTRODUCTION

This is the third in a series of papers dedicated to observations of stars in the solar neighborhood [see Henry *et al.* (1994), hereafter TSN1 and Kirkpatrick *et al.* (1995), hereafter TSN2]. Using a variety of observations, including optical and infrared spectroscopy, infrared speckle imaging, and wide-field infrared imaging, we are providing a comprehensive description of nearby M dwarfs, which account for 80% of the stars in the solar neighborhood. Despite their great numbers, our current understanding of M dwarfs remains rather poor. Given the important role of these stars in the total mass of the Galaxy, the dynamics of clusters, star formation theory, and their similarities to brown dwarfs, a better understanding of the basic properties of M dwarfs stands to impact a number of research fields in fundamental ways.

In TSN1 standard spectral types were given for late-type dwarfs within 8 pc of the Sun and an empirically derived relation between spectral type and M_V was used to identify additional M dwarfs that lie within 8 pc. TSN2 provided spectra and finder charts for 20 extreme M dwarfs ($\geqslant M7$), and work dedicated to finding additional nearby low-mass M dwarfs was presented. In this paper, TSN3, we discuss a wide-field near-infrared search for very low-mass stellar and substellar companions to nearby M dwarfs. Many searches for low-mass companions orbiting nearby M dwarfs have been completed recently or are currently underway. These include radial velocity studies for close companions at separations less than a few AU (Marcy & Benitz 1989; Campbell *et al.* 1988), infrared speckle searches for companions separated from primaries by 1–10 AU (Henry & McCarthy 1990; Henry 1991), deep infrared imaging of M dwarfs (Skrutskie *et al.* 1989; Rieke & Rieke 1989) and infrared photometry of white dwarfs (Zuckerman & Becklin 1987, 1992) covering regions out to a few hundred AU. Though these surveys are beginning to define the low-mass stellar population around nearby M dwarfs, there has been no complete wide-field infrared search of a large sample of M dwarfs. With the advent of large format infrared arrays, it has become possible for the first time to conduct such a comprehensive wide-field (>100 AU) search for low-mass companions.

The basic concept behind our wide-field search is similar to that of van Biesbroeck's faint companion search of (van Biesbroeck 1961), which was done photographically to a limiting V magnitude of 18, except that ours is conducted

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in the near infrared where substellar companions should be much more easily detected. It is important to note that two of the objects found during van Biesbroeck's search, VB 8 and VB 10, remain among the 20 lowest luminosity red objects known (TSN2), and are still used as benchmark comparisons for brown dwarf candidates. In fact, both of these companions to nearby M dwarfs, separated from their primaries by 221″ and 74″, respectively, would have been missed by the previous deep infrared surveys of Rieke & Rieke (1989) and Skrutskie *et al.* (1989). Since all of the M dwarfs observed in this program have also been observed with infrared speckle techniques (Henry & McCarthy 1990; Henry 1991), the total field coverage of the combined surveys spans separation of ~1–10 and ~100–1000 AU, and all of this region is sampled at least to the end of the main sequence. Given the uncertainties associated with identifying true brown dwarfs based solely upon spectra or broadband photometry, searching for brown dwarf companions to nearby M dwarfs has distinct advantages. The distances are known to high precision and in the cases of small separations a mass measurement through orbital characterization is possible.

In this paper we describe a large scale program of wide-field near-infrared imaging of nearby M dwarfs observable from Mauna Kea. Possible low-mass companions are identified based upon their locations in color–magnitude diagrams (hereafter CMDs) of point sources detected in the fields surrounding primaries. False detections are most likely due to contamination from background K and M giants, which are sufficiently red and faint (due to their great distance in the Galaxy) that they will populate the same region as brown dwarfs and low-mass companion stars in such CMDs. Nonetheless, follow-up imaging or spectroscopy can easily discriminate between true low-mass companions and background giants, since low-mass companions would have radically different spectra and exhibit detectable common proper motion on time scales of only a few years.

2. DATA ACQUISITION AND PROCESSING

Observations were made on two telescopes on Mauna Kea over the course of four pairs of observing runs between 1991 August and 1992 August. A total of 66 primaries was observed. The first run of each pair was made on the University of Hawaii's 24 inch Planetary Patrol telescope, using the facility 256×256 NICMOS3 infrared camera (Hodapp *et al.* 1992). This small telescope was used because it offered a very wide field (8×8 arcmin, 2.1 arcsec pixels) when coupled with the facility camera with its 2:1 reimaging optics. Images were recorded at J and K' (Wainscoat & Cowie 1992) in a dithered pattern with a program M star near the center of the field. A total exposure time of about 1 h was used for both J and K' observations (25×150 s=3750 s at K' and 15×250=3750 s at J). Snapshots typically lasting a few seconds duration were also recorded in J, H, and K' in order to perform photometry of M dwarfs that would have been saturated in the deep exposures.

Images were processed using conventional techniques. Each raw frame was dark subtracted and divided by a median sky flat. Images were then registered and a final median image extracted from the data cube. Using the median rather than the sum of images comprising each data cube suppressed bad pixels quite effectively in the final image.

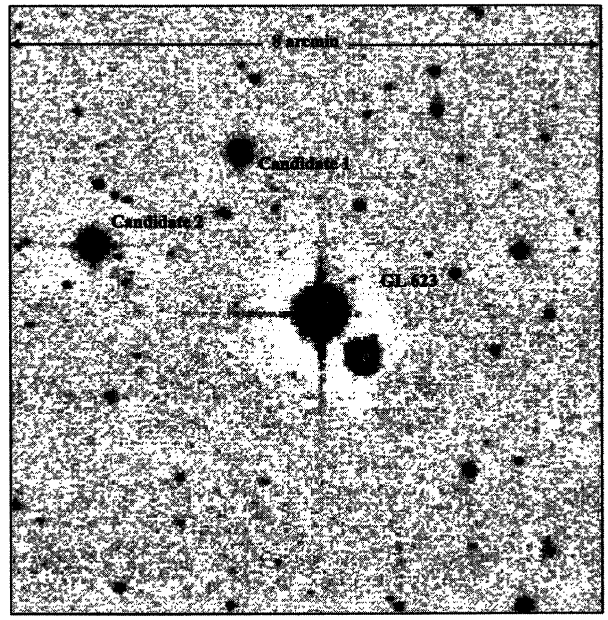

FIG. 1. A representative 1 hr J-band image of GL 623 is shown, as observed from the UH 24″. North is up and east to the left. The total field of view is 8 arcmin on a side and the round flare to the lower right of the primary is simply an internal reflection in the camera optics. For comparison, the size of the field used by Skrutskie *et al.* (1989) is shown as a white box on top of the halo immediately surrounding the primary in this image, indicative of the large amount of previously unexplored area this survey sampled.

