THE ASTRONOMICAL JOURNAL VOLUME 109, NUMBER 2 FEBRUARY 1995

THE SOLAR NEIGHBORHOOD. II. THE FIRST LIST OF DWARFS WITH SPECTRAL TYPES OF M7 AND COOLER[1]

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Received 1994 September 2; revised 1994 October 11

ABSTRACT

Spectra and finder charts are given for 20 dwarfs having types of M7 or later, and a spectral classification scheme is introduced for types M7 V to M9 V. Three of these dwarfs are later than M9 and have spectra in which VO absorption appears greatly enhanced. First results are also presented for a spectroscopic follow-up of unclassified proper motion targets, begun in an attempt to identify other low-luminosity members of the solar neighborhood.

1. INTRODUCTION

Obtaining a database of extremely red dwarfs is an important first step toward a better understanding of the faint red corner of the H–R diagram. To date, several very late M dwarfs have been uncovered through follow-up of proper motion surveys, and several more have been uncovered through photometric surveys of the field. Others have been detected as companions to known nearby stars. Despite the inhomogeneities inherent in this database, the possibility still exists that the latest M dwarfs are younger than earlier M dwarfs (Hawkins & Bessell 1988; Bessell 1991; Kirkpatrick *et al.* 1994). This, in turn, suggests that such objects may be brown dwarfs or may at least represent a mixture of stellar and substellar objects (Kirkpatrick & McCarthy 1994; Kirkpatrick *et al.* 1994; Reid *et al.* 1994). Only accurately determined dynamical masses significantly below the hydrogen burning minimum mass range of 0.074–0.080 $\mathscr{M}_\odot$ can confirm their possible substellar nature, and as a preliminary step toward acquiring masses, the latest dwarfs should be surveyed for signs of multiplicity. Also, their frequency of occurrence in the solar neighborhood is still poorly known, so keeping an updated list of these objects is necessary if their number density is to be determined.

We present the list of very late M dwarfs in Sec. 2. Their spectra are presented and spectral types quantified in Sec. 3. In Sec. 4 each object is reviewed in a historical context to address the method used in its discovery and to highlight any unusual spectral or photometric characteristics. Results of our spectroscopic follow-up survey, undertaken to identify other late M dwarfs near the Sun, are discussed in Sec. 5. Interesting implications are presented and future avenues of study are outlined in Sec. 6. The paper is summarized in Sec. 7.

2. TARGET LISTS

Our list of targets has been drawn from several sources, as further discussed in Sec. 4. Some objects have been included because they are known to have a very late spectrum or very red colors, while others have been included because they *may* be very red and of very late type (see Sec. 5). Although additional targets remain in our observing lists, we now present a list of the first 20 dwarfs having types of M7 or later, as classified using the spectroscopic criteria in Sec. 3. Class M7 was chosen as the cutoff for two reasons: (1) The mass–luminosity relations of Henry & McCarthy (1993), if pushed to masses lower than the empirical data, suggest that objects at the theoretical brown dwarf upper limit of 0.074–0.080 $\mathscr{M}_\odot$ may have absolute magnitudes corresponding to spectral types around M7—an effect also suggested by the extrapolation of the spectral class vs mass relation of Kirkpatrick & McCarthy (1994) to substellar masses. (However, it is possible that future data at lower masses may show that these relations downturn sharply as the substellar mass limit is approached, hence the need to study these objects in more detail). (2) The galactic distribution of M dwarfs appears to change markedly around a type of M6–6.5, indicating that objects classified as M7 and later may belong to a population which is kinematically different from—i.e., younger than—earlier M dwarfs (Kirkpatrick *et al.* 1994), although this effect is currently based on only a few objects.

This list of 20 late dwarfs is presented in Table 1. Object

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[1] Observations reported here were obtained at the Multiple Mirror Telescope Observatory, a facility operated jointly by the Smithsonian Institution and the University of Arizona.

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0004-6256/95/109(2)/797/11/$0.90

TABLE 1. Dwarfs with spectral types of M7 V or later.

Object Name (1)	RA (1950) (2)	Dec (1950) (3)	Epoch (4)	Pos. Ref. (5)	μ ($''$yr^{-1}) (6)	θ (°) (7)	μ Ref. (8)	Obs. Date (UT) (9)	Telescope[a] (10)	Int. (s) (11)	Spectral Type[b] (12)	$\pi \pm \sigma$ ($''$) (13)	π Ref. (14)	In GJ91? (15)	M_V (16)	M_{I_C} (17)	$M_{K_{CIT}}$ (18)	Phot. Ref. (19)
BRI 0021-0214	00:21:51.1	−02:14:59	1992.5	1	0.212[c]	320	1	1993 Nov 01	McD	1200	*≥M9.5 V*	.0825±.0034	1	no	—	14.65	10.22	1
PC 0025+0447	00:25:07.6	+04:47:06	1991.5	2	<0.04	—	2	1991 Oct 17	MMT	10800	*M9.5 V*	(.015)	2	>25pc	—	—	—	—
RG 0050-2722	00:50:28.4	−27:22:17	1978	3	0.098	26.0	3	1991 Sep 15	MMT	3600	M8: V	.0505±.0031	3	no	20.02	15.18	11.06	2
CTI012657.5+280202	01:24:52.5	+27:50:23	1990	4	—	—	—	1990 Sep 13	MMT	3900	M8.5 V	(.020)	4	>25pc	—	—	—	—
LP 412-31	03:18:07	+18:43.8	1950	5	0.446	123	4	1992 Sep 04	MMT	2700	M8 V	(.11)	5	no	—	—	—	—
LHS 2065	08:51:05.6	−03:18:07	1992.1	1	0.576	250.2	5	1990 Jan 21	MMT	1500	M9 V	.1173±.0015	6	yes	19.15	14.79	10.33	3
LHS 2243	10:13:46	+28:07.2	1950	6	0.510	190.5	5	1992 Feb 25	MMT	2386	M8 V	(.12)	5	no	—	—	—	—
LHS 2397a	11:19:18.1	−12:56:46	1992.1	1	0.515	261.0	5	1990 Nov 22	MMT	1500	M8 V	.0700±.0021	6	yes	18.80	14.18	10.00	3
CTI115638.4+280000	11:54:42.6	+28:12:32	1990	4	—	—	—	1990 Jan 20	MMT	2700	M7 V	(.020)	4	>25pc	—	—	—	—
BRI 1222-1222	12:22:17.1	−12:21:58	1992.5	1	—	—	—	1993 Mar 17	McD	3600	M9 V	(.063)	5	no	—	—	—	—
LHS 2632	12:44:29	+32:04.5	1950	6	0.794	273.6	5	1992 Feb 25	MMT	2390	M7.5 V	(.09)[d]	5	no	—	—	—	—
LHS 2645	12:50:51	+40:50.8	1950	6	0.689	160.9	5	1992 Feb 25	MMT	2385	M7.5 V	(.09)	5	no	—	—	—	—
GD 165 B	14:22:12.0	+09:30:44	1992.5	1	0.259	235.5	6	1991 May 07	MMT	7200	*≥M10 V*	.0278±.0034	7	>25pc	—	16.47	11.39	1
LHS 2924	14:26:36.3	+33:24:06	1992.1	1	0.802	206.2	5	1989 Jul 13	MMT	1980	M9 V	.0908±.0013	6	yes	19.37	15.00	10.46	3
GL 569 B	14:52:08	+16:18.3	1950	7	0.335	108.4	7	1989 Jul 14	MMT	2100	M8.5 V	.0956±.0114	8	yes	—	13.8	9.5	4
LHS 3003	14:53:42	−27:57.1	1950	6	0.965	210.1	5	1993 Mar 17	McD	1200	M7 V	.1524±.0035	9	yes	17.96	13.44	9.84	3
TVLM 513-46546	14:58:54.5	+23:01:50	1987.3	1	0.07	30	8	1993 Mar 16	McD	3600	M8.5 V	.1008±.0023	1	no	—	15.11	10.79	1
TVLM 868-110639	15:07:41.2	−02:29:47	1986.1	1	0.381	273	8	1993 Mar 17	McD	3600	M9 V	.0575±.0019	1	no	—	14.59	10.24	1
vB 8	16:52:55	−08:18.2	1950	6	1.190	222.5	5	1993 Mar 15	McD	1200	M7 V	.1545±.0007	6	yes	17.74	13.18	9.76	3
vB 10	19:14:31	+05:04.8	1950	6	1.461	203.1	5	1989 Jul 10	MMT	1800	M8 V	.1701±.0008	6	yes	18.65	13.95	9.95	3

Notes to TABLE 1

[a] McD = 2.7-m telescope at McDonald Observatory, Mt. Locke, Texas; MMT = Multiple Mirror Telescope on Mt. Hopkins, Arizona.

[b] Spectral types in italics represent tentative classifications.

[c] Irwin et al. (1991) find $\mu = 0.18 \pm 0.01''\mathrm{yr}^{-1}$, and Tinney (1993) finds $\mu = 0.14''\mathrm{yr}^{-1}$ at $\theta = 330°$.

[d] Comparison of V and I photometry of vB 8 and LHS 2632 in Hartwick et al. (1984) to V and I photometry of vB 8 and vB 10 in Leggett (1992) suggests a parallax only half this large.

REFERENCES TO POSITIONS: (1) Tinney et al. 1993; (2) Schneider et al. 1993; (3) Reid & Gilmore 1981; (4) Kirkpatrick et al. 1994; (5) Luyten 1974a; (6) Luyten 1979b; (7) Gliese & Jahreiss 1991

REFERENCES TO PROPER MOTIONS: (1) Luyten 1980; (2) Schneider et al. 1993; (3) Ianna 1993; (4) Luyten 1974a; (5) Luyten 1979b; (6) Zuckerman & Becklin 1992; (7) Gliese & Jahreiss 1991; (8) Tinney 1993

REFERENCES TO PARALLAXES: (1) Tinney 1993; (2) Schneider et al. 1993; (3) Ianna 1994; (4) Kirkpatrick et al. 1994; (5) this paper; (6) Monet et al. 1992; (7) Zuckerman & Becklin 1992; (8) Gliese & Jahreiss 1991; (9) Ianna 1993

REFERENCES TO PHOTOMETRY: (1) Tinney et al. 1993; (2) Reid & Gilmore 1984; (3) Leggett 1992; (4) Forrest et al. 1988

names and coordinates are given in columns (1)–(3). All coordinates are given in equinox 1950, where the epoch of observation is given in column (4). The references for each of these positions is given in column (5). Proper motions and directions, when known, are given in columns (6)–(7). The references for these are given in column (8). Finder charts for each of the entries in Table 1 are given in Fig. 1. The finder charts have been made from the 1950 Palomar Observatory Sky Survey, so the current positions of these proper motion objects will be different. This displacement provides an additional confirmation of each target.

3. SPECTRA

Spectra covering 6300 to 9000 Å are presented in Fig. 2 and were acquired at the 4.5 m Multiple Mirror Telescope on Mt. Hopkins, Arizona, and the 2.7 m McDonald Telescope on Mt. Locke, Texas. The dates of observation, telescope used, and integration times are given in columns (9)–(11) of Table 1. Details of the observing setups are provided in Henry *et al.* (1994).

3.1 Quantifying Spectral Types for Very Late M Dwarfs

For these late dwarfs a quantitative classification scheme is now presented which incorporates the previously assigned types of M7 V for vB 8, M8 V for vB 10, and M9 V for LHS 2924 (Boeshaar & Tyson 1985). The least-squares minimization technique presented in Kirkpatrick *et al.* (1991), which for early- and mid-M dwarf spectra has the advantage of assigning types based on both spectral features and spectral slope, becomes less efficient at assigning types for the latest M dwarfs. This is because the numerous TiO bands begin to saturate for such cool dwarfs, so the classifications begin to rely too strongly upon the slope (color) of the spectrum.

For spectra typed as M7 or later, an additional classifier is required to assure that the strengths of the temperature-dependent features are adequately reflected in the spectral type. The best feature over the 6300–9000 Å spectral range is the VO absorption band centered at 7445 Å because it is strongly dependent on temperature and is not contaminated by telluric bands.[3] This VO ratio is calculated as follows:

$$\text{VO ratio} = \frac{0.5625(F_{7350\rightarrow7400\ \text{Å}}) + 0.4375(F_{7510\rightarrow7560\ \text{Å}})}{F_{7420\rightarrow7470\ \text{Å}}},$$

where $F_{\lambda_1\rightarrow\lambda_2}$ is the flux integrated between wavelengths λ_1 and λ_2. This is simply the ratio of flux expected in the absence of the VO feature (as interpolated between "continuum" points on either side of the band) to the actual flux observed at 7445 Å. From this ratio alone, an M dwarf subclass can be assigned as follows:

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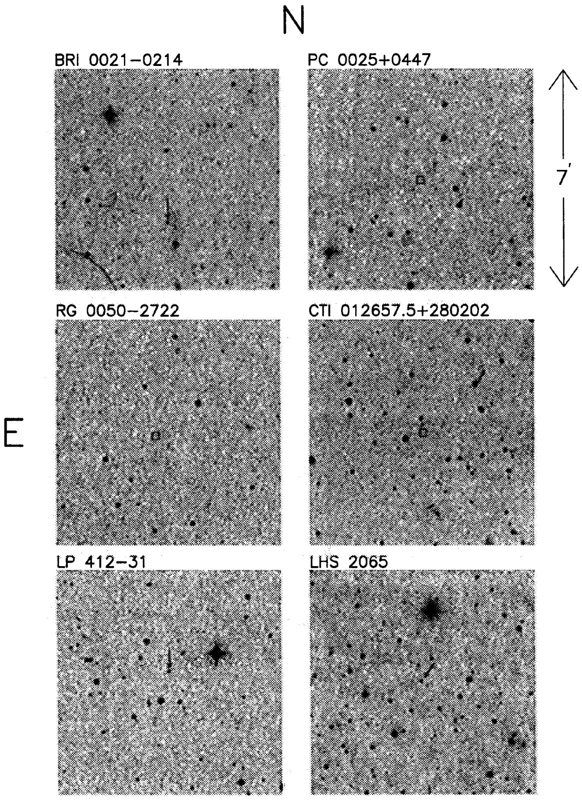
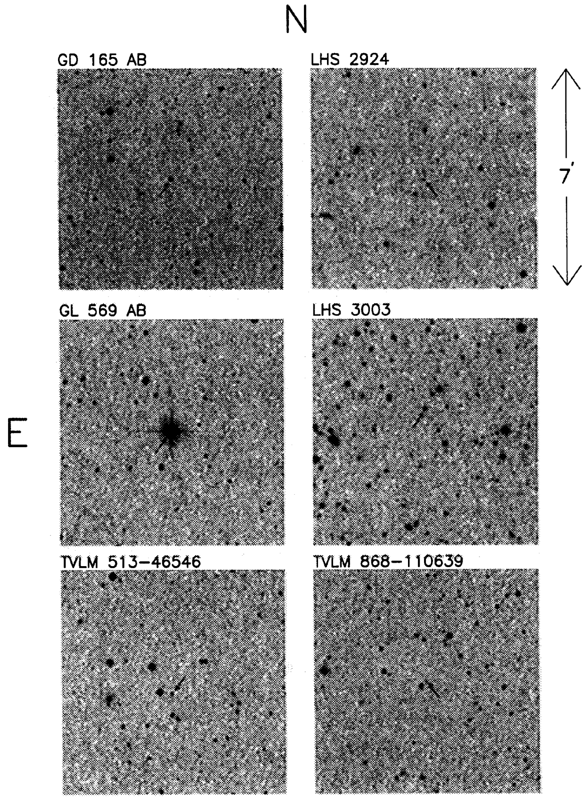
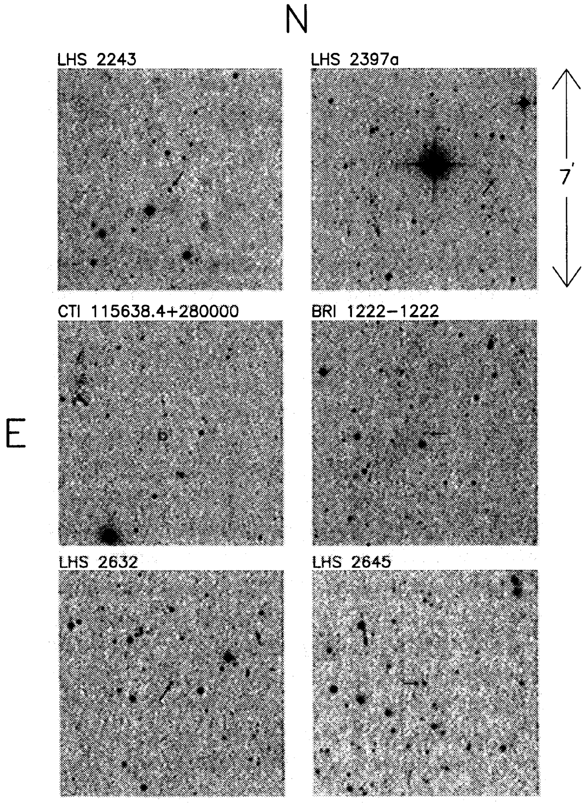
[3] The VO features at 7900 and 8600 Å could not be used in a similar way for lack of suitable "continuum" points. As shown in Sec. 4, the 7455 Å feature itself begins to fail this test beyond type M9 V.







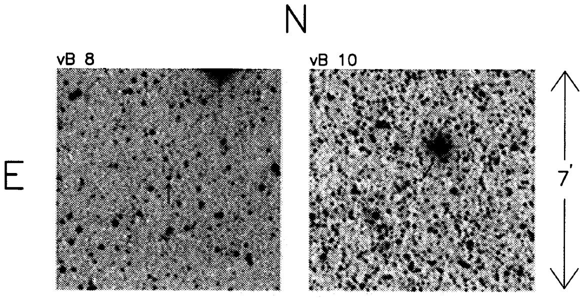


FIG. 1. Finding charts for the 20 late M dwarfs listed in Table 1. The charts have been digitized from the 1950 Palomar Observatory Sky Survey E plates and are 7 arcmin on a side with north up and east to the left. For the two objects in close binaries, GD 165 B and GL 569 B, the brighter A component is marked. Infrared images showing the position of B relative to A can be found in Becklin & Zuckerman (1988) for GD 165 B and in Forrest *et al.* (1988) for GL 569 B. Four other objects are invisible on the E plates, so their approximate positions are indicated by boxes—detailed finding charts can be found in Schneider *et al.* (1991) for PC 0025+0447, Reid & Gilmore (1981) for RG 0050−2722, and Kirkpatrick *et al.* (1994) for the two CTI targets. For the high-motion objects vB 8 and vB 10, Figs. 6 and 7 of Boeshaar & Tyson (1985) provide finder charts at a more recent epoch.

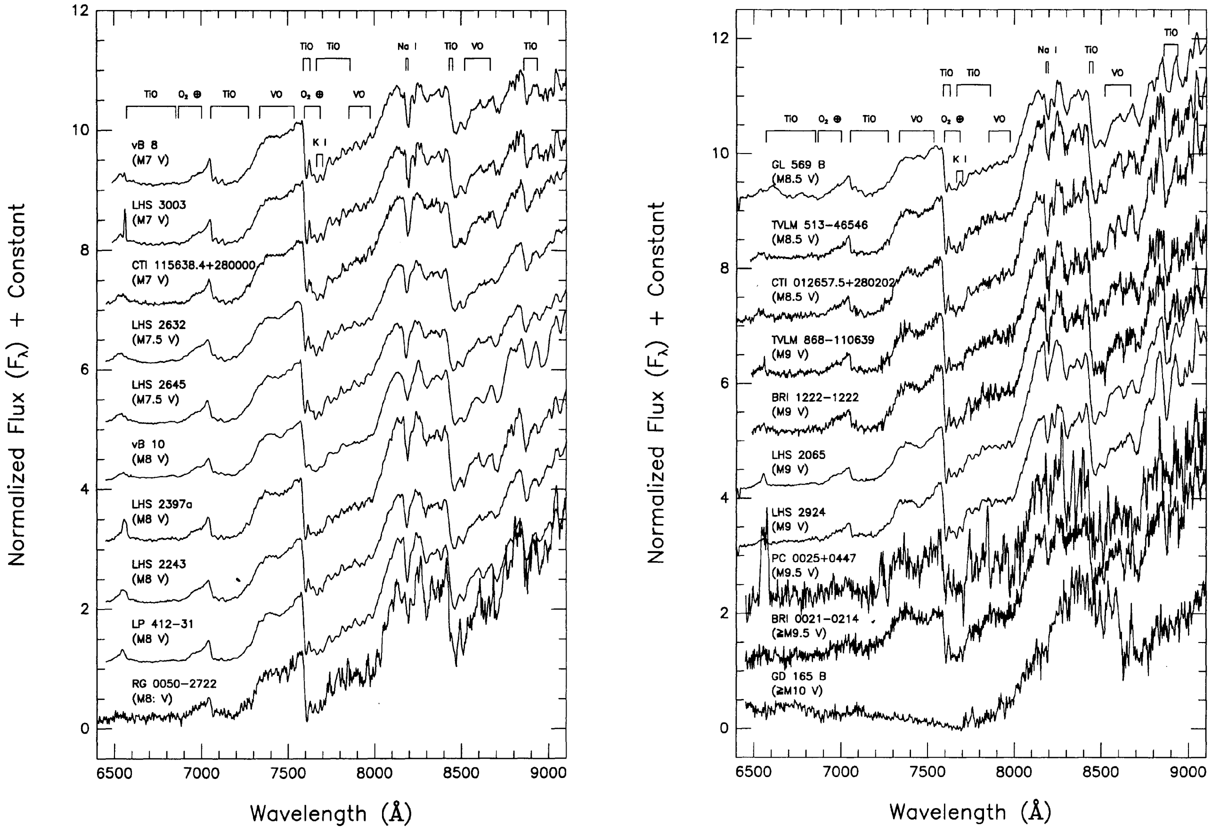


FIG. 2. Spectra of the 20 late M dwarfs listed in Table 1. The flux scale of each spectrum is normalized to unity at 7500 Å (except for GD 165 B, which has been normalized arbitrarily), and integral offsets have been added to separate the spectra vertically. The MMT and McDonald spectra have resolutions of 18 and 12 Å, respectively. Prominent features are marked at the top portion of each panel. (Note that atmospheric absorption features such as the A and B bands of O_2 have not been removed.)

Subclass 7: $1.02 \leqslant \mathrm{VO\ ratio} < 1.07$
(for vB 8, VO ratio$=1.040$),
Subclass 8: $1.07 \leqslant \mathrm{VO\ ratio} < 1.12$
(for vB 10, VO ratio$=1.087$),
Subclass 9: $1.12 \leqslant \mathrm{VO\ ratio} < 1.17$
(for LHS 2924, VO ratio$=1.158$).

The *final* classifications for dwarfs of type M7 or later are made by averaging the spectral subclass (7, 8, or 9) given by the minimization technique of Kirkpatrick *et al.* (1991) and the subclass (7, 8, or 9) given by the VO ratio above, leading to half-integral subtypes of M7, M7.5, M8, M8.5, and M9. The resulting spectral types are given in column (12) of Table 1 and are accurate to a half subclass.[4] Note that BRI 0021−0214, PC 0025+0447, and GD 165 B are cooler than spectral type M9, so their classifications should be regarded as tentative. Quantitative classifications for types of M9.5 and later will be produced after more of these objects are discovered.

3.2 Assigning Parallaxes and Absolute Magnitudes

These spectral types can be used to estimate distances to objects lacking trigonometric parallax determinations. Column (13) of Table 1 lists these parallaxes, where nonparenthetical entries are trigonometric values and parenthetical ones are estimates using spectral types and photometry. References for these are given in column (14). For four objects (LP 412−31, LHS 2243, LHS 2632, and LHS 2645) we have made estimates by comparing Luyten's crude *pg* and *R* magnitudes of these objects to the *pg* and *R* magnitudes he lists for objects (from our Table 1) of similar spectral type and of known trigonometric π. As shown in the footnote to LHS 2632, these estimates should be regarded as highly uncertain. Of the 20 objects included in Table 1, 16 fall within the 25 pc distance limit of the Catalogue of Nearby Stars (Gliese & Jahreiss 1991). Column (15) indicates the seven objects which are currently included in the catalog, the nine which should be added, and the four that fall beyond 25 pc.

For those with trigonometric parallaxes, absolute V, I_C, and K_{CIT} magnitudes are given in columns (16)–(18) of

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[4] The two techniques most often give identical results; the values from the minimization technique are the same as those from the VO ratio for twelve of the objects. When there is disagreement, no systematic difference is apparent; for three of the objects the value given by the minimization technique is one subclass *larger* than that given for the VO ratio, whereas for another two objects, it is one subclass *smaller*. Classifications for the remaining three objects—RG 0050−2722, GD 165 B, and GL 569 B—represent special cases and are discussed more fully in Sec. 4.

Table 1. The photometric references are given in column (19).

4. NOTES ON INDIVIDUAL OBJECTS

Notes on the discovery and classification of each of the objects in Table 1 are given below:

BRI(=B, R, and I photographic plates) 0021−0214, type≥M9.5 V (tentative)—Originally identified by Luyten (1980), this object was rediscovered during a photometric survey for high-*z* quasars by Irwin *et al.* (1991), who recognized its low luminosity and gave it the BRI designation listed above. The original Luyten designation—LP 585−86—has not been retained here because the NLTT Catalogue (Luyten 1979a) also lists another object (at 1950 R.A. =00:36:16, Dec=+03:25.8) with the same discovery name. Of the objects listed in Table 1, only GD 165 B has a cooler spectrum. The calculated VO ratio of this object is only 1.093 because the "continuum" on the redward side of the 7445 Å band is contaminated by the VO absorption itself. The tentative spectral type reflects the fact that the VO bands appear stronger than those in the next object discussed below. For more on this intriguing object, see Basri & Marcy (1994).

PC(=Palomar CCD grism survey) 0025+0447, type M9.5 V (tentative)—Discovered serendipitously by Schneider *et al.* (1991) during a grism survey for high-*z* quasars, this object has Hα emission with an equivalent width ten times larger than any other dMe known. Despite this peculiarity, PC 0025+0447 is a continuation of the spectral sequence to temperatures cooler than that of the M9 dwarfs. A 3800–8800 Å spectrum of this object acquired at the Keck telescope is presented in Mould *et al.* (1994). Discussion on whether PC 0025+0447 is a brown dwarf or a star can be found in Graham *et al.* (1992) and Mould *et al.* (1994). PC 0025+0447 has a VO ratio=1.345, but this is based on our noisy spectrum. A by-eye comparison to LHS 2924 and LHS 2065, both of type M9 V, shows that the VO features in PC 0025+0447 appear slightly stronger, implying a slightly later spectral type.

RG (=Reid & Gilmore) 0050−2722, type M8: V—Discovered by Reid & Gilmore (1981) during a survey for M dwarfs toward the South Galactic Cap, this was the first very late dwarf discovered via purely photometric means. Follow-up work by Liebert & Ferguson (1982) showed that its spectrum resembles that of vB 10. RG 0050−2722 is the only entry in Table 1 having spectral determinations from the VO ratio and the least-squares minimization technique (see Sec. 3) differing by more than one subclass. Its spectrum has a VO ratio[5] indicating a type of M7 V but a spectral slope which is clearly redder than an M8 V. We therefore assign RG 0050−2722 a spectral type of M8: V to reflect this discrepancy. As Table 1 shows, it has absolute magnitudes indicative of class M9 (although the scatter in absolute magnitude at a given spectral subclass is large, perhaps due to metallicity effects), but its $I-K$ color of 4.12 is intermediate between the M8 dwarfs vB 10 ($I-K=4.00$) and LHS 2397a ($I-K=4.18$).

CTI (=CCD/Transit Instrument) 012657.5+280202, type M8.5 V—Discovered by Kirkpatrick *et al.* (1994), this is the reddest dwarf found in the photometric survey of the CCD/Transit Instrument.

LP (=Luyten Palomar) 412−31, type M8 V—Originally identified by Luyten (1974a), this object was first recognized as a very late M dwarf during the search discussed in Sec. 5.

LHS (=Luyten Half Second) 2065, type M9 V—Originally identified as a high-motion object by Luyten (1972) and named LP 666−9, this object was first recognized as having a very cool spectrum by Bessell (see Reid 1987).

LHS 2243, type M8 V—Originally identified as a high-motion object by Luyten (1974b) and named LP 315−53, this object was first recognized as a very late M dwarf during the search discussed in Sec. 5.

LHS 2397a, type M8 V—Originally identified as a high-motion object by Luyten (1979b) and given an alternate designation of LP 732−94, this object was first recognized as having the colors of a very late M dwarf by Probst and Bessell (see Liebert *et al.* 1984).

CTI 115638.4+280000, type M7 V—Discovered by Kirkpatrick *et al.* (1994), this is one of the latest dwarfs found in the photometric survey undertaken by the CCD/Transit Instrument.

BRI 1222−1222, type M9 V—Identified as a very red object by Irwin *et al.* (see Tinney *et al.* 1993), this dwarf was first recognized as having a very low luminosity by Tinney *et al.* (1993).

LHS 2632, type M7.5 V—Originally identified as a high-motion object by Luyten (1976) and named LP 321−222, this object was first recognized as a very late M dwarf during the search discussed in Sec. 5. Earlier *VRI* photometry by Hartwick *et al.* (1984) also showed LHS 2632 to be very red.

LHS 2645, type M7.5 V—Originally identified as a high-motion object by Luyten (1974a) and named LP 218-8, this object was first recognized as a very late M dwarf during the search discussed in Sec. 5.

GD (=Giclas Degenerate) 165 B, type ≥M10 V (tentative)—Discovered by Becklin & Zuckerman (1988) as a close companion to the white dwarf GD 165 A (separation 4″), this object has the latest spectral type and lowest luminosity of any known dwarf (Kirkpatrick *et al.* 1993; Zuckerman & Becklin 1992). GD 165 B is the most promising brown dwarf candidate known, but unfortunately the separation of the binary implies a large orbit with period of over 1000 yr, making dynamical mass determinations impossible. The VO ratio cannot be computed from our spectrum because the detected flux in this wavelength region is dominated by spillover light from the white dwarf primary, GD 165 A [see Kirkpatrick *et al.* (1993) for details]. The uniqueness of this spectrum suggests a type later (i.e., ≥M10 V) than the other objects in Table 1. To demonstrate this uniqueness, Fig. 3 shows the spectral sequence decreasing in temperature from BRI 1222−1222 to BRI 0021−0214 to GD 165 B. Note that the main differences seen between the spectra of the two BRI objects comes in the regions covered by

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[5] A higher signal-to-noise spectrum should be taken to see if this VO ratio still holds.

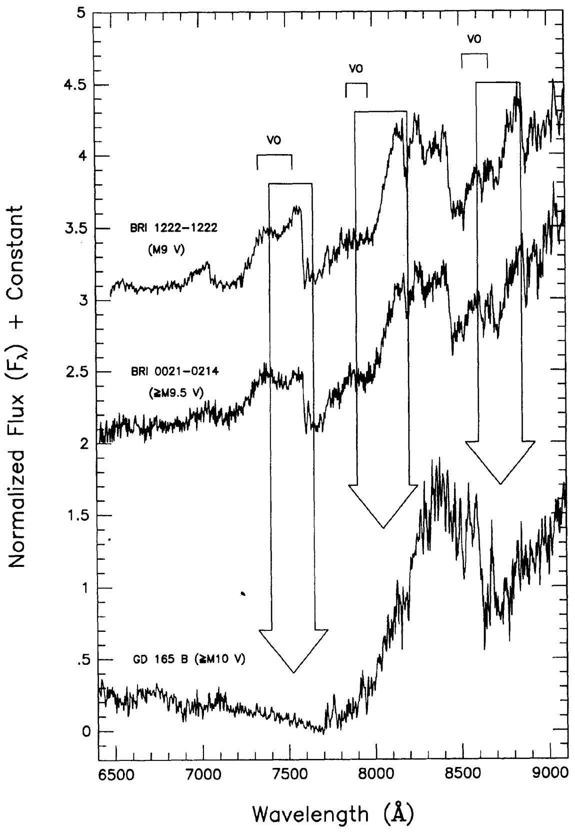

FIG. 3. Spectra of three of the latest objects from Fig. 2. Note that the main differences between the M9 spectrum of BRI 1222−1222 and the cooler spectrum of BRI 0021−0214 are the height of the pseudocontinuum points at 7550 and 8250 Å and the depth of the feature near 8700 Å (marked by arrows). In each case, these represent areas of increased absorption in the spectrum of the cooler object. Note also that each of these absorptions falls on the red side of a known VO band system, suggesting that the redward edges of the VO bands gain strength at lower temperatures. If these increased absorptions are extrapolated to lower temperatures, then they could produce the pseudocontinuum peak at 8350 Å seen in the spectrum of GD 165 B, shown at the bottom of the panel. An increasingly red continuum combined with enhanced VO absorption could, therefore, explain the peculiar spectral appearance of GD 165 B.

the arrows. In each case, these are areas of increased absorption in the spectrum of the cooler object (BRI 0021−0214). If this increase in absorption continues down the temperature sequence, then the "bump" between 8300 and 8600 Å in the spectrum of GD 165 B can be explained as a relative opacity minimum located between these strong bands. Note that each of these increased absorptions lies on the redward edge of one of the VO bands labelled in Fig. 2 (and again in Fig. 3 for clarity). It appears, therefore, that it is a redward strengthening of the VO bands which may be causing the unusual spectral appearance of GD 165 B. However, the situation is far from certain. Although of a very different surface gravity, late-type M giants do not show this sort of behavior in their VO band systems (see spectra in Bessell 1991). The possibility remains that the enhanced absorption seen in our spectrum of GD 165 B is caused by some previously unidentified absorption species.

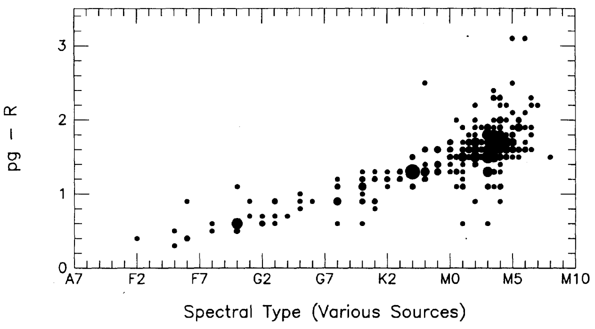

FIG. 4. Luyten $pg-R$ color vs dwarf spectral class for objects with $\mu \geq 1\overset{''}{.}00$ yr^{-1} (Luyten 1979b) and with spectral types in the literature. White dwarfs, subdwarfs, and higher luminosity objects like Arcturus are not included. The smallest circles represent 1 data point each; where 2 data points fall together, a slightly larger circle is drawn, etc. The largest circle, at type K4, represents the superposition of 11 different points. The horizontal axis shows tick marks for every unit subclass, where no subclasses are labelled as K6, K8, or K9 in accordance with Kirkpatrick *et al.* (1991). The scatter is large due to large $pg-R$ color errors and to heterogeneous classifications, but nonetheless it is clear that very red candidates (later than M5) can be selected by using the $pg-R$ color as a preliminary selection criterion.

LHS 2924, type M9 V—Originally identified as a high-motion object by Luyten (1979a) and named LP 271−25, the late spectral type and low luminosity of this object were first reported by Probst & Liebert (1983). With this announcement, LHS 2924 became the "dwarf of lowest luminosity"—a title which vB 10 had held for the previous 39 years and a title which GD 165 B now holds.

GL (=Gliese) 569 B, type M8.5 V—Discovered by Skrutskie *et al.* (1987b) as a close companion to the M dwarf GL 569 A (separation 5″), this object has an orbital period of ~500 yr. Its status as a possible brown dwarf has been addressed in Forrest *et al.* (1988) and Henry & Kirkpatrick (1990). Our spectrum of GL 569 B suffers from contamination by the primary, so its spectral type was assigned more carefully, as described by Henry & Kirkpatrick (1990).

LHS 3003, type M7 V—Originally identified as a high-motion object by Luyten (1975) and named LP 914−54, the extremely red colors of this object were first reported by Hartwick *et al.* (1984). Its late spectral type was first announced in Ruiz *et al.* (1990).

TVLM (=Tinney Very Low Mass) 513−46546, type M8.5 V—Discovered by Tinney *et al.* (1993) as the result of a photometric survey using POSS-II plates, this object was confirmed to have a very low luminosity by Tinney (1993).

TVLM 868−110639, type M9 V—Discovered independently by Tinney *et al.* (1993) and by Irwin (1994; whose discovery name is BRI 1507−0229), this object was also confirmed to have a very low luminosity by Tinney (1993).

vB (=van Biesbroeck) 8, type M7 V—Discovered by van Biesbroeck (1961) as a common proper motion companion (separation 221″) to the Wolf 629/630 AB system, this object was confirmed to have an extremely cool spectrum by Walker (1980). It is one of the few dwarfs listed in Table 1 that has been monitored for signs of duplicity. An astrometric perturbation was reported by Harrington *et al.* (1983), and an infrared companion was detected by McCarthy *et al.* (1985) at a separation of 1″. Follow-up observations by groups such

TABLE 2. Spectroscopic observations of proper motion objects from the NLTT Catalogue.

Object Name (1)	RA (1950) (2)	Dec (1950) (3)	μ (″/yr) (4)	θ (°) (5)	Obs. Date (UT) (6)	Telescope (7)	Int. (s) (8)	Spectral Type (9)	Color (10)	$pg - R$ (11)	R (12)
LP 704-43	00:02:34	−11:35.9	0.314	109	1992 Sep 03	MMT	1500	M4.5 V	m+	3.6	17.2
LP 465-27	00:27:01	+10:05.4	0.238	117	1992 Sep 04	MMT	1500	M5.5 V	m+	3.0	17.3
LP 405-39	00:35:43	+16:42.5	0.292	109	1992 Sep 04	MMT	1500	M5.5 V	m+	3.4	17.1
LP 766-89	00:58:21	−19:49.6	0.371	148	1992 Sep 03	MMT	1500	M5 V	m+	3.5	17.2
LP 467-31	01:13:54	+13:03.8	0.410	155	1992 Sep 04	MMT	300	<K5	m+	3.5	17.3
LHS 1252	01:25:44	+01:56.0	0.621	109	1991 Nov 13	MMT	2400	M6 V	m+	>3.2	17.8
LP 708-98	01:31:44	−11:14.8	0.250	216	1992 Sep 04	MMT	1500	M4.5 V	m+	3.5	17.5
LP 885-45	02:16:03	−27:54.4	0.290	214	1992 Sep 04	MMT	748	M4.5 V	m+	3.4	17.0
LP 353-59	02:22:45	+23:55.2	0.235	116	1992 Sep 03	MMT	1200	M4.5 V	m	3.5	17.4
LP 410-39	02:28:30	+20:49.3	0.404	70	1992 Sep 03	MMT	600	M5 V	m+	3.7	17.2
LP 471-17	02:47:47	+11:13.1	0.335	185	1992 Sep 03	MMT	900	sdM	m	3.0	18.0
LP 412-31[a]	03:18:07	+18:43.8	0.446	123	1992 Sep 04	MMT	2700	M8 V	m+	3.2	17.6
LP 300-55	03:29:59	+32:36.4	0.210	125	1993 Oct 31	McD	2400	M4.5 V	m+	4.0	16.8
LHS 1630	04:05:13	−24:36.6	0.658	163	1993 Oct 31	McD	780	M3.5 V	m	2.8	12.0
LHS 1691	04:37:23	+15:33.6	0.597	170	1991 Nov 13	MMT	1200	sdM	m	3.3	17.4
LHS 1807	06:00:14	−20:20.1	0.579	356	1993 Oct 31	McD	600	M3 V	m+	2.8	12.2
LP 159-47	06:01:59	+47:20.4	0.233	146	1993 Mar 17	McD	3600	M4.5 V	m	3.5	17.4
LP 160-38	06:30:56	+50:24.8	0.217	160	1993 Mar 16	McD	2400	<K5 V	m	3.5	17.3
LP 365-19	07:29:06	+26:20.1	0.248	203	1993 Mar 14	McD	3600	M4.5 V	m	3.3	17.1
LP 785-18	08:34:03	−19:10.0	0.215	162	1993 Oct 31	McD	1200	M3 V	m+	3.0	13.2
LHS 2045	08:41:18	+06:11.9	0.516	141	1990 Nov 23	MMT	1200	sdM	m+	3.3	17.5
LHS 2067[b]	08:51:43	−24:35.6	0.630	78	1991 May 07	MMT	600	sdM	m+	2.7	17.7
LHS 2068[b]	08:51:44	−24:35.6	0.630	78	1991 May 07	MMT	600	<K5	g-k	0.9	17.9
LHS 5142	08:59:34	+00:45.2	0.496	261	1990 Jan 21	MMT	900	M6 V	m+	3.8	17.2
LP 427-38	09:22:50	+17:17.7	0.225	273	1993 Mar 15	McD	4800	M6 V	m+	3.5	17.2
LP 608-54	09:52:34	−00:26.5	0.298	144	1993 Mar 17	McD	3600	M4 V	m+	3.5	17.1
LP 315-11	09:54:35	+26:47.2	0.374	261	1993 Mar 16	McD	3600	M4.5 V	m+	3.5	17.3
LP 166-56	09:58:56	+45:59.4	0.191	276	1993 Mar 14	McD	2400	M5 V	m+	3.2	17.5
LHS 2238[c]	10:11:33	+44:09.8	0.976	230	1992 Feb 25	MMT	300	sdM	m	2.0	12.2
LHS 2243[a]	10:13:46	+28:07.2	0.510	190	1992 Feb 25	MMT	2386	M8 V	m	3.4	17.4
LHS 2352	11:04:04	+33:53.5	0.636	181	1992 Feb 25	MMT	2387	sdM	m+	3.0	17.8
LP 672-19	11:14:53	−09:20.5	0.269	163	1993 Mar 17	McD	3600	M2 V	m+	3.6	17.2
LP 792-32	11:29:41	−19:46.2	0.286	282	1993 Mar 14	McD	3600	M3.5 V	m+	3.3	17.2
LHS 2487	11:56:25	−27:26.6	0.510	303	1993 Mar 16	McD	3600	M4 V	m+	3.5	16.7
LP 434-36	12:01:37	+15:06.3	0.294	155	1993 Mar 15	McD	3600	M4.5 V	m+	3.4	17.3
LHS 2632[a]	12:44:29	+32:04.5	0.794	274	1992 Feb 25	MMT	2390	M7.5 V	m	3.1	17.6
LHS 2645[a]	12:50:51	+40:50.8	0.689	160	1992 Feb 25	MMT	2385	M7.5 V	m+	3.0	17.5
LP 796-36[d]	13:01:25	−21:25.7	0.348	258	1993 Mar 14	McD	1200	M3: V	m+	2.3	17.1
LP 497-97	13:26:43	+09:33.6	0.269	263	1993 Mar 14	McD	3600	M4.5 V	m	3.8	17.0
BD +10°2550[e]	13:26:48	+09:33.5	0.269	263	1993 Mar 14	McD	120	<K5	g	0.6	9.0
LP 855-41	13:34:57	−22:17.2	0.345	137	1993 Mar 16	McD	3600	M5 V	m+	3.4	17.0
LHS 2826	13:53:32	−27:49.1	0.509	260	1992 Feb 25	MMT	888	M4.5 V	m+	2.7	14.3
LP 912-63	14:09:18	−31:44.3	0.268	200	1993 Mar 15	McD	1680	M4.5 V	m+	3.5	16.5
LP 912-62[f]	14:09:18	−31:44.3	0.268	204	1993 Mar 15	McD	1680	M3 V	m+	2.4	14.1
LHS 2887[c]	14:14:55	+31:56.7	0.606	257	1992 Feb 25	MMT	354	M4.5 V p	m	2.3	12.2
LHS 2980	14:45:44	+16:06.6	0.549	282	1992 Feb 25	MMT	2388	M6.5 V	m+	3.1	17.6
LP 803-33	15:45:30	−19:43.5	0.273	228	1993 Mar 15	McD	3000	M5 V	m+	4.0	17.0
LP 759-25[g]	22:02:57	−11:18.9	0.339	242	1992 Sep 04	MMT	977	M5.5 V	m+	3.3	16.7
LHS 3768	22:08:22	−19:54.6	0.597	226	1992 Sep 03	MMT	1500	sdM	m+	3.6	17.1
LP 400-63	22:47:23	+25:31.0	0.238	221	1992 Sep 03	McD	1500	M5.5 V	m+	3.4	17.6
G 156-67[h]	22:53:43	−10:57.3	0.384	221	1993 Nov 01	McD	300	sdM	m+	2.3	13.5
LHS 3933	23:17:34	+11:34.1	0.628	134	1993 Nov 01	McD	4500	M6 V	m	3.0	18.0

Notes to TABLE 2

[a] Also in Table 1.

[b] A common proper motion pair. The spectral type of M10 (III) given for LHS 2067 by Bessell (1991) is erroneous; the wrong objects are indicated on the finder chart in Luyten & Albers (1979). The correct pair is ~ 55″ NE of the pair which is marked (i.e, ~ 4 mm above and to the left on the chart).

[c] The LHS Catalogue (Luyten 1979b) gives $pg - R = 2.5$ for LHS 2238 and LHS 2887.

[d] Luyten (1977) gives $pg - R = 3.5$ for LP 796-36.

[e] This star has LP 497-97 as a common proper motion companion, separation 79″ at $\theta = 276°$.

[f] This star has LP 912-63 as a common proper motion companion, separation 3″ at $\theta = 78°$.

[g] Also known as BRI 2202-1119 (Tinney et al. 1993).

[h] The machine-readable version of the NLTT Catalogue (Warren et al. 1988) gives $pg - R = 4.3$ for G 156-67.

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TABLE 3. Update on the spectroscopic follow-up of very red Luyten proper motion objects.

				— Previous Work —		— This Paper (Table 2) —			
Source Catalog (1)	Restriction on μ (2)	Restriction on color (3)	Total No. of Such Objects (4)	Number Observed (5)	Number of $\geq$M7 Dwarfs (6)	Number Observed (7)	Number of $\geq$M7 Dwarfs (8)	Number Remaining (9)	Estimated No. of Remaining $\geq$M7 Dwarfs (10)
LHS[a]	$\geq 0''.48$ yr^{-1}	$pg-R \geq 2.5$	134	43	4	18	3	73	8-12
NLTT[b]	$<0''.48$ yr^{-1}	$pg-R \geq 3.0$	543	1	0	29	1	513	~17(?)
NLTT[b]	$<0''.48$ yr^{-1}	$2.5 \leq pg-R < 3.0$	1845	~2	0	—	—	~1843	inestimable

[a] Luyten (1979b).
[b] Luyten (1979a, 1980).

as Perrier & Mariotti (1987) and Skrutskie *et al.* (1987a) showed that this companion was spurious, and Monet *et al.* (1992) also reported that the astrometric perturbation was not subsequently confirmed. Later infrared speckle interferometry by Henry (1991) found no companion to limits of M_K=11.8, 13.6, and 13.9 at separations of 2, 5, and 10 AU, respectively.

vB 10, type M8 V—Discovered by van Biesbroeck (1944) as a common proper motion companion (separation 74″) to BD +4°4048, this object was the lowest-luminosity dwarf known until 1983. It was originally thought to have a spectral type of mid M (Herbig 1956) based on an early, very noisy spectrum at blue wavelengths. More than 20 years passed before technology was able to deliver a spectrum extending into the red, shown in Liebert *et al.* (1978). Astrometric observations suggested a companion to vB 10 with a 4.9 yr period (Harrington *et al.*, 1983), but this perturbation has not been confirmed (Monet *et al.* 1992). Using infrared speckle interferometry, Henry (1991) found no companion to a limit of M_K=12.1 at separations of 5 to 10 AU.

5.. SPECTROSCOPIC FOLLOW-UP OF LUYTEN OBJECTS

Four of the entries in Table 1—LHS 2065, LHS 2397a, LHS 2924, and LHS 3003—were recognized through spectroscopic follow-up of the brighter, higher motion objects listed in the LHS Catalogue (Luyten 1979b). Follow-up of many of the fainter LHS targets and of the smaller motion objects listed in the NLTT Catalogue (Luyten 1979a, 1980) has not been done. In an attempt to uncover other late dwarfs in the solar vicinity, we have begun a spectroscopic campaign to classify some of the reddest, though still unstudied, objects identified during Luyten's proper motion surveys.

The LHS and NLTT Catalogues list crude *pg* and *R* magnitudes and an estimated "color class" (giving the star's expected spectral class) for each object. Both the color class and the $pg-R$ color can be used as an estimate of the object's redness. Published spectral types, as compiled in Kirkpatrick (1992), have been reported for 82% of the LHS stars having $\mu \geq 1''.00$ yr^{-1}. Figure 4 plots $pg-R$ against spectral type for this sample. Though the scatter is large due to large color errors and to heterogeneous classifications, it is clear that very red candidates (later than M5 V) can be chosen using the $pg-R$ color as a preliminary criterion for selection.

Classification spectroscopy of some of these previously uninvestigated Luyten targets has been obtained at the MMT and McDonald Observatory. The object list and resulting classifications are given in Table 2. Column (1) gives the name of the object, and columns (2)–(5) give the position (equinox and epoch 1950) and proper motion information as listed in the NLTT Catalogue (Luyten 1979a, 1980). Columns (6)–(8) give the date, telescope, and integration time for the spectroscopic observations. Column (9) lists our spectral type determination. Columns (10)–(12) give the Luyten (1979a, 1980) color class, $pg-R$ color, and *R* magnitude.

Higher motion objects ($\mu \geq 0''.48$ yr^{-1}, given by their LHS designations in Table 2) are included in our observing program if they have $pg-R \geq 2.5$. As shown in Table 3, there are 134 such LHS stars, 43 of which have been classified by previous investigators and another 18 of which have first-time-classifications reported in Table 2. Smaller motion objects ($\mu < 0''.48$ yr^{-1}, listed by LP and G designations in Table 2) are included in our observing program if $pg-R \geq 3.0$. As shown in Table 3, there are 543 of these stars (and an additional 1845 having $2.5 \leq pg-R < 3.0$), only 1 of which has been classified by previous investigators. First-time classifications for 29 more are given in Table 2. Three objects (LHS 2067, LP 497−97, and LP 912−63) are companions to bluer stars (LHS 2068, BD +10°2550, and LP 912−62) for which spectral types are also presented in Table 2. As the predicted numbers in Table 3 show, there are still many unclassified M7 and later dwarfs remaining in the Luyten catalogs.

As would be expected from a proper-motion-selected sample, these red objects comprise two distinct groups—nearby mid- to late-M dwarfs and more distant subdwarfs of extreme type. Most of the observed objects are normal M dwarfs, the latest examples of which are LP 412−31, LHS 2243, LHS 2632, and LHS 2645, whose extreme spectral types have earned inclusion in Table 1. A total of eight objects have been classified as subdwarfs as judged from the strength of the 6750–7050 Å CaH band, and spectra of each of these is shown in Fig. 5. These subdwarfs range from mild examples like LHS 2067 to extreme ones like LHS 3768 and LHS 2352. In fact, the spectrum of LHS 2352 is as red as that of LHS 1742a, the benchmark of the end of the subdwarf main sequence, but has even weaker (in fact, almost absent) TiO bands. Although beyond the scope of this paper, these intriguing objects are worthy of their own follow-up investigations.

The results of this spectroscopic survey are shown graphically in Fig. 6. Solid circles represent 153 objects from Gliese & Jahreiss (1991) for which we have spectroscopic observations classified on the standard system of Kirkpatrick *et al.* (1991). Open triangles are those dwarfs listed in Table 2. Clearly, our attempt at filling in the upper right corner of

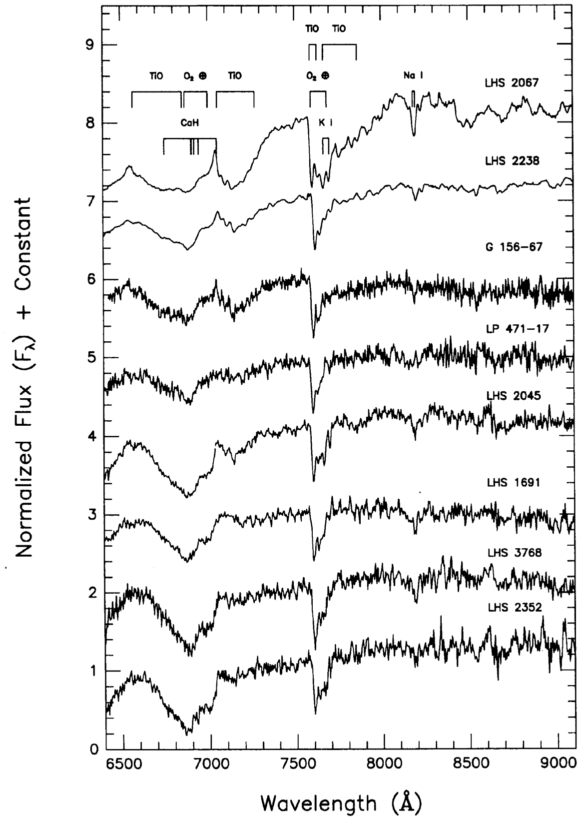

FIG. 5. Spectra of the subdwarfs listed in Table 2. Normalizations, offsets, and resolutions are the same as in Fig. 1. Mild subdwarfs are shown at the top of the panel, and more extreme cases, characterized by enhanced CaH absorption combined with weak or absent TiO absorption, are shown at the bottom.

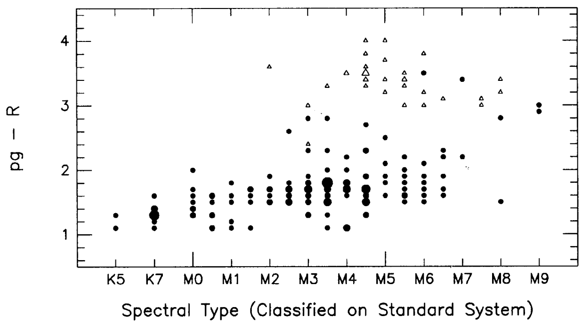

FIG. 6. Luyten $pg-R$ color vs dwarf spectral type for objects classified on the standard system of Kirkpatrick *et al.* (1991). Solid circles represent objects from the Catalogue of Nearby Stars (Gliese & Jahreiss 1991), where superpositions of points appear as larger dots. Open triangles represent the dwarfs listed in Table 2. Despite the extreme $pg-R$ colors of these Table 2 dwarfs, only four have spectral types later than M7 V, indicating that the Luyten $pg-R$ colors become even more inaccurate for these objects which lie near the plate limit in pg.

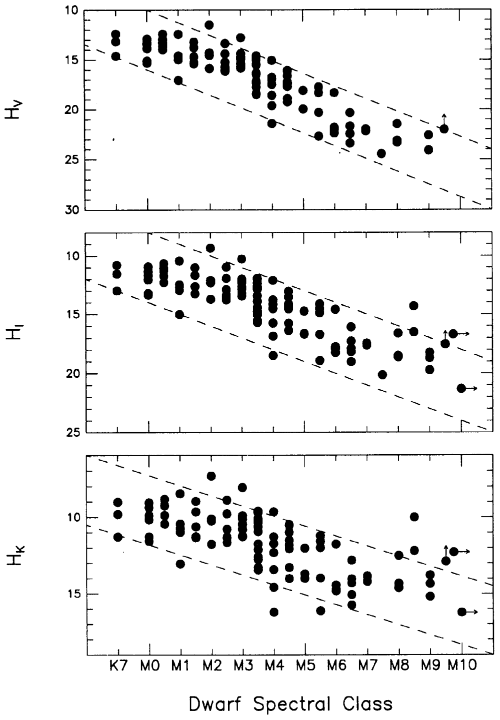

FIG. 7. Reduced proper motion (H) vs dwarf spectral class for objects classified on the standard system of Kirkpatrick *et al.* (1991). The reduced proper motion at V is defined by $H_V = V + 5\log\mu + 5$ (and similarly for I and K). The point with the upward arrow is PC 0025+0447, whose observed value of μ is an upper limit. The points with the rightward arrows are BRI 0021−0214 and GD 165 B, whose spectral types may be later than what is shown. The large majority of late-K through late-M dwarfs falls between the dashed lines, drawn to have the same slope as the observed absolute magnitude vs spectral class relation (see Table 3 of Kirkpatrick & McCarthy 1994). However, later than type M7, the measured values of the reduced proper motion appear to be smaller on average than what is expected from the trend defined by earlier dwarfs. See text for discussion.

Fig. 6 has met with limited success because of the faintness of the entries in Table 2—Luyten's $pg-R$ colors, which are only crude estimates anyway, become even more inaccurate for these objects since most lie near the plate limit in pg. We are currently exploring alternative means of selecting red objects from the Luyten sample, including the use of machine-measured POSS-I magnitudes from the University of Minnesota Automated Plate Scanner.

6. DISCUSSION AND FUTURE PLANS

Figure 7 shows the reduced proper motion H $(=m + 5\log\mu + 5)$ for a set of dwarfs classified on the same system. The trend of reduced proper motion with spectral class appears to change around spectral class M7. Specifically, the observed values of H for cooler dwarfs are smaller than expected if the trend for earlier dwarfs is extrapolated to later types. (This is most noticeable at I and K because the late dwarfs of smaller motion have not been observed at V magnitudes and hence cannot be plotted in the H_V vs spectral class diagram.) At first glance, this effect might be ascribed to a selection bias. The dwarfs earlier than M7 come mainly from the nearby (≤25 pc) sample and were discovered primarily through proper motion surveys. Cooler dwarfs come from Table 1 and have been discovered through a combination of proper motion and photometric surveys. Regardless, the dwarfs of M7 and later which one would expect to populate the lower half of the dashed envelope in the H_K vs spectral class diagram would have proper motions of ~1.″00 yr^{-1} or greater, yet almost all of the known objects with motions this large have already been investigated photometrically and spectroscopically (Table 5.1 of Kirkpatrick 1992; Dahn *et al.* 1983). Apparently, therefore, such objects do not exist. This fact implies that the reduced proper motion, which can also be written as $H=M+5\log v_T-3.38$ (where v_T is the tangential velocity in km/s), may truly be smaller than expected for the latest dwarfs, meaning that their tangential velocities are also smaller on average. Statistically, this would imply a smaller overall space motion, indicating that these objects may be younger than early- to mid-M dwarfs.

The suggestion that these very late M dwarfs may comprise a young population raises the issue of whether such objects are stellar or substellar. Ten of the objects in Table 1 have now been scrutinized for the presence of the Li I doublet at 6707 Å (Martín *et al.* 1994; Mould *et al.* 1994; Basri & Marcy 1994). The feature has not been detected, implying that these objects have masses greater than $\sim 0.06\ \mathscr{M}_\odot$. This does not, however, rule out the possibility that the entries in Table 1 are brown dwarfs because they could still be substellar and have masses between ~0.06 and $\sim 0.08\ \mathscr{M}_\odot$. To be certain, dynamical mass determinations need to be obtained, and this requires the discovery of close binaries. The 16 field objects listed in Table 1 (where the companions to known stars—GD 165 B, GL 569 B, vB 8, and vB 10—have been omitted) are too faint to be imaged by current infrared speckle techniques, which can probe to $M_K \approx 8$. These objects should be imaged by the repaired HST and monitored via radial velocity programs to search for possible companions. Approximately 42% (Fischer & Marcy 1992) of early- to mid-M dwarfs have companions, which implies that ~7 of these field objects should have secondaries if their multiplicity rate is similar. Specifically, ~2 of these are expected to be very close objects falling within 10 AU of their primaries. (Of the others, ~1.5 are predicted between 10 and 100 AU, with another ~1.5 falling between 100 and 1000 AU. The ~2 remaining ones are expected beyond 1000 AU.)

Our spectroscopic observations, including a proposed extension into the southern hemisphere, are continuing in an effort to uncover more of these late dwarfs, and photometric observations of all the dwarfs in Table 1 are also planned. We are acquiring spectra of M dwarfs at near-infrared (J,H,K) wavelengths to extend the spectral sequence across the region of peak flux. These infrared observations provide a broader wavelength coverage, enabling bolometric magnitudes and, with the use of improved model atmosphere calculations (Allard 1990; Allard *et al.* 1994), effective temperatures to be estimated. These estimates will allow the observed late M dwarfs to be placed on the theoretical H–R diagram and compared to calculations from interior models.

7. SUMMARY

Spectra and finder charts have been presented for 20 dwarfs of type M7 or later, and a quantitative spectral classification scheme is given for types M7 through M9. Three of the objects have types later than M9, but quantitative classifications for these extremely cool dwarfs, whose spectra appear to be dominated by enhanced VO absorption, must await the discovery of additional examples.

Using our spectral types together with available photometry, we have estimated distances to those objects lacking trigonometric parallaxes. 16 of the 20 objects fall within 25 pc, and 9 of these are not included in the most recent edition of the Catalogue of Nearby Stars (Gliese & Jahreiss 1991). Our own spectroscopic survey for very late M dwarfs has uncovered four nearby, previously overlooked objects with types of M7 or later. With continued follow-up and discovery of additional examples, we hope to put better constraints on their number density near the Sun and to determine whether such objects are stars or brown dwarfs.

We would like to thank Randy Whited and Fritz Benedict for the POSS-I scans used in Fig. 1. JDK acknowledges support from the W. J. McDonald Fellowship of the University of Texas at Austin and from the Visitors Program at the Space Telescope Science Institute. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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