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MASS–SPECTRAL CLASS RELATIONSHIP FOR M DWARFS

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ABSTRACT

We derive mass–spectral class relationships for M dwarfs in the mass range $0.075 \leq m/M_{\odot} \leq 0.6$, which corresponds to a spectral range of M0–M10. The stellar models are based on the most recent nongray atmosphere models presently available. The results are in excellent agreement with the observed relationship derived by Kircpatrick & McCarthy for dwarfs of spectral type earlier than M7. We show that the spectral subclass is definitely not a linear function of mass and increases abruptly as the substellar mass limit is approached. This behavior reflects the observed trends in color, magnitude, and luminosity as a function of the mass and stems from the very physical properties of very low mass stars.

Objects older than 1 Gyr with a spectral type earlier than M10 (for solar metallicity) are predicted to be main-sequence very low mass stars. For objects with such a spectral class to be bona fide brown dwarfs, they must be younger than 1 Gyr.

Subject headings: stars: evolution — stars: low-mass, brown dwarfs

1. INTRODUCTION

The field of brown dwarf (BD) research bloomed recently with the recent observation of two bona fide brown dwarfs (Rebolo, Martin, & Magazzù 1995; Nakajima et al. 1995). The most natural parameter to distinguish substellar objects from hydrogen-burning stars is the *mass*, with the limit hydrogen-burning minimum mass (HBMM) $\sim 0.07\ M_{\odot}$ for solar metallicity (Chabrier, Baraffe, & Plez 1996). However, in most cases, the mass is not a directly observable quantity, and one must rely on an accurate mass-luminosity (m-L) relationship to identify the mass of the observed object. Moreover, by definition brown dwarfs never reach thermal equilibrium and the luminosity and effective temperature depend on the age, which adds an extra degree of freedom in the mass determination. These difficulties prompted brown dwarf hunters to propose different methods, based on *directly observable* (spectroscopic) quantities, to identify substellar objects. The first diagnostic is the presence of Lithium absorption features in the spectrum (Rebolo et al. 1992; Basri, Marcy, & Graham 1996), the second is the mass–spectral type relationship (Kirkpatrick & McCarthy 1994, hereafter KMC94). The predicted Lithium abundances as a function of age for very low mass stars (VLMSs) and BDs (see, e.g., Nelson, Rappaport, & Chiang 1993) have been examined in a former paper (Chabrier et al. 1996). In the present Letter we derive a theoretical mass–spectral type (m-Sp) relation for these objects. Comparison is made with the empirical relation derived by KMC94. Age and metallicity effects are carefully examined. In order to determine the present uncertainties in the VLMS models, calculations have been conducted with all presently available nongray atmosphere models, and comparisons with the KMC94 observations are examined in four different optical and infrared bandpasses.

2. OBSERVATIONS

Kirkpatrick & McCarthy (1994) have obtained high signal-to-noise spectra of several low-mass, nearby composite systems. Each of these systems consists of an M dwarf primary and an object whose dynamical mass (Henry & McCarthy 1993) places it near the BD limit. The spectral type of the primary and the percentage of flux attributable to each component are known from infrared speckle data, yielding the determination of the spectrum of the secondary. Since the absolute magnitude of the composite system is known from parallax measurements, in several infrared bandpasses (Leggett 1992), the colors and absolute magnitudes for individual components can be generated by differential photometry, using Leggett (1992) compilation (see KMC94 for details). All these objects are identified, from kinematic and photometric observations, as belonging to the young/old disk population, with solar-like metallicities $[M/H] \approx 0$ to -0.5 (Leggett 1992).

From these observations, KMC94 (see their Table 7) provide a determination of the spectral class of each component from three different signatures—the colors, the absolute magnitude, and the spectrum—and obtain an observationally determined m-Sp relationship. The error bar claimed by these authors ranges from ± 0.5 to ~ 1 subclass (see figures below). The dynamical masses of the two faintest objects, GL 234B and LHS 1047B, are 0.083 ± 0.023 and $0.055 \pm 0.032\ M_{\odot}$, respectively, with spectral types M4.5 and M6.5. Later spectral types have been identified by Kirkpatrick, Henry, & Simons (1995) (see also Jones et al. 1995), but the masses of these objects have not been determined.

