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Adam Burrows
Departments of Physics and Astronomy
University of Arizona
Tucson, Arizona 85721

W. B. Hubbard and J. I. Lunine
Lunar and Planetary Laboratory
University of Arizona
Tucson, Arizona 85721

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ASTRONOMY ON THE EDGE: THE PHYSICAL THEORY OF BROWN DWARFS AND LATE *M* DWARFS

ADAM BURROWS
Departments of Physics and Astronomy, University of Arizona, Tucson, Arizona 85721

W. B. HUBBARD AND J. I. LUNINE
Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721

ABSTRACT We summarize some of the details of and issues surrounding the theory of late *M* dwarfs and brown dwarfs. New theoretical plots of direct use to observers attempting to derive physical quantities such as mass and age from data are provided. Using our recent stellar and substellar models and spectra we speculate on what the recently detected halo MACHO's can and can not be.

INTRODUCTION

Stars less massive than $0.5M_{\odot}$ must represent more than two-thirds by number and perhaps more than 50% by mass of all stars in the galactic disk (Kroupa, Tout, and Gilmore 1993; Tinney 1993). Despite their manifest importance, *M* dwarfs have only recently received commensurate observational and theoretical attention. With the growth and steady improvement of infrared astronomical technology (InSb arrays, cryostats, speckle, etc.), the search for and study of dim red/infrared stars and substellar objects (brown dwarfs) has accelerated. Surveys of the solar neighborhood (Henry and McCarthy 1990; Tinney, Mould, and Reid, 1993), parallax and proper motion surveys (Luyten 1963; Monet *et al.* 1992), and color surveys (Gilmore *et al.* 1985; Kirkpatrick 1992; Leggett and Hawkins 1988; Hawkins 1986), have been supplemented in recent years by cluster searches in the Pleiades (Stauffer *et al.* 1989; Simons and Becklin 1992; Hambly, Hawkins and Jameson 1991), in the Hyades (Leggett and Hawkins 1988; Bryja *et al.* 1992, 1993; Leggett 1993), in Rho Ophiuchus (Comeron *et al.* 1993), and in IC2602 (Hambly 1993), and by radial velocity surveys (Marcy and Benitz 1989; McMillan *et al.* 1985; Cochran, Hatzes, and Hancock 1991), by IR speckle interferometry (McCarthy 1976; Henry 1991), by halo searches (Richer and Fahlman 1992), and, most recently, by microlensing searches (Alcock *et al.* 1993; Aubourg *et al.* 1993; Udalski *et al.* 1993) to complete the late *M* dwarf census. Hand in hand, the list of candidate brown dwarfs has swollen beyond twenty (Table I). Since the fortuitous false start of VB8B and in parallel with the observational explosion, the theoretical studies of late *M* dwarfs and brown

dwarfs have improved in sophistication and are international in scope (D'Antona and Mazzitelli 1985; D'Antona 1987; Nelson, Rappaport, and Joss 1986a,b, 1993; Stringfellow 1986, 1991; Dorman, Nelson and Chau 1989; Burrows *et al.* 1989, 1993). Importantly, new theoretical spectral syntheses are being published (Allard 1991, 1993; Saumon *et al.* 1994; Kui 1991) that in principle can be compared directly with the IR photometry and spectrophotometry accumulating in the literature to extract such physical parameters as gravities, metallicities, effective temperatures, and masses.

TABLE I Brown Dwarf Candidates and Lowest Luminosity M Dwarfs. [a]

Name	K	J−K	M_K	Mass ($M_\odot$)	Spectral Type
(a) Field stars and very wide binary companions					
GD165B	14.09	1.66	11.78	-	>M9
LHS2065	10.75	1.34	10.31	-	M9
LHS2924	10.68	1.24	10.48	-	M9
GL569B	9.65	1.13	9.55	-	M8.5
PC0025+0447	14.93:	-	-	-	M9.5
(b) Unresolved companions					
G29-38B?	13.45	-	12.70	-	-
HD114762B	-	-	-	>0.011	-
(c) Companions with astrometric mass determinations					
G208-44B	8.28	1.06	10.00	0.087 ± 0.014	-
GL623B	8.85	1.13	9.46	0.079 ± 0.010	-
LHS1047B	8.04	1.01	9.42	0.057 ± 0.079	-
Ross 614B	7.24	1.09	9.17	0.085 ± 0.030	-
(d) From Tinney *et al.* 1993:					
TVLM 868-110639	11.44	1.28			
TVLM 513-46546	10.77	1.19			
TVLM 513-8328	13.03	1.14			
BRI 0021-0214	10.64	1.26			
(e) Clusters:					
ρ Oph: 7 Objects (Comeron *et al.* 1993)					
Pleiades: 3 Objects (Stauffer *et al.* 1989)					

[a]Data taken from Henry (1991), Kirkpatrick, Henry, and McCarthy (1991), Latham *et al.* (1989), Schneider *et al.* (1991), Becklin and Zuckerman (1988), Tinney, Mould, and Ried (1993), Comeron *et al.* (1993), and Stauffer *et al.* (1989). Table adapted from Burrows and Liebert 1993.