A custom program was then used to search each J and K' pair for point sources detected above a 3σ noise threshold, corresponding to 16.5 mag at J and K', and photometric measurements were made on all detected point sources using a 5×5 pixel (10″) aperture. All photometry was calibrated against standards listed in Elias *et al.* (1982). Another program was used to match sources detected at both J and K', generating a final list of targets detected at both wavelengths. From there a J vs $J-K'$ CMD was constructed for all sources detected at both wavelengths. False detections, generally created by diffraction spikes from bright stars in the field, were eliminated from the photometry results manually. Figure 1 shows a typical J image of a relatively high Galactic latitude field (b=44 °), with GL 623 in the center of the field. The approximate size of the field used by Skrutskie *et al.* (1989; 7 arcsec radius) is shown as a box to demonstrate how they would have missed by a large margin the widely separated binaries to which our program is sensitive. The ring of flux to the lower right of the primary star is an internal reflection in the optics of the facility infrared camera.

The follow-up UH 2.2 m run to each 24″ run was primarily dedicated to observing candidate low-mass companions with sufficient spatial resolution to establish first epoch astrometry measurements with respect to background field stars. With the relatively high proper motions associated with program M dwarfs, typically only a few years would be required to confirm or reject candidates as true companions. The UH 2.2 m was also used to observe M dwarfs that were too far south for observations at the 24″ due to pointing restrictions. The 2:1 optics in the UH facility infrared camera provided 0.″7 pixels at the 2.2 m. In order to cover the same amount of sky at the 2.2 m that was covered in each 24″ observation, a 3×3 mosaic pattern was used. A total of 300 s was spent at each mosaic position at J and K' (3×100 s at J and 4×75 s at K'), yielding comparable point source sensitivity to the exposures recorded at the 24″. Like the 24″ observations, a set of snapshots was recorded at J, H, and K' to expand the dynamic range of the final photometry to include bright stars that would have been saturated in the deeper exposures. Data reduction was handled in a similar manner as the 24″ images, except individual fields around program M dwarfs were reconstructed into wide-field mosaic images spanning the same 8×8 arcmin dimensions as the 24″ images. Mosaics were constructed by defining registration offsets based upon stars that were imaged in overlapping areas of adjacent fields. Photometric measurements were made through essentially identical procedures and software used in the 24″ data analysis, with the end result once again being a J vs $J-K'$ CMD containing all point sources detected in an 8×8 arcmin field centered on the program M dwarfs.

The original observing list was identical to that used in the infrared speckle survey of Henry (1991). The search was intended to be volume limited, and as of 1991 January the target list included all known M dwarfs within 8 pc and north of −25°, gleaned from the *Second Catalog of Nearby Stars* (Gliese 1969), its update (Gliese & Jahreiss 1979), and a few targets found in the literature (e.g., LHS 292).

During the past five years, however, this nearby star census has continued to develop and the list of nearby M dwarfs has changed. In order to present a comprehensive picture of the multiplicity of nearby red dwarfs in a volume limited sample, we list in the first section of Table 1 the complete sample of 75 systems having red dwarf primaries with (1) $M_V \geqslant 8.0$ mag, (2) trigonometric parallaxes ⩾0.125, and (3) declinations north of −30° (thereby including 3/4 of the sky). Of these 75 systems we observed 66 but discarded 3 due to crowding, leaving a total of 63 systems included in the survey. It is possible to use an absolute magnitude cut-off because errors in the absolute magnitudes are small given the proximity and high quality trigonometric parallaxes of the sources, taken from the Gliese & Jahreiss (1991). M_V values listed in Table 1 are given only with one tenth magnitude precision in cases where estimates were made for the primary, e.g., in close multiples. The second section of Table 1 lists 8 M dwarfs that were observed yet no longer meet the above criteria. These M dwarfs have revised distances placing them beyond 8 pc or are not primaries. Finally, to complete the census of red dwarfs, we list five unobserved M dwarfs that meet the census criteria but are companions to brighter stars.

3. DATA ANALYSIS

3.1 Phase I of the Data Analysis

An example of a CMD appears in Fig. 2. The main sequence at the distance of the primary is also shown as a dashed line using data from Kirkpatrick & McCarthy (1994). For a median distance of ∼5.8 pc for targets in the program, the corresponding median search radius is ∼100–1400 AU. After creating a CMD for each field, isochrones for substellar companions were established using a technique similar to that described in Simons & Becklin (1992). In detail, the spectrophotometry listed in Berriman & Reid (1987) for low-mass field stars was assumed to be representative of the M dwarfs in our program fields, and it was assumed that they could be extrapolated to the colors of $\sim 10^{10}$ yr old brown dwarfs. Linear least square fits were made to the photometry and $T_{\rm eff}$ values listed in Berriman & Reid (1987) to create expressions describing $J-K$ color and J bolometric corrections to $T_{\rm eff}$. These derived relations are

$$J=5\log D-2.5\log\left(\frac{L_{BD}}{L_\odot}\right)+1.59\log T_{\rm eff}-7.68, \qquad (1)$$

$$J-K=7.06-1.78\log T_{\rm eff}. \qquad (2)$$

With the distances D to each primary star known from Gliese & Jahreiss (1991), the brown dwarf "X" model created by Burrows *et al.* (1993) was used to define $L_{BD}/L_\odot$ and $T_{\rm eff}$ so that simple substitution into the above equations would yield a unique theoretical brown dwarf isochrone for each primary star. The Burrows *et al.* (1993) *X* model represents a refinement over the earlier models produced by Burrows *et al.* (1989), incorporating improved atmospheric and interior physics while assuming a mixing length of 1, solar metallicity, and a He fraction of 0.25. Our lower magnitude limit of $J=16.5$ leads to a lower-mass sensitivity of $\sim 0.03\ \mathscr{M}_\odot$ using this model.

The CMD shown in Fig. 2 was derived from the field depicted in Fig. 1. The lines denote the Burrows *et al.* (1993) isochrones assuming ages of either 6×10^8 (approximately the age of the Pleiades) or 10^{10} yr, with mass points spanning 0.08–0.03 $\mathscr{M}_\odot$. In this particular case two objects lie just above the brown dwarf regime in the CMD, implying masses of $\sim 0.1\ \mathscr{M}_\odot$, if they are true companions to GL 623. Note that there is a well-defined separation between the location of field M dwarfs in such a plot and that of brown dwarf candidates such as GD 165B (Becklin & Zuckerman 1988). This separation verifies the basic operating principle behind this technique of searching for low-mass companions to nearby M dwarfs. As additional examples, the technique identified GL 643 and GL 644C (VB 8) as companions to 644 ABD. Note also that the 10^{10} yr isochrones were used throughout the analysis to define candidates even though such an isochrone is likely too old for the M dwarfs in question since Henry (1991) found a typical age of $\sim 4\times 10^9$ yr for this sample. Nonetheless, this approach in defining a brown dwarf zone in the CMDs reduces the chance of missing brown dwarf candidates like GD 165B in this initial screening process since, as seen in Fig. 2, an older age tends to push isochrones closer to the location of field M dwarfs. Though the technique is weighted in favor of creating false

TABLE 1. Target list of Gliese program stars.

Primary Name	Known Components	Trig. Parallax (")	M_V (primary)	M_V Ref	Observing Data location	Observing Data date	Photometry on Primary[a] J (mag)	H (mag)	K' (mag)	M_J (mag)	notes	proper motion "/yr	P.A.
Objects Meeting Survey Criteria													
GJ 1002		.2128±.0033	15.40	L	--	--	--	--	--	--		2.041	203.6
GJ 1005*	AB	.1887±.0084	13.5		UH 24"	Jan 1992	7.87	6.85	6.66	9.25	b	0.863	133.6
GL 15*	AB	.2895±.0049	10.39	L	UH 24"	Aug 1991	4.78	4.16	3.96	7.09		2.912	81.8
GJ 2005	ABC	.1328±.0091	15.42	GJ	--	--	--	--	--	--		0.614	354.9
GL 54.1		.2674±.0030	14.19	L	--	--	--	--	--	--		1.345	62.3
GL 65*	AB	.3807±.0043	15.1	HM	UH 24"	Jan 1992	6.39	5.79	5.54	9.29	b	3.368	80.4
GL 83.1*		.2238±.0029	14.04	L	UH 24"	Aug 1991	7.41	6.98	6.65	9.16		2.097	147.8
GL 109*		.1256±.0027	11.06	SH	UH 24"	Jan 1992	6.85	6.28	6.00	7.34		0.923	113.8
GL 185*	AB	.1296±.0075	9.02	GJ	UH 2.2 m	Feb 1992	--	--	--	--	b	0.308	211.1
GL 205		.1723±.0031	9.13	L	UH 24"	Jan 1992	4.61	3.97	3.75	5.79		2.235	159.9
GL 213*		.1665±.0039	12.64	L	UH 2.2 m	Oct 1991	--	--	--	--		2.571	128.4
LHS 1805		.1322±.0029	12.32	GJ	--	--	--	--	--	--		0.831	190.1
G 99-49		.1863±.0062	12.68	GJ	--	--	--	--	--	--		0.241	108
GL 229*	AB	.1749±.0067	9.33	L	UH 24"	Mar 1992	5.24	4.45	4.31	6.45	b	0.737	190.2
GL 234*	AB	.2421±.0017	12.8	HM	UH 2.2 m	Feb 1992	--	--	--	--		0.997	134.8
GL 251*		.1736±.0022	11.21	L	UH 24"	Jan 1992	6.00	5.59	5.33	7.20		0.851	242.3
GJ 1093		.1289±.0035	15.07	L	--	--	--	--	--	--		1.225	137.3
GL 268*	AB	.1646±.0031	13.1		UH 24"	Jan 1992	6.69	6.18	5.94	7.77	b	1.052	207.9
GL 273*		.2644±.0020	11.97	L	UH 24"	Jan 1992	5.61	5.12	4.87	7.72		3.761	171.2
GL 285*		.1611±.0041	12.19	L	UH 24"	Mar 1992	6.65	6.06	5.83	7.69		0.604	221.4
GL 299*		.1480±.0026	13.68	L	UH 24"	Mar 1992	8.34	7.92	7.71	9.19		5.211	167.1
GL 300		.1700±.0102	13.22	L	UH 24"	Jan 1992	7.57	6.98	6.75	8.72		0.707	177.5
GJ 1111*		.2758±.0030	16.99	L	UH 24"	Jan 1992	8.23	7.63	7.36	10.43		1.29	242.2
GJ 1116*	AB	.1913±.0025	15.47	GJ	UH 24"	Jan 1992	7.71	7.29	7.00	9.12	b	0.874	267.7
GL 338	AB	.1625±.0020	8.67	GJ	UH 24"	Jan 1992	4.86	4.21	4.10	5.91		1.662	249.6
GL 380		.2132±.0027	8.23	L	--	--	--	--	--	--		1.454	248.9
GL 388*		.2039±.0028	10.87	L	UH 2.2 m	Feb 1992	5.35	4.79	4.61	6.90	c	0.506	264
GL 393*		.1362±.0041	10.32	L	UH 24"	Mar 1992	6.20	5.60	5.39	6.87		0.949	218.2
LHS 292		.2210±.0036	17.32	L	UH 2.2 m	Feb 1992	--	--	--	--		1.644	158.5
GL 402*		.1451±.0048	12.46	L	UH 24"	Mar 1992	7.22	6.69	6.44	8.03		1.15	225.1
GL 406*		.4183±.0025	16.56	L	UH 24"	Mar 1992	7.04	6.42	6.16	10.15		4.696	234.6
GL 408*		.1446±.0044	10.82	L	UH 24"	Mar 1992	6.22	5.71	5.52	7.02		0.465	239.9
GL 411*		.3973±.0018	10.47	L	UH 24"	Jan 1992	4.04	3.57	3.39	7.04		4.807	186.8
GL 412*	AB	.1888±.0061	10.14	L	UH 24"	Mar 1992	5.48	4.95	4.78	6.86		4.528	282.1
GL 445*		.1915±.0053	12.23	L	UH 2.2 m	Feb 1992	--	--	--	--		0.863	55.5
GL 447*		.3011±.0019	13.51	L	UH 24"	Mar 1992	6.59	5.94	5.72	8.98		1.348	152
GJ 1156		.1529±.0030	14.73	GJ	--	--	--	--	--	--		1.301	279.1
GL 473*	AB	.2322±.0043	15.0		UH 24"	Mar 1992	6.93	6.38	6.08	8.76	b	1.811	277.4
GL 514*		.1387±.0029	9.76	L	UH 24"	Jan 1992	5.81	5.30	5.05	6.52		1.552	134.3
GL 526		.1840±.0013	9.79	L	UH 24"	Mar 1992	5.23	4.65	4.48	6.55		2.325	129.8
GL 555*		.1590±.0066	12.32	L	UH 24"	Mar 1992	6.82	6.27	6.03	7.83		0.69	330.3
LHS 3003		.161±.006	17.05	L	--	--	--	--	--	--		0.965	210.1
GL 581*		.1579±.0065	11.55	L	UH 24"	Mar 1992	6.60	6.08	5.86	7.59		1.224	256.3
GL 623*	AB	.1317±.0039	11.1	HM	UH 24"	Aug 1991	6.70	6.37	5.96	7.30	b	1.231	111.6
GL 625*		.1593±.0046	11.11	L	UH 24"	Mar 1992	6.61	6.06	5.86	7.62		0.42	108
GL 628*		.2447±.0063	12.02	L	UH 24"	Mar 1992	5.87	5.30	5.15	7.81		1.175	183.4
GL 644*	ABCD+643	.1539±.0026	11.4		UH 24"	Aug 1992	5.18	4.64	4.44	9.22	b,e	1.183	222.2
G 203-47		.1318±.0310	12.40	GJ	--	--	--	--	--	--		0.428	129
GL 661*	AB	.1595±.0031	10.97	GJ	UH 24"	Aug 1991	5.64	4.97	4.85	6.65	b	1.582	171.3
GL 673		.1289±.0035	8.08	L	--	--	--	--	--	--		1.315	206.1
GL 686		.1289±.0026	10.17	L	--	--	--	--	--	--		1.361	43.2
GL 687		.2127±.0020	10.86	L	--	--	--	--	--	--		1.304	194.8
GL 699*		.5453±.0010	13.23	L	UH 24"	Aug 1991	--	--	--	--	f	10.31	355.8
GL 701		.1259±.0047	9.87	L	UH 24"	Aug 1992	6.11	5.51	5.40	6.61	g	0.644	121.1
GJ 1224		.1327±.0037	14.24	GJ	--	--	--	--	--	--		0.664	238.2
LHS 3376		.1373±.0053	14.17	GJ	--	--	--	--	--	--		0.623	131.3
GJ 1230*	ABC	.1302±.0283	13.00	GJ	UH 24"	Aug 1991	7.48	6.95	6.70	8.05	b	0.501	85.3
GL 725*	AB	.2861±.0018	11.18	L	UH 2.2 m	Oct 1991	--	--	--	--		2.273	323.3
GL 729		.3411±.0081	13.13	L	UH 24"	Aug 1992	6.33	5.70	5.50	8.99	g	0.72	106.7
GL 752	AB	.1767±.0024	10.36	L	UH 24"	Aug 1992	5.55	4.82	4.64	6.79	g	1.466	204.2
GJ 1245*	ABC	.2120±.0043	15.4	HM	UH 24"	Aug 1991	8.18	7.56	7.47	9.81	b	0.731	143.1
GL 809*		.1335±.0026	9.13	L	UH 2.2 m	Oct 1991	--	--	--	--		0.772	180.5
GL 829*	AB	.1478±.0026	11.16	L	UH 24"	Aug 1991	6.28	6.02	5.58	7.13	b	1.058	69.8
GL 831*	AB	.1256±.0045	12.6		UH 24"	Aug 1992	7.18	6.65	6.43	7.67	b	1.194	90.8
LHS 3799		.1341±.0056	13.89	GJ	--	--	--	--	--	--		0.778	158.3
GL 860*	AB	.2519±.0023	11.8	HM	UH 2.2 m	Oct 1991	--	--	--	--		0.943	245.4
GL 866*	ABC	.2943±.0035	14.2		UH 24"	Aug 1992	6.50	5.80	5.59	8.84	b	3.254	46.6
GL 873*		.1970±.0025	11.73	L	UH 24"	Aug 1991	6.08	5.40	5.29	7.55		0.901	238.7
GL 876*		.2113±.0048	11.80	L	UH 24"	Aug 1992	5.91	5.27	5.14	7.53		1.143	123.5
GL 880*		.1482±.0025	9.51	L	UH 24"	Aug 1992	5.33	4.70	4.52	6.18		1.071	254.8
GL 884		.1284±.0068	8.40	L	--	--	--	--	--	--		0.911	274.1
GL 896*	AB	.1519±.0037	11.29	GJ	UH 24"	Aug 1992	5.86	5.33	5.14	6.77	b	0.56	91.7
GJ 1286		.1386±.0035	15.40	GJ	UH 24"	Aug 1992	8.96	8.39	8.26	9.67		1.157	137.4
GL 905*		.3156±.0016	14.79	L	UH 24"	Aug 1991	6.82	6.20	5.95	9.32		1.617	177
GL 908*		.1779±.0056	10.23	L	UH 24"	Aug 1992	5.78	5.23	5.07	7.03		1.37	133.4

TABLE 1. (continued)

Primary Name	Known Components	Trig. Parallax	M_V	M_V Ref	Observing Data		Photometry on Primary				notes	proper motiom	
		(")	(primary)		location	date	J (mag)	H (mag)	K' (mag)	M_J (mag)		"/yr	P.A.
					Observed Objects No Longer Meeting Survey Criteria								
GL 34	B	.1684±.0031	--	GJ	UH 2.2 m	Oct 1991	--	--	--	--	h	1.213	114.9
GL 105	B	.1294±.0043	--		UH 24"	Jan 1992	3.94	3.60	3.44	4.50	i	2.322	51.4
GL 166	C	.2071±.0025	--	L	UH 24"	Jan 1992	--	--	--	--	f,j	4.073	212.4
GL 169.1	A	.1819±.0011	--	SH	UH 2.2 m	Oct 1991	--	--	--	--	j	2.383	144.8
GL 283	B	.1120±.0050	--	L	UH 2.2 m	Feb 1992	--	--	--	--	j,k	1.252	116.6
GL 450*		.1235±.0133	10.18	L	UH 24"	Mar 1992	6.44	6.09	5.74	6.90	k	0.35	321
GL 493.1		.1228±.0046	13.85	GJ	UH 24"	Mar 1992	8.43	7.94	--	8.88	f,k	0.973	284.4
GL 570	BC	.1742±.0060	--		UH 24"	Mar 1992	--	--	--	--	d,i	1.933	149.7
					Unobserved M Dwarf Companions to Brighter Stars								
GL 33	B	.1359±.0037	--		--	--	--	--	--	--	i,l,m	1.367	146.4
GL 53	B	.1345±.0029	--		--	--	--	--	--	--	h	3.77	114.7
GL 423	C	.1305±.0223	--		--	--	--	--	--	--	h,m	0.727	216.2
GL 423	D	.1305±.0223	--		--	--	--	--	--	--	h,m	0.727	216.2
GL 820	B	.2887±.0019	--	L	--	--	--	--	--	--	i	5.22	52.4

NOTES to TABLE 1

a = the error on each measurement is ±0.05 mag; only targets with "Observing Data" listed were actually observed and lack of JHK' photometry on some primaries only means that snapshots were not acquired
b = multiple components in photometry aperture
c = short exposure photometry measured at UH 88"
d = BC contaminated by A in photometry
e = quintuple system; ABD in photometry aperture
f = photometry error in short exposures
g = background confusion leads to large numbers of false candidates
h = primary is G dwarf
i = primary is K dwarf
j = primary is white dwarf
k = new parallax < 0.125
l = not listed in GJ 1991
m = not known if the component is a red dwarf
GJ = Gliese and Jahreiss (1991)
HM = Henry and McCarthy (1993); estimated M_V to 0.1 mag
L = Leggett (1992)
SH = Stauffer and Hartmann (1986)
* = Searched completely for companions between 1-10 and 100-1000 AU

detections (by field stars lying above the isochrone), such a weighting in the screening process is warranted in order to make the survey as thorough as possible since candidates can be reliably rejected quite easily through follow-up observations.

Beyond the obvious population of field stars and the theoretical brown dwarf regime in the CMD, there are many extremely red objects detected ($J-K'>1$) that increase in number at fainter magnitudes. Deep near-infrared imaging in extra-galactic programs (e.g., Gardner 1992) indicates that these targets are unresolved background galaxies and quasars, whose number density rises rapidly at such near infrared magnitudes and which have colors in the $1.0<J-K<2.0$ range.

Three fields recorded at low Galactic latitudes (GL 701, GL 729, and GL 752) had to be discarded from Phase I of our program due to heavy contamination in the brown dwarf region of the CMD by reddened field stars. Such CMDs simply cannot be used to identify candidate low mass companions in low latitude fields. This reduced the actual number of stars formally included in Phase I of this survey to 63. Though 2.2 μm observations were made through a K' instead of a K filter (to boost sensitivity) it should be noted that the impact on measured colors and isochrone fits is small compared to the other noise sources in the photometry (see Davidge & Simons 1994) and is certainly irrelevant for the purposes of identifying possible low-mass companions.

3.2 Phase II of the Data Analysis

Objects such as GL 229B (Nakajima *et al.* 1995), given its $J-K$ color, would not be detected in this initial screening process. Phase II of this survey will reveal objects like GL 229B by acquiring second epoch infrared frames of all fields. Because of the large motions of the nearby target stars, common proper motion companions can be readily detected given the 5–6 year time baseline between these new frames and the first epoch images. In this way, we will detect companions without any *a priori* color assumptions. Results from this search will be reported in a future paper.

4. FOLLOW-UP OBSERVATIONS OF CANDIDATE LOW-MASS COMPANIONS

Table 2 lists photometry, spectroscopy, and the results of a common proper motion search using Digitized Sky Survey (DSS) frames of candidate companions. Spectra were obtained for 11 of the 19 candidates in order to determine whether or not they are true companions and, if not, to discover what types of objects were identified. These spectroscopic observations were made on the nights of UT 1993 March 15–17 at the McDonald Observatory 2.7 m telescope using a 2″ slit and the Large Cassegrain Spectrograph equipped with a 1024×1024 Craf/Cassini CCD. A 300 line/mm grating with a GG475 order-blocking filter was used

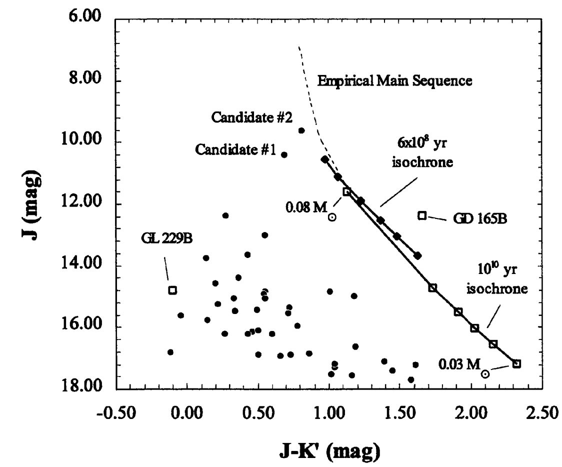

FIG. 2. A color-magnitude diagram for all point sources (except the central primary) detected in Fig. 1 is shown. Two Burrows *et al.* (1993) *X* model isochrones are shown, each spanning 0.08–0.03 $\mathscr{M}_\odot$. A dashed line shows an empirical main sequence derived from Kirkpatrick & McCarthy (1993). In this case a pair of stars (seen to the northeast of the primary in Fig. 1) lie just above the hydrogen break at 0.08 $\mathscr{M}_\odot$. Subsequent spectroscopy of these objects proved them to be background sources. Also shown are points corresponding to GL 229B and GD 165B if they were companions of GL 623. Note how GL 229B would have been confused as a background star in this program due to its blue $J-K'$ color.

to cover the range of 6400–9200 Å at a resolution of 12 Å. Comparison of the data to the standard spectral sequence for red stars established by Kirkpatrick *et al.* (1991), allows the determination of both spectral class and luminosity. All 11 were found to be background sources, including one supergiant, seven giants, two dwarfs and one quasar. All of the stellar sources are confirmed to be red and only mimic companions to the nearby target M dwarfs because of line of sight confusion. The single quasar identified presumably has emission lines falling in the J and K' bands that result in a $J-K'$ color similar to that of a very red dwarf (Neugebauer *et al.* 1982), although we do not have an infrared spectrum to confirm this.

The mean proper motion of the 66 primary targets observed in this survey is 1.66 arcsec/yr. The combination of the DSS frames and POSS I prints (taken in the early 1950s) and the infrared frames provides a 40 year baseline, and yields a mean total motion of 66 arcsec, or 32 pixels on the infrared camera used in the observations. Two groups of candidates have been checked for common proper motion. The first includes those with $M_J \leqslant 11$ while the second includes objects falling near our brown dwarf isochrones. All of the 19 potential companions were visible on the DSS plates and none were found to have common proper motion.

5. MULTIPLICITY OF M DWARF PRIMARIES SEARCHED

5.1 Stellar Companions

We are uniquely poised to compare directly the multiplicity of M dwarfs at two distinct separation regimes. For the following discussion, we define five zones that must be searched around a star to be certain to discover all companions: 0–1, 1–10, 10–100, 100–1000, and 1000–10 000 AU. While there may be a few companions beyond 10 000 AU, there is debate as to whether or not they will be gravitationally bound, as in the case of Proxima Centauri (Matthews & Gilmore 1993). For nearby stars, the first zone is the realm of radial velocity searches, the second is that of infrared speckle imaging, and the third is most efficiently searched in coronagraphic surveys. The two final zones are searched with wide-field work, although this survey samples only the 100–1000 AU zone completely.

Fifty of the M dwarfs included in this wide-field survey have also been searched for companions throughout the 1–10 AU range to the end of the main sequence using infrared speckle imaging (Henry 1991). These 50 stars are indicated by a * symbol on Table 1. As described by the mass–luminosity relations of Henry & McCarthy (1993), the absolute infrared magnitudes at the end of the stellar main sequence are $M_J \sim 11.0$, $M_H \sim 10.3$, $M_K \sim 10.0$. In both the infrared speckle survey and Phase I of this deep infrared survey, these limits have been reached, so companions with masses as low as 0.07–0.08 $\mathscr{M}_\odot$ would have been detected.

While the sample is rather modest in size, it is the first time that a direct comparison can be made for M dwarfs in which two separation regimes have been completely sampled. We find that of the 50 primaries, 12 have companions between 1 and 10 AU, while only 3 have companions between 100 and 1000 AU. For comparison, the same 50 stars are known to have 5 companions from 0 to 1, 5 from 10 to 100, and 1 beyond 1000 AU. However, these three zones have not yet been fully explored, even for this sample.

In all, there are 30 singles, 16 doubles, 3 triples, and 1 quintuple in the sample of 50, yielding a multiplicity fraction, $N_{\rm multiples}/N_{\rm systems}=40\%$. This value is similar to that found for M dwarfs by Henry & McCarthy (1990), 34%, and Fischer & Marcy (1992, hereafter FM), 42%. This is not surprising given that some of the same systems are included, although the overlap is far from complete. For example, only 19 of the 50 stars in our sample are found in the FM visual binary sample. The number of companions per primary, $N_{\rm companions}/N_{\rm systems}=0.52$, also matches the value of 0.55 found by FM. However, note that the value from our sample of 50 stars is a minimum value because three of the search zones have not yet been fully explored.

The distribution of companions in the separation zones is worthy of special attention. Using the FM relation dN/da, which describes the number of companions N, per unit semimajor axis a, we can find the number of companions expected in each zone, and specifically in the two zones which have been fully searched. While the two integration methods described by FM yield similar total multiplicities, 55% and 58%, there are subtle differences in the number of companions expected in each zone depending on precisely how one computes the multiplicity fraction.

Here we (slightly) modify their first method, and adopt the measured value within a decade zone throughout the zone. (Method I). In effect, we are adopting a constant dN/da relation within a zone. The values adopted are those listed in their Table 2, except for the innermost zone where we have taken the average of their two radial velocity bins. Their listed value for the 1–10 AU zone is from an earlier

TABLE 2. Follow-up observations of candidates.

Gliese Number of Target	Candidate	J (mag)	J-K' (mag)	Follow-Up Spectroscopy	CPM?
GL 109	1	16.07	1.61	--	no
GL 234AB	1	9.67	0.94	<K5 I (distinctly reddened)	no
GL 273	1	9.50	0.76	--	no
GL 283B	1	11.19	1.11	<K5 III (distinctly reddened)	no
GL 300	1	8.39	0.70	K7 III	no
GL 514	1	17.56	2.50	QSO (probably IRAS 13275+1038)	no
GL 555	1	10.03	0.49	<K5 III	no
GL 570BC	1	12.27	0.97	K5 V	no
GL 623AB	1	9.61	0.81	M0 III	no
	2	10.39	0.69	M3 V ~ 6× further away than GL 623A	no
GL 644ABD	1	9.04	0.96	M0 III	no
	2	10.15	0.90	K7 III	no
	3	10.03	0.40	M2 III	no
GL 1230ABC	1	9.20	0.73	--	no
GL 1245ABC	1	9.98	0.86	--	no
GL 809	1	11.13	0.85	--	no
GL 860AB	1	13.91	1.70	--	no
GL 873	1	9.20	0.83	--	no
	2	9.58	0.93	--	no

sample of 31 stars searched for companions with infrared speckle techniques (6 companions were found). As mentioned above, we have 12 companions around 50 stars in the present sample, which is entirely consistent with the FM value. In Method II, we have integrated the parabolic fit to the dN/da values from 0 to 10 000 AU, thereby smoothing variations due to the effects of a small number statistics. Table 3 lists the number of companions expected per 100 stars for each method, as well as what is found in the sample of 50 stars included here. The results indicate that both methods predict more stellar companions from the FM data in the 100–1000 AU zone than were found in this study. However, the number of actual companions known, three, is very small, and only two more companions would provide a match for Method I, so we do not believe this difference to be significant. Furthermore, while it appears that the smoothed companion separation distribution provided by Method II (presumably the more accurate method) is a worse representation of the actual multiplicity fractions known in the five zones, only when a much larger number of stars has been sampled can be difference between the FM dN/da relation and surveys be reconciled.

5.2 *Why So Few New Brown Dwarf Companions?*

The issue of why no new brown dwarf candidates were detected in this program is an entirely different question than why no new stellar companions were found. First, we stress that there are two types of brown dwarf candidates, those that are red like GD 165B and those that are blue like GL 229B (Nakajima *et al.* 1995; Oppenheimer *et al.* 1995). The recent discovery of GL 229B, which has a $J-K$ color of -0.2 and a $T_{\rm eff}\sim1000$ K, demonstrates that sufficiently low-temperature brown dwarfs are actually quite blue in the near infrared. In contrast, GD 165B is only ~800 K warmer than GL 229B yet has a dramatically redder $J-K$ color ($J-K=1.66$; see Kirkpatrick *et al.* 1993 for details). This transition between a brown dwarf being intrinsically red or blue is due to methane formation in the upper absorbing layer of its atmosphere and perhaps the presence of grains. Plotted in Fig. 2 are points corresponding to GD 165B and GL 229B assuming they were companions to GL 623, to illustrate this strong transition in color. The photometry used for GL 229B ($J=14.2$, $J-K=-0.2$) comes from Matthews *et al.* 1995 and that for GD 165B from Becklin & Zuckerman (1988). Note how a brown dwarf candidate like GD 165B would have been identified in Phase 1 of this program while brown dwarfs as cool as GL 229B would have been confused with background objects. A partial explanation for the lack of brown dwarfs discovered as companions to date is therefore that they do not have the red colors generally assumed. The exact nature of this color transition awaits further discoveries of targets like GD 165B and GL 229B. Only through our planned second epoch imaging of our program fields will we be able to assess the real impact of objects like GL 229B on this program, since candidates will then be screened solely on the basis of proper motion, not color. In any event, it seems unlikely that deep methane absorption occurs precisely at the stellar/substellar break (GL 229B has an estimated mass of 0.02–0.06 $\mathscr{M}_\odot$), hence this can only be a partial explanation for the lack of detections in the programs summarized in Table 4. Furthermore, radial velocity surveys are insensitive to cooling curves or brown dwarf colors, yet have still failed to find any confirmed brown dwarfs.

Another possible explanation for the lack of brown dwarf candidate detections in past studies is that they cool much faster than expected, triggering methane formation. Since brown dwarfs are fully convective and their interiors can be expressed through polytropic relations, purely analytical expressions for basic properties like luminosity, minimum mass, $T_{\rm eff}$, etc. can be derived with confidence. Burrows & Liebert (1993) point out how well such simple analytical

TABLE 3. M dwarf multiplicity.

Range (AU)	dN/da value	Method I (%)	Method II (%)	known for our 50 (%)
0-1	3.30×10^{-2}	3.3	3.9	≥10
1-10	2.26×10^{-2}	20.3	10.8	24[a]
10-100	1.34×10^{-3}	12.1	18.1	≥10
100-1000	1.15×10^{-4}	10.4	16.9	6[a]
1000-10000	5.7×10^{-6}	5.1	8.8	≥2
Total 0-10000		51.2	58.5	≥52

NOTES to TABLE 3

[a] completely sampled to the end of the main sequence for our 50 stars

TABLE 4. Comparison of various Brown Dwarf surveys.

Survey	Technique	Number Stars Sampled	Claimed Limiting Mass Sensitivity	Search Radius	Number of brown dwarfs predicted	
			($M_\odot$)	(AU)	q = 0	q = 2.8
Marcy & Benitz (1989)	Radial Velocity, M stars	70	0.01	0-3	0.3	3.4
Murdoch *et al.* (1993)	Radial Velocity, F5-K5 stars	29	0.01	0-3	0.1	1.4
Campbell *et al.* (1988)	Radial Velocity, 12 late-type dwarfs + 4 giants	16	0.01	0-13	0.2	1.6
Zuckerman & Becklin (1987)[a]	IR excess, WD's in Hyades & Pleiades	14	0.02	0-300	0.3	3.6
Zuckerman & Becklin (1992)	IR excess + direct imaging, white dwarfs	200	0.07	0-300	1.7	19.4
Skrutskie *et al.* (1989)	Direct K imaging, M stars + Pleiads	63	0.05	20-70	0.4	3.7
Rieke & Rieke (1989)[b]	Direct K imaging, M stars	~100	0.03	20-100	0.7	7.6
TSN3[c]	Direct J & K' imaging, M stars	63	0.03	100-1400	0.6	6.8

NOTES to TABLE 4

[a] Hyades parameters used to define values in all columns
[b] survey parameters extracted from Burrows and Liebert (1993)
[c] assumes a median distance of 5.8 pc in defining the sensitivities

models match the much more sophisticated numerical models published to date and derive analytical expressions for brown dwarf cooling curves, finding $L_{BD} \propto t^{-1.3}$ and $T_{\rm eff} \propto t^{-0.3}$. Using these scaling relations and Eqs. (1) and (2), a 0.08 $\mathscr{M}_\odot$ brown dwarf would have to cool a factor of ~20 times faster than predicted in order for it to reach $T_{\rm eff} \sim 1000$ and therefore be confused as a background object by this program, like GL 229B. We therefore doubt that brown dwarfs are simply cooling too fast to be detected as companions to M dwarfs.

The preponderance of null results found by numerous searches for brown dwarf companions to stars, including the studies listed in Table 4, as well as this survey, suggest that brown dwarf candidates like GD 165B are rare objects. To date only radial velocity surveys and the adaptive optics work of Nakajima *et al.* (1995) would have been sensitive to blue candidates like GL 229B, hence it is difficult to assess the significance of past failures to find such candidates without a greater sample size (see below). Many of the studies in Table 4 have identified M dwarfs that have theoretical masses approaching the stellar/substellar break, hence have demonstrated that the techniques employed are viable, yet only GD 165B has emerged as a strong candidate from such research.

One can estimate the number of brown dwarfs that should have been found in the regions sampled by these programs, based upon certain assumptions and the expression:

$$N_{BD} = n_{\rm sample} \int_{r_{\rm inner}}^{r_{\rm outer}} f(a)da \, \frac{\int_{m_1}^{0.08} m^{-q} dm}{\int_{m_1}^{m_2} m^{-q} dm}. \quad (3)$$

Here, $f(a) = dN/da$ is the relation defined in FM for the distribution of secondary separations. Note that this distribution is already normalized so integrating over an infinite radius yields the total number of secondaries per M star. Mass functions are assumed to be described by simple power laws of the form $dn/dm = m^{-q}$, with m_1 representing the lower-mass limit of the survey, and m_2 representing the upper mass cutoff, typically 0.6 $\mathscr{M}_\odot$ for M dwarfs. The term m_1 was only allowed to go down to 0.05 $\mathscr{M}_\odot$ regardless of the claimed survey sensitivity except for Zuckerman & Becklin (1992), which only reached to ~0.07 $\mathscr{M}_\odot$. Table 4 is therefore an attempt to predict the number of GD 165B-type brown dwarfs that should have been found to date. The term $n_{\rm sample}$ is the number of primaries sampled in the survey characterized by inner and outer search radii, $r_{\rm inner}$ and $r_{\rm outer}$, respectively (in AU). This calculation is obviously critically dependent on the nature of the substellar mass function, which has yet to be measured reliably. The mass functions found by Henry (1991) and Zuckerman & Becklin (1992) for stellar secondaries to M dwarfs and white dwarfs, respectively, were both either flat or rising slightly, hence tend to favor $q \sim 0$ to 1 values in this calculation. An attempt at a direct measure of the substellar mass function was made by Simons & Becklin (1992), who searched for free-floating brown dwarfs in the Pleiades at infrared wavelengths. They found a significantly higher mass function index ($q = 2.8$) for brown dwarfs than for low-mass secondaries, and their index is taken to represent an upper limit in the range considered. Table 4 outlines the result of applying Eq. (3) to several past surveys as well as TSN3. In the case of this program, if the flat mass function observed for low-mass companions to M dwarfs extends well into the brown dwarf regime, the null result here is only marginally significant, since only ~1 brown dwarf with a mass $\geqslant 0.05$ $\mathscr{M}_\odot$ should have been found. A steeper mass function though renders the null result to be quite significant. Summing the total number of brown dwarfs that should have been found with $0.05<\mathscr{M}/\mathscr{M}_{\odot}<0.08$ from all of the searches in Table 4 leads to the prediction that ~4 brown dwarfs should have been found under the conservative assumption that the mass function is flat through the brown dwarf regime and ~48 for an optimistic ($q=2.8$) mass function. The fact that these combined surveys have turned up only GD 165B seems significant and is probably indicative of either something inhibiting brown dwarf formation, some mechanism inhibiting their ability to bind as pairs with stars, or a combination of these and other factors.[2]

FM argue that since the mass function of secondaries to M dwarfs mimics that of the field, a natural explanation is that secondaries were captured soon after formation, when the local density of forming stars was still high enough to support gravitational capture. The CORAVEL study of Duquennoy & Mayor (1991) also shows that the secondaries of G dwarfs have a similar mass spectrum as the field. If brown dwarf companions are captured as free floating members of small protostellar clusters, then a higher value of q may be appropriate in this calculation and the lack of detected brown dwarfs in this and other programs is then even more significant. McDonald & Clarke (1993) extend upon the arguments made by FM by modeling the formation of binaries in young clusters through dynamic capture and found that a strong bias toward the formation of binaries among stars, not stars and brown dwarfs, emerges. The responsible mechanism is essentially one of mass segregation in which early in the dynamical evolution of a very young cluster the two most massive stars form a hard binary which completely dominates small cluster evolution. Most interactions of lower-mass objects with a hard binary result in the ejection of the low-mass objects from the cluster and further hardening of the binary. Eventually, three-body interactions are rare due to depletion of the cluster of all of the low-mass components and a halo of dissociated low mass objects forms around the central binary. Such mass segregation has been seen in relatively young open clusters like the Pleiades (van Leeuwen 1980) and, when coupled with the observation that the mass function of secondaries matches that of free-floating stars, potentially explains why brown dwarfs are rarely found as secondaries to stars.

If this dynamical biasing mechanism explains the paucity of stellar/substellar binaries found in the field, then this has the rather unfortunate implication that it will be in general difficult to identify brown dwarfs with complete confidence since the only way to do so is through direct mass measurement via binary orbital measurements. Young open clusters may therefore remain the logical harbingers of free-floating brown dwarfs that can be detected through modern techniques in significant numbers and indirect spectroscopic mass measurements like searches for Li absorption (Magazzu *et al.* 1993), deep methane absorption (Oppenheimer *et al.* 1995), or measurements of surface gravity (Davidge & Boeshaar 1993) will be needed to help discriminate between stellar and substellar candidates.

[2]For example in TSN2 we point out that objects like VB 10 (extreme M dwarfs) may in fact be substellar.

6. CONCLUSIONS

A total of 63 nearby M dwarfs have been observed using wide field J and K' imaging in an attempt to find new low-mass companions. Depending on the nature of the substellar mass function, we predict that somewhere between ~1 and 7 new brown dwarf companions with $0.05\leqslant\mathscr{M}/\mathscr{M}_{\odot}\leqslant0.08$ should have emerged from this survey. To date, follow-up observations of possible companions have shown them all to be background objects. No new stellar or substellar companions have been identified yet in this survey. Combining the null result of this program with the null results from similar searches suggests that red substellar secondaries like GD 165B are anomalously rare. This in turn suggests that either a mechanism inhibiting their formation is at work, or past failures to detect brown dwarfs is in part due to methane absorption creating unexpectedly blue colors for these objects, rendering some search techniques ineffective.

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