The data of KMC94 are reproduced reasonably well by a simple *linear* m-Sp relation (eq. [11] of KMC94). *Extrapolating* this relation below $0.08\ M_{\odot}$, KMC94 predict that objects of class M7 or later are likely to be brown dwarfs. However, as they very cleverly notice, there is no reason to believe that the trend is correct as the hydrogen-burning limit is approached. We will show below that such a linear behavior and the extrapolation are not supported by theoretical analysis.

3. THEORY

We have recently derived evolutionary models aimed at describing the mechanical and thermal properties of VLMSs.

These models are based on nongray atmophere models and accurate boundary conditions between the interior and the atmosphere profiles, two necessary conditions for an accurate description of VLMS evolution (Chabrier et al. 1996; Chabrier & Baraffe 1996).

The first generation of these stellar models were based on the so-called "Base" atmosphere models of Allard & Hauschildt (1995, hereafter AH95). These models improved significantly the comparison with the observed Pop I and Pop II M dwarf sequences (Monet et al. 1992), down to the bottom of the main sequence, with respect to previous models based on gray atmospheres (Baraffe et al. 1995). The AH95 models have been improved recently by including more accurate molecular line lists and by using the so-called opacity-sampling technique in the treatment of the monochromatic absorption coefficients. This yields the "NextGen" NG2 models (Allard & Hauschildt 1996). Another set of nongray atmosphere models for M dwarfs, based on different line lists for molecular opacities, has been derived by Brett (1995a, hereafter B95, 1995b) and completed by Plez. These two sets of atmosphere models have been derived from independent sources and thus provide a good determination of the present uncertainties in the atmosphere and stellar VLMS models. These models have already been used to derive a theoretical *m*-L relationship for VLMSs. The stellar models based on the "NG2" and the B95 atmosphere models were found to lead to similar results, in various bandpasses. Both types of models accurately reproduce the observationally derived mass-M_V relation (Henry & McCarthy 1993) down to the bottom of the main sequence (MS) (Chabrier et al. 1996). This clearly illustrates the significant recent improvement in the treatment of VLMS atmosphere and interior models.

The present calculations proceed as follows. The theoretical models predict mass-magnitude-color relationships. Using the color–spectral class relations of KMC94 (see their Table 3) for *four* different colors, we derive a theoretical spectral type, from the predicted colors, for a given mass. This yields a theoretical *m*-Sp relationship. The results for the NG2 atmosphere models are shown in Figure 1. Models based on B95 atmospheres (not shown in the figure for sake of clarity) give similar results (less than 1 subclass difference). The calculations correspond to an age $\tau = 10$ Gyr, about the age of the Galactic disc (Segretain et al. 1994; Hernanz et al. 1994), and a solar metallicity. Agreement between theory and observation is very satisfactory over the whole mass range, except when using the *R* band. This shortcoming stems from the *extreme sensitivity* of the spectral type determination when using the $(V - R)$ color, as can easily be seen from Table 3 of KMC94. Variations of less than 10% around $V - R = 1$ correspond to *four spectral classes*, from M0 to M4.

The spread in the spectral types determined from the models, based on the four different colors (see Fig. 1 caption), clearly illustrates the uncertainty in the theoretical relation. The uncertainty (if we except the *R* band) is ~0.5 in the spectral subclass for $m \gtrsim 0.25\ M_\odot$ and ~1–1.5 below. This is consistent with *observational* uncertainties. On the other hand, comparison with observations in a color-magnitude diagram shows that models based on NG2 or B95 atmospheres are shifted blueward by ~0.5 in $V - I$ (Chabrier & Baraffe 1996). This yields a ~0.5–1 subclass underestimation (see KMC94), within the theoretical and observational uncertainties mentioned above. Interestingly enough, the four different *m*-Sp relations merge below 0.1 $M_\odot$, i.e., near the HBMM, where all

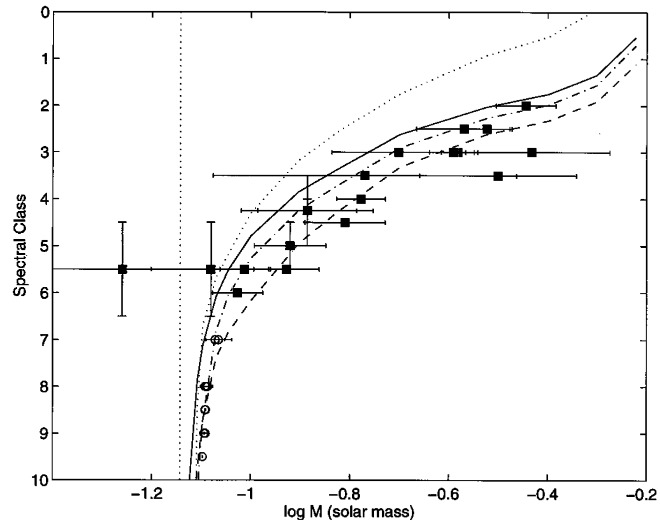

FIG. 1.—Mass–spectral class relationship. The stellar models are based on the NG2 (Allard & Hauschildt 1996) atmosphere models. Metallicity [M/H] = 0 and age $\tau = 10^{10}$ yr. The theoretical spectral class is deduced from different colors, namely, $V - R$ (*dotted line*), $V - I$ (*solid line*), $V - K$ (*dot-dashed line*), and $I - K$ (*dashed line*) using Table 3 of KMC94. *Filled squares*, data of KMC94; *open circles*, data of Kirkpatrick et al. (1995). The mass of the Kirkpatrick et al. 1995 objects is deduced from agreement between theory and observations in different available colors, which yields the present error bars for these objects, as shown in the figure. The vertical dotted line indicates the HBMM.

models predict similar spectral classes. These results confirm that the present, most recent, VLMS stellar models now reach quantitative agreement with all observations, as already shown for the *m*-*L* and *m*-$T_{\rm eff}$ relationships (Chabrier et al. 1996), with an uncertainty of about 0.5–1.5 subclass. Table 1 gives the spectral type–magnitude–temperature–mass relations derived from the present models.

The case of the lowest mass object LHS 1047 deserves special attention. Recent observations of this object (Martín, Rebolo, & Magazzù 1994) do not show any Lithium absorption feature. This implies a *lower* limit $m \approx 0.06\ M_\odot$ for this object (Chabrier et al. 1996), suggesting that the dynamically determined average mass in Figure 1 is likely to be underestimated.

The theoretical relation clearly exhibits an inflection point around M2, i.e., $m \approx 0.4-0.5\ M_\odot$ ($T_{\rm eff} \approx 3500$ K), in *all* bandpasses. This trend reflects the well-known behavior observed in the *m*-*L* and *m*-$T_{\rm eff}$ relationships, a direct conse-

TABLE 1

CHARACTERISTIC OF THE MODELS FOR [M/H] = 0, $\tau = 10^{10}$ yr

$M/M_\odot$	Spectral Type	$T_{\rm eff}$	$L/L_\odot$	M_V	M_I	M_K
0.075	>10	1837.	−4.10	22.88	16.98	11.96
0.078	8–10	2088.	−3.83	20.93	15.86	11.20
0.080	7–8.5	2206.	−3.70	19.97	15.30	10.89
0.085	6–7.5	2415.	−3.48	18.24	14.24	10.37
0.090	5.5–7	2556.	−3.33	17.14	13.53	10.05
0.100	5–6	2734.	−3.12	15.85	12.65	9.61
0.125	4–5	2965.	−2.81	14.32	11.55	8.95
0.150	3.5–4.5	3082.	−2.62	13.53	10.94	8.52
0.200	2.5–3.5	3254.	−2.33	12.46	10.11	7.86
0.300	2–2.5	3403.	−1.97	11.31	9.12	6.99
0.400	2–2.5	3484.	−1.73	10.63	8.51	6.42
0.500	1.5–2	3602.	−1.49	9.90	7.88	5.85
0.600	0.5–1	3823.	−1.21	8.96	7.12	5.19

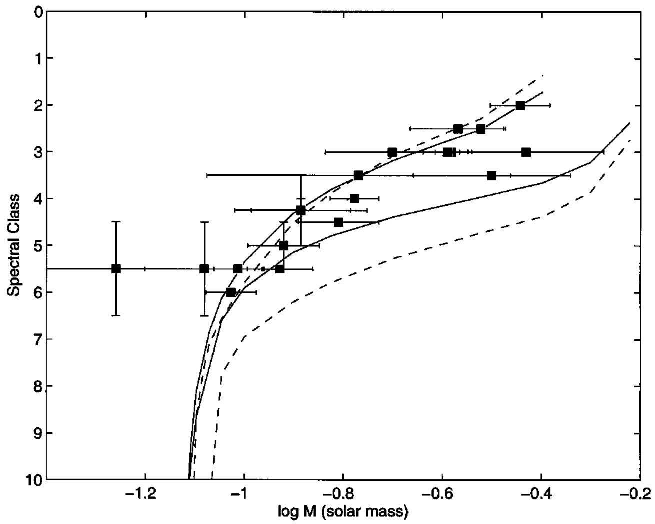

FIG. 2.—Metallicity effect. The stellar models are based on the "Base" (AH95) atmosphere models. *Lower lines*, [M/H] = 0; *upper lines*, [M/H] = −0.5. The spectral types are deduced from $V-I$ (*solid line*) and $I-K$ (*dashed line*). *Filled squares*, data of KMC94.

quence of H_2 molecular dissociation (Kroupa, Tout, & Gilmore 1990; Chabrier et al. 1996), and thus relies on physical grounds. This feature, not taken into account in the KMC94 fitting formula, clearly invalidates a linear mass–spectral type relation and predicts that objects in the range ≈0.2–0.5 $M_\odot$ exhibit similar spectral types ∼M2–M3 for solar metallicities.

The most striking prediction of our calculations is the severe drop in the m-Sp theoretical relation for ≳M5, for all colors. This drop, similar to the one observed in the m-L and m-$T_{\rm eff}$ relations, reflects the onset of ongoing electron degeneracy in the stellar interior characteristic of the end of the stellar domain. This clearly shows that the mass–spectral type relation characteristic of the *stellar* domain cannot be extrapolated into the substellar regime and already breaks down at the bottom of the MS ($m \approx 0.10\ M_\odot$). The HBMM ∼ 0.072 $M_\odot$ (Chabrier et al. 1996) corresponds to a type later than M10 (a type M10 corresponds to $m \approx 0.078\ M_\odot$ with NG2, for an age $t > 1$ Gyr). The transition region between stellar and substellar objects is characterized by a severe steepening of the m-Sp relation from ∼M6 to M10, for solar-like metallicity.

This predicted steepening below ∼0.1 $M_\odot$ is supported by the recent spectral analysis of very low mass objects down the bottom of the stellar domain by Kirkpatrick et al. (1995) and Jones et al. (1995). The *predicted* mass for these objects, obtained from the present theoretical mass-color relations, for any age $\tau \geq 1$ Gyr, are shown in Figure 1, with the observationally determined spectral type. This shows convincingly that the spectral type is *not* a monotonic relation in mass and increases drastically for types later than M6, i.e., $m \lesssim 0.10\ M_\odot$, $T_{\rm eff} \lesssim 2700$ K (see Table 1).

Figure 2 shows the same calculations as Figure 1 when using the "Base" (AH95) atmosphere models, for two colors. The differences between Figures 1 and 2 illustrate the recent improvement in VLMS stellar models. The stellar models based on the "Base" atmosphere models clearly overestimate the observed spectral class, for solar metallicity. This reflects the underestimation of the V-flux (larger M_V) with the "Base" models (Chabrier et al. 1996), which yields a larger $V-I$ and thus a later spectral class.

Metallicity effect.—In order to examine the effect of the metallicity spread characteristic of the young disk–old disk population, calculations have also been conducted for [M/H] = −0.5, with the "Base" models ("NextGen" and Brett-Plez atmosphere models are only available for solar metallicity). The results are shown on Figure 2. The effect of metallicity is larger for the earlier spectral types (≲M6) than for later types. This reflects the observed and predicted trend in the M_V-$(V-I)$ diagram for $M_V > 15$ (Monet et al. 1992; Baraffe et al. 1995). This decreasing sensitivity of bandpasses and spectral classifications below $T_{\rm eff} \sim 3000$ K may suggest their limited adequacy for characterizing very cool objects. For early spectral types, the metallicity dispersion yields differences in the m-Sp relation larger than those arising from the theoretical uncertainties in the colors. This suggests that the metallicity, for a known age, can be determined with reasonable accuracy (Δ[M/H] ≲ 0.5) from the theoretical m-Sp relation, over most of the VLMS mass range.

Interestingly enough, the uncertainty in the models arising from the color determination is almost negligible (<1/2 subclass) for [M/H] = −0.5. Though this feature is likely to be fortuitous and to arise from a shortage of the models (we know from the mass-M_V relation that the "Base" models underestimate the V-flux by ∼0.5 mag; Chabrier et al. 1996), it may also suggest that a substantial number of objects in the KMC94 sample have sligthly subsolar metallicities, so that the color–spectral type empirical determination is not quite accurate for solar metallicity.

Age effect.—The age severely affects the spectral type determination of *substellar objects* since, by definition, these objects never reach thermal equilibrium and their luminosity (≡magnitude) and effective temperature (≡colors) decrease monotonically with time. Indeed, young ($\tau < 10^9$ yr) brown dwarfs and VLMSs at the limit of the HBMM will exhibit spectral classes characteristic of the aforementioned steep region (M6 to M10) of the m-Sp relation. However, assuming a constant stellar formation rate and an age of 10 Gyr for the Galactic disk (Segretain et al. 1994; Hernanz et al. 1994), objects younger than 1 Gyr—the zero age MS for objects with $m \geq 0.08\ M_\odot$—represent ∼10% of the actual population and thus are not numerous enough to modify the predicted behavior of the m-Sp relation.

Figure 3 shows the m-Sp relation for several isochrones. This provides a new, independent diagnostic to identify genuine brown dwarfs. Whereas old ($\tau > 1$ Gyr) bona fide brown dwarfs will have spectral types ≫M10, objects in the range M6–M10 will either be very young (<1 Gyr) brown dwarfs or VLMSs ($m < 0.1\ M_\odot$) on the main sequence.

4. CONCLUSION

We have derived theroretical mass–spectral type relationships characteristic of M dwarfs down to the very bottom of the main sequence. These relations, based on the latest generation of low-mass star evolutionary models, reproduce the observational relations derived by Kirkpatrick & McCarthy (1994) within the error bars in several optical and infrared colors. These comparisons show that, though further improvement is still needed in the atmosphere models, in particular in infrared bandpasses, the present models are now reaching reasonable

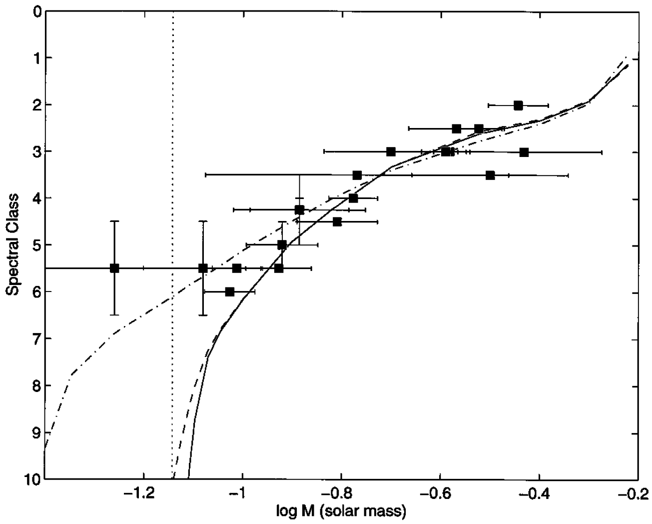

FIG. 3.—Same as Fig. 1 for several isochrones. For sake of clarity, only spectral classes deduced from the $I-K$ color are shown. *Solid line*, $\tau = 10^{10}$ yr; *dashed line*, $\tau = 10^9$ yr; *dash-dotted line*, $\tau = 10^8$ yr.

quantitative agreement with the observations and thus provide more accurate mass determinations.

Uncertainties in the present theory are examined by conducting calculations with all presently available nongray atmosphere models. Stellar models based on the most recent atmosphere models (Allard & Hauschildt 1996; B95) yield similar results and are in excellent agreement with the observations. We estimate uncertainties in the present theory to be ~0.5–1.5 in the spectral subclass, comparable to the observational undetermination.

The calculations show that the linear relation proposed by Kirkpatrick & McCarthy (1994) does not take into account the effect of molecular dissociation around $T_{\rm eff} = 3500$ K, i.e., $m \approx 0.4-0.5\ M_\odot$ for solar metallicity, and that the true mass–spectral type relation exhibits an inflection point around 0.25 $M_\odot$, i.e., a spectral class ~M2–M3. The most striking result of the present analysis is the prediction of a completely different spectral type relation for objects at the bottom of the main sequence and below, i.e., $m \lesssim 0.10\ M_\odot$. For an age $\tau \geq 1$ Gyr, the stellar-substellar domain is characterized by a steepening of the m-Sp relation from M6 to ~M10 and by a spectral type greater than M10 for the hydrogen-burning minimum mass. This steepening reflects the observed severe drop in the mass-luminosity relationship (Henry & McCarthy 1993; Chabrier et al. 1996) and is supported by recent spectroscopic observations of low-mass objects near the stellar limit (Kirkpatrick et al. 1995; Jones et al. 1995).

The metallicity dispersion, important for objects with masses $m > 0.1\ M_\odot$, i.e., spectral types earlier than M6, decreases below this limit. This may suggest that the present spectral classifications are inappropriate for characterizing objects below $T_{\rm eff} \approx 3000$ K. The strong metallicity dependence of the spectral type over most of the VLMS range provides an interesting tool for determining the metallicity of observed M dwarfs.

The age is a crucial parameter near and below the HBMM. For a brown dwarf at this limit ($m \approx 0.072\ M_\odot$), a cooling time from 10^8 to 10^9 and 10^{10} yr corresponds to a shift in the spectral type from ~M6 to M10 and greater than M10, respectively. This provides a powerful diagnostic for determining the age or the mass of a brown dwarf, since any object with a spectral type characteristic of the region from M6 to ~M10 must be either a *young brown dwarf*, with $\tau < 1$ Gyr, or a very low mass star on the main sequence.

The present calculations, added to other successful comparisons with observations (Baraffe et al. 1995; Chabrier & Baraffe 1995; Chabrier et al. 1996), assess the reliability of the present models in the description of the structural and thermal properties of very low mass stars, and the derivation of accurate mass functions for these objects (Méra, Chabrier, & Baraffe 1996; Méra, Chabrier, & Schaeffer 1996).

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