Given this ferment in activity near the main sequence edge, it is appropriate to step back and summarize the current issues that still surround the theory of late M dwarfs and brown dwarfs. This paper is meant to be such a review, but will not be comprehensive due to the enforced brevity of these pages. A more

complete discussion of the current status of the theory at the faint end of the mass function may be found in the recent papers by Burrows and Liebert (1993), Stevenson (1991), Burrows *et al.* (1993), and Nelson, Joss, and Rappaport (1993).

BROWN DWARF EXOTICA: A PRÉCIS

M dwarfs have masses between $\sim 0.075M_\odot$ and $0.5M_\odot$ and burn hydrogen stably on the hydrogen main sequence for more than a Hubble time. Those below $\sim 0.3M_\odot$ are fully convective. Substellar objects below the lower M dwarf edge are called brown dwarfs, though the term "infrared dwarfs" may be more appropriate. These objects are not massive enough to burn hydrogen stably and reach the main sequence, but the most massive of them can burn hydrogen for billions of years before dimming. The precise edge mass depends on metallicity (Z) and helium fraction (Y_α) and ranges from $0.072M_\odot$ to $0.095M_\odot$. Table II depicts some of the edge characteristics for various combinations of Z and Y_α. The low values of $T_{\rm edge}$ and $L_{\rm edge}$ shown in Table II explain this subject's late maturation.

TABLE II The Lower Edge of the Main Sequence

Model	Y_α	$Z/Z_\odot$	$M_{\rm edge}$	$T_{\rm edge}(K)$	$L_{\rm edge}/L_\odot$
B	0.22	1	0.080	1770	6.59×10^{-5}
G	0.25	1	0.077	1760	6.21×10^{-5}
H	0.28	1	0.074	1740	5.72×10^{-5}
P^a	0.22	0	0.098	3710	1.52×10^{-3}
Q^a	0.25	0	0.094	3620	1.20×10^{-3}
X^b	0.25	1	0.0767	1747	6.13×10^{-5}
Z^b	0.25	0	0.094 (0.092 NG^c)	3630	1.26×10^{-3}

[a]Low-resolution calculations for α-dependence study alone.
[b]New, high-resolution models.
[c]Non-Grey

Brown dwarfs are in one sense massive Jupiters and in another low-mass, hydrogen white dwarfs. During most of their lives they are supported by electron degeneracy pressure. They are comprised predominantly of liquid metallic hydrogen/helium mixtures, can achieve central densities from 50 gm/cm^3 to 2000 gm/cm^3 (depending on mass, Z, and Y_α) and central temperatures of as much as $\sim 2.5 \times 10^6$ K, and have high surface gravities around 350 earth gravities when old. At these high gravities, the photospheres are at relatively

high densities ($\rho_e \sim 10^{-5\pm1}$gm/cm^3). Such high densities and low T_e's (cf. Table 2) imply that the atmospheres are dominated by molecules such as H_2, H_2O, CO, TiO, VO, FeH, MgH, and CaH. This exotic soup of chemicals leads to a rich spectrum and most of the complications of brown dwarf and late M dwarf work. Furthermore, grains can form near and above the photosphere at the low temperatures (<2500K) encountered in the thin ($\leq 10^{-10}M_\odot$) "stellar" skins. With radii near that of Jupiter's ($\lesssim 0.1R_\odot$), low effective temperatures (< 1800 K, when old), low luminosities ($< 6 \times 10^{-5}L_\odot$ at $Z = Z_\odot$), M_V's ≥ 19.5, and emissions in mostly the I, J, H, and K bands, brown dwarfs are unique among "stellar" objects. However, it should be emphasized that the properties, both observable and physical, of M dwarfs and brown dwarfs form a continuum in the $0.01M_\odot$ to $0.2M_\odot$ range. A logical study of each branch recognizes that the transition between objects above and below the edge is seamless.

The major distinguishing property of brown dwarfs is that unlike M dwarfs, which settle into a long and stable main sequence life, brown dwarfs continue to cool. They are not massive enough to achieve hydrogen ignition temperatures before becoming degenerate. After degeneracy sets in, surface cooling no longer increases the central temperature via the canonical "negative-specific-heat" effect, and the brown dwarf continues on its perpetual pre-main sequence phase into obscurity.

After the deuterium burning phase (see below), which lasts no longer than a few $\times 10^7$ years, brown dwarf cooling follows simple power-laws (Burrows and Liebert 1993; Stevenson 1991). The luminosity (L_e) and effective temperatures (T_e) as a function of both time (t) and mass (M) can be given approximately by the relations,

$$L_e \simeq 4 \times 10^{-5} L_\odot \left(\frac{10^9 \text{ yr}}{t}\right)^{1.3} \left(\frac{M}{0.05M_\odot}\right)^{2.6} \tag{1}$$

$$T_e \simeq 1550\text{K} \left(\frac{10^9 \text{ yr}}{t}\right)^{0.32} \left(\frac{M}{0.05M_\odot}\right)^{0.83} \tag{2}$$

for solar metallicity and

$$L_e \simeq 10^{-5} L_\odot \left(\frac{10^9 \text{ yr}}{t}\right)^{1.25} \left(\frac{M}{0.05M_\odot}\right)^{2.4} \tag{3}$$

$$T_e \simeq 1140K \left(\frac{10^9 \text{ yr}}{t}\right)^{0.31} \left(\frac{M}{0.05M_\odot}\right)^{0.77} \tag{4}$$

for zero metallicity (as derived from Burrows *et al.* 1993). The zero-metallicity brown dwarfs cool more quickly because metal-free opacities are substantially lower than metal-rich opacities. Lower-opacity atmospheres are much leakier.

MODEL INPUTS

The essential elements of any comprehensive theoretical investigation of stellar evolution near the main sequence edge are a general equation of state of hydrogen/helium mixtures in both the molecular and metallic regimes, a complete

set of molecular and atomic opacities, along with an accurate atmospheric algorithm, and screened nuclear rates for all of the important fusion processes. A subset of interesting issues concerning each of these inputs is identified in each of the following subsections.

The Equation of State

The equation of state (EOS) that we have employed to date in our simulations is that of Marley and Hubbard (1988, MH), where the metallic regime was calculated by Hubbard and DeWitt (1985). Recently, we have incorporated into our Henyey code the more sophisticated hydrogen EOS of Saumon and Chabrier (1992, SC) (now updated to include helium) and have performed some preliminary comparison runs. Surprisingly, for times later than 10^8 years, M dwarf and brown dwarf evolution for the two different equations of state is very similar. However, at earlier epochs, when a substantial fraction of the "star" is in the lower-density state, the differences between the SC and MH EOS's translate into significant differences in the evolutionary predictions. The precise stellar signature of this interesting thermodynamic effect will be the subject of a future study (Burrows, Saumon, Hubbard, and Lunine 1994).

Despite the different approaches to the high-density EOS employed by SC, MH, and other workers (e.g. Magni and Mazzitelli 1979), the variations among the derived pressures at a given density, temperature, and composition are slight. This could (and should) be interpreted to mean that the derived old brown dwarf radii are known to better than 10%. Since a point in the HR diagram (L_e vs. T_e) is a point at a given radius, the theoretical HR trajectories for old brown dwarfs and late M dwarfs are reliable enough to call into question any color-T_e calibration that shifts data rightward from the theoretical tracks by more than 200 K (Liebert, these proceedings).

Atmospheres

Variations between theoretical models in the literature can generally be traced to differences in the way the atmospheres are treated. For our solar metallicity models, we used the Rosseland mean opacities of Alexander, Johnson, and Rypma (1983) and Tsuji (1971). These prescriptions apply to dense, low-temperature molecular atmospheres and include H_2, He, H_2^-, H^-, He^-, CaH, MgH, SiH, FeH, TiO, VO, H_2O, CO, CN, CH_4, H, Mg, Si, Ca, electron scattering, and Rayleigh scattering. The collision-induced opacities of H_2 and He were taken from Lenzuni *et al.* (1991). Clouds of refractory grains that can condense out below $T_e \sim 2500$ K and veil the spectra were handled with the approach of Lunine *et al.* 1989 (see also Burrows *et al.* 1989). Cloud physics may well turn out to be a major source of ambiguity in the atmospheres of cool brown dwarfs and further work on this is definitely needed (Stevenson 1986; Lunine *et al.* 1989).

For a given composition, T_e, and gravity, hydrostatic grey atmospheres were calculated using the Feautrier method as implemented in the code of Bergeron, Wesemael, and Fontaine (1990). The atmospheres are convective and a mixing-length parameter, $\alpha(= \ell/H_p)$, of 1.0 was used. The dependence on α was explored previously by Burrows *et al.* (1989) and found to be minor around $\alpha = 1.0$. A grid of these atmospheres was pre-calculated and stored. This pro-

cedure enabled us to interpolate in an atmosphere table during the evolutionary runs and greatly sped up computation. A major conclusion of our atmosphere studies was that the use of the Eddington approximation can lead to errors of as much as 300 K in T_e for a given mass at a given epoch and should be avoided. Furthermore, our preliminary *non-grey*, zero-metallicity calculations (Burrows *et al.* 1993; Saumon *et al.* 1994) suggest that the non-grey/grey difference can be as much as $\sim$ 100 K in T_e at a given M and t.

NUCLEAR PROCESSES

The major nuclear processes at the central temperature (5×10^5 K-6×10^6 K) and central density (10 gm/cm^3 – 2000 gm/cm^3) regimes encountered by late M dwarfs and brown dwarfs are

$$p + p \rightarrow d + e^+ + \nu_e \tag{5}$$

$$p + d \rightarrow {}^3\mathrm{He} + \gamma \qquad , d \text{ burning} \tag{6}$$

$$\left.\begin{array}{ll} & p + {}^6\mathrm{Li} \rightarrow {}^3\mathrm{He} + {}^4\mathrm{He} \\ \text{and} & p + {}^7\mathrm{Li} \rightarrow 2\,{}^4\mathrm{He} \quad . \end{array}\right\} \text{Li burning} \qquad \begin{array}{r} (7) \\ (8) \end{array}$$

The classical pp chain is truncated at ^{3}He due to the low core temperatures. Reaction (5) is the rate-limiting process in heat generation, reaction (6) is responsible for most of that heat and for the consumption of primordial deuterium ($Y_d \sim 2 \times 10^{-5}$) and reactions (7) and (8) deplete lithium. Lithium may be important as a brown dwarf marker, since objects below $0.06 M_\odot$ retain their pre-stellar lithium for a Hubble time (Rebolo *et al.* 1992), but is not important for energy generation. However, "stars" more massive than $\sim 0.015 M_\odot$ (and, hence, most brown dwarfs) achieve central temperatures ($\geq 5 \times 10^5$K) sufficient to consume primordial deuterium. During this "quasi deuterium main sequence" phase ($10^6 - 3 \times 10^7$ years), contraction and cooling are almost completely halted. In fact, the luminosities for stellar or substellar objects between $0.2 M_\odot$ and $0.02 M_\odot$ in the first $10^6 - 3 \times 10^7$ years are as much as $2 - 4$ times higher with primordial deuterium than without. Curiously, increasing Y_d from 2×10^{-5} to 5×10^{-5} increases L_e during this early epoch by $\sim$ 50%. This fact suggests that Y_d can be derived from the luminosities of light "stars" in young clusters once *all* other issues are resolved.

RESULTS: MODELS *X* AND *Z*

The evolutionary calculations performed by our group have been described in detail elsewhere (Burrows *et al.* 1989, 1993; Burrows and Liebert 1993) and we will not repeat those papers here. We have investigated the Y_α, Y_d, and α dependences from $0.01 M_\odot$ to $0.2 M_\odot$ and for ages between 10^6 years and 2×10^{10} years. The models we highlight here are models X and Z of Burrows *et al.* 1993 in which $\alpha = 1.0$, $Y_\alpha = 0.25$, and the metallicity is solar (model X) or zero (model Z). With model Z we explore the properties of an extreme halo population (Pop. III?) and characterize the extreme subdwarf envelope. The differences between models X and Z are instructive, if only because together they almost bracket the entire range of theoretical expectations.

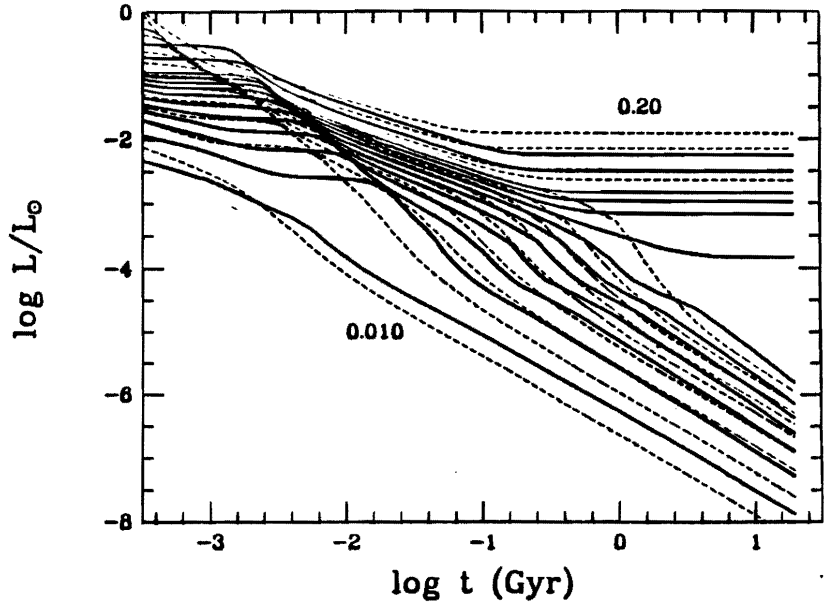

FIGURE I Log Luminosity (in $L_\odot$) versus log time (in Gyr) for models X (solid) and Z (dashed) of Burrows *et al.* 1993. The masses included range from $0.01M_\odot$ to $0.2M_\odot$

Figure I depicts the evolution of the bolometric luminosity with time for brown dwarfs and M dwarfs between $0.01M_\odot$ and $0.2M_\odot$. The solid lines are for model X and the dashed lines are for model Z. Figure I is richly illustrative of the entire stellar branch. At late times beyond 10^9 years, we can clearly see the bifurcation between the M dwarfs and brown dwarfs. For model X, this happens near 0.077 $M_\odot$ and for model Z it happens near $0.092M_\odot$. The split is earlier and more precipitous for model Z. The ridges between 10^6 years and a few times 10^7 years mark the deuterium burning phase. This occurs earlier and at higher luminosities for model Z because zero metallicity atmospheres have low opacities that retain heat less efficiently. As Figure 1 demonstrates, brown dwarfs do indeed cool as power laws after $\sim 10^8$ years (cf. eqs. 1–4).

Figure II shows the time evolution of the radii of objects with masses from $0.01M_\odot$ to $0.2M_\odot$ for model X. The partial halts seen are a consequence of deuterium burning and can occur for the more massive stars at radii that are significantly larger than their final cold or main sequence radii. Note that the brown dwarf curves cross at late times. This behavior reflects the inverted $R(M)$ relation for cold, degenerate objects.

Among the important observables are T_e, L_e, and the gravity, g. Without an independent kinematic determination of the mass and an age, it is difficult to test or use the theory of M and brown dwarfs. A point on the HR diagram is useful, but without an age or another third quantity such as the mass or the gravity, the complete evolutionary theory can not be tested in depth. However, if a cool star has a well-measured T_e or L_e, there is an age/mass correlation for a given composition and theory that can useful to investigators trying to constrain the object's properties. Figures III and IV depict "iso-T_e's" and "isoluxes" for model X in age-mass space. We see in Figure III that if T_e is measured, only

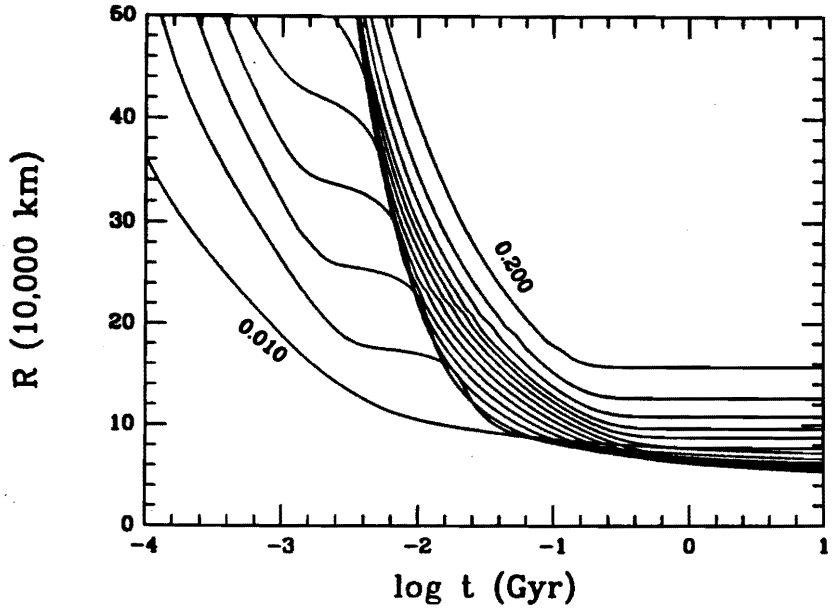

FIGURE II The evolution of the radius (in units of 10^4 km) with time (in Gyr) for model X of Burrows *et al.* 1993 with masses from $0.01M_\odot$ to $0.2M_\odot$.

a certain one-dimensional relation exists between the object's age and mass, within errors (both theoretical and observational). Note that for a given effective temperature, there is a *minimum* possible mass. If the age is known, the mass can be identified, but if the mass is known, the age might be double-valued. The dearth of points in the lower left-hand corner of Figure III is a consequence of the sparseness of the model X calculational grid below $\sim 0.05M_\odot$ (Burrows *et al.* 1993). The terminations in the top right should continue as vertical lines on the main sequence. Note that for a given T_e, there is a maximum mass possible after about 10^7 years. Figure IV shows the age-mass correlation for luminosities between $10^{-1}L_\odot$ and $10^{-5}L_\odot$. For instance, from Figure IV we see that if an object's measured luminosity is $10^{-5}L_\odot$, then it can not be more massive than $0.075M_\odot$, whatever its age. Figures III and IV can be used with great profit to extract useful information about an object, whether stellar or substellar.

Good gravity indicators in the spectra of cool "stars" have yet to be identified, but once they are figures like Figures V and VI for model X show that gravity may be a good model discriminant. Figure V depicts the evolution of gravity with T_e at a given mass. In principle if both are known, the star's mass can be read off the plot. This is particularly true below 2500 K and would be possible, but difficult near 3000 K. For example if the measured T_e is 2000 K and $\log_{10}g = 4.5$, then the mass is near $0.02M_\odot$. Figure V allows one to estimate the age as well (given the model X assumptions). A more direct route to the age, given g, is via Figure VI, from which a range of masses and ages can be read for a given measured gravity, even without T_e (or L_e). Figures such as Figures III–VI, novel as they are, should eventually prove very useful to theorist and observer alike.

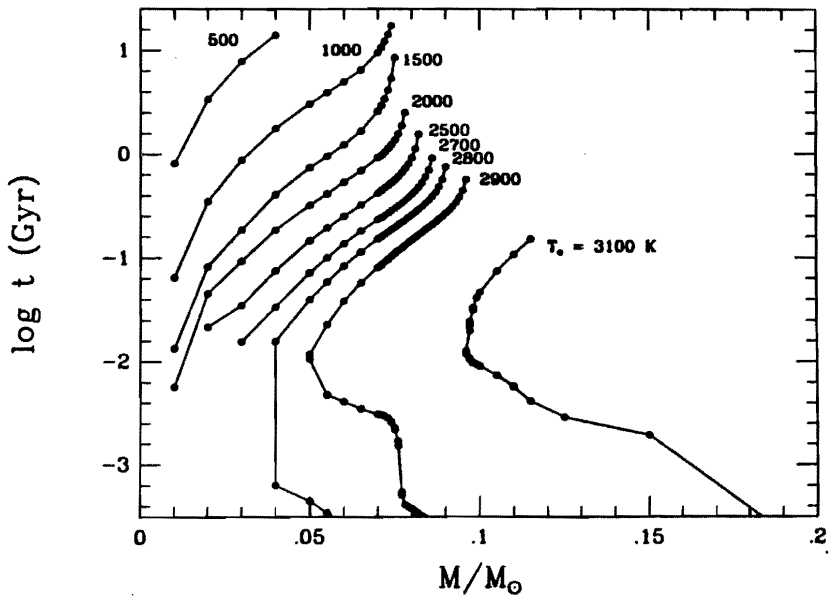

FIGURE III The possible combinations of age and mass for a given detected effective temperature using model X of Burrows *et al.* 1993. The terminations in the upper right should continue vertically.

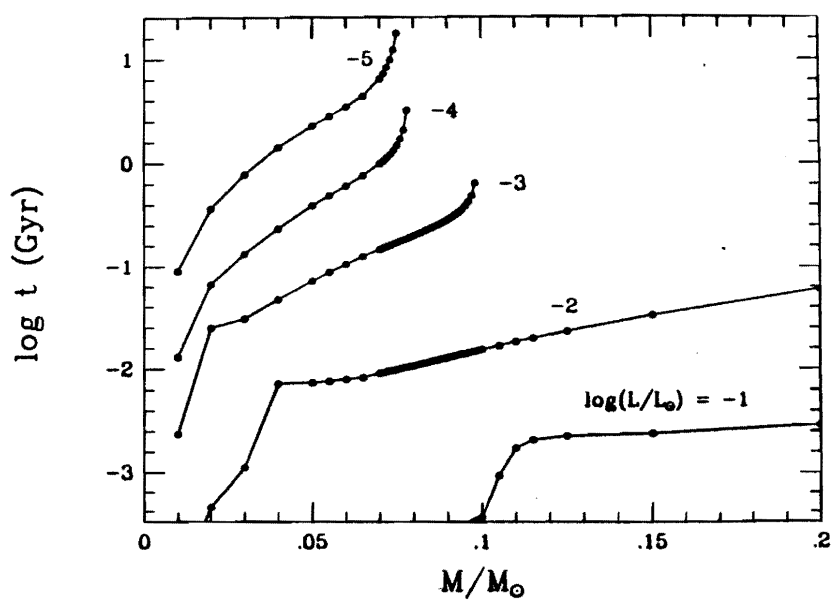

FIGURE IV Same as Figure III, but for a given detected luminosity from $10^{-5}L_\odot$ to $10^{-1}L_\odot$.

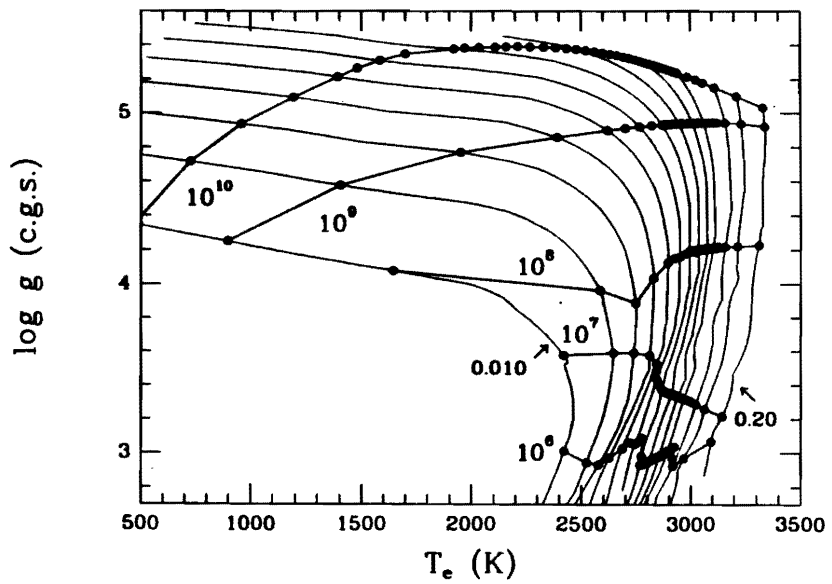

FIGURE V Log gravity (g) in cm/s^2 versus T_e (in K) for a given mass from $0.01M_\odot$ to $0.2M_\odot$. Model X of Burrows *et al.* 1993 was used to generate the plot. The lines indicate 10^6, 10^7, 10^8, 10^9, and 10^{10} year isochrones. Because not all models are relaxed by 10^6 years, the 10^6-year isochrone is a bit saw-toothed.

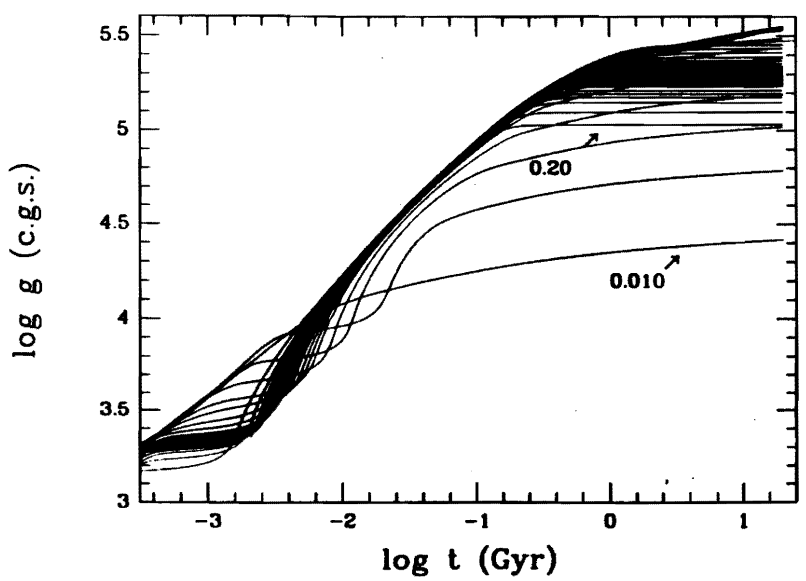

FIGURE VI Log gravity (in cm/s^2) versus time (in Gyr) for model X (Burrows *et al.* 1993) with masses from $0.01M_\odot$ to $0.2M_\odot$

TABLE III Approximate Magnitudes Near the Main Sequence Edge[a]

	a) $M = 0.077M_\odot$ $Z = Z_\odot$	b) $M = 0.092M_\odot$ $Z = 0.0$	c) Edge Subdwarf	d) $M = 0.08M_\odot$ $Z = 0.0$
M_V	19.5	12.8	14.5	19.4
M_R	18	12.0	14.0	18.4
M_I	-	11.2	11.8	19.6
M_K	11	11.1	-	24.4
M_B	-	14.0	-	22.0
M_{Bol}	15.3	12.2	12.1	19.5

[a]See text for discussion.

MACHOS AND ZERO-METALLICITY MODELS

The recent observation of microlensing events of LMC giants by halo objects (Alcock *et al.* 1993 (Livermore); Aubourg, *et al.* 1993 (EROS)) and by what appears to be a bulge M dwarf (Udalski *et al.* 1993) has sparked speculation about the cool star and/or brown dwarf content of the halo. Can MACHOs be the galactic dark matter? The question that naturally arises is whether such a population could have been detected already or can now be detected in a dedicated search. The Livermore and EROS groups detected lensing of an $R = 19$, $V = 19.6$ giant in the LMC. They infer a lens mass of $10^{-1\pm0.5}M_\odot$. At a distance of $\sim$ 10kpc and with a transverse velocity of $\sim$ 200 km/s (typical of the halo), the lens would be moving at $0.1''/25$ years, a depressingly slow rate. Without knowing the metallicity and mass of the lens star, we can't predict its brightness. However, we can present estimates of its band emissions under a variety of reasonable assumptions. Table III lists estimates of the absolute magnitudes in various photometric bands of, a) the edge solar metallicity M dwarf ($0.077M_\odot$, model X), b) the edge zero-metallicity M dwarf (0.092 $M_\odot$, model Z), c) an edge subdwarf, and d) a $0.08M_\odot$, 10^{10} year old zero-metallicity brown dwarf. The data of Monet *et al.* (1992) and the theoretical work of Saumon *et al.* (1994) and Burrows *et al.* (1993) were used to compile these estimates, good to perhaps a few tenths of a magnitude. As Table III hints, low metallicity M dwarfs are "bright", solar metallicity brown dwarfs are dim, and zero-metallicity brown dwarfs are exceedingly dim and anomolously blue. At 10 kpc, a solar-metallicity edge M dwarf has a V magnitude of 34.5 and a K magnitude of 26, while a zero-metallicity edge M dwarf has a V magnitude of 28 and an R magnitude of 27. A zero-metallicity brown dwarf has a V magnitude of 34.4 and a K magnitude of 39.4! Clearly, a brown dwarf halo population of whatever metallicity would be very difficult to detect photometrically. A solar-metallicity M dwarf population would also be difficult (but easier) to acquire. However, a subdwarf or zero-metallicity M dwarf population would be *many* magnitudes brighter from V through I and should already have been detected (if there in

abundance) in deep pencil-beam surveys. As a case in point, Tyson (1988) observed in B, R, and I to completeness limits of 27.7(B), 26.6(R), and 25.1(I) in 10 fields, each ~11 square arcmins in size. If the dark matter were made up of zero-metallicity brown dwarfs and M dwarfs with a continuous Salpeter mass function extending from $0.01 M_{\odot}$, Tyson (1988) should have seen in R a few *thousand* M dwarfs per field. If this population were subdwarfs and they extended into the dark matter halo to provide the "dark" matter, Tyson (1988) would have seen *hundreds* of them. Instead, he has identified no such population of stars, while detecting more than one thousand galaxies per field! In order for the dark matter halo to be made up of cool stars, they must be *brown dwarfs*, not M dwarfs and the halo mass function must be discontinuous. Solar metallicity M dwarfs at the requisite halo density would have been identified in the solar neighborhood by their kinematics and have not been (Monet *et al.* 1992). Furthermore, a subdwarf or zero-metallicity halo population sufficient to make up the halo dark matter would have been detected in the local subdwarf sample with about one hundred times the actual observed number density (Liebert, private communication).

However, after 25 years, a high resolution ($\leq 0.1''$) coronographic search for the Livermore and EROS lens would require a technology that could discern magnitude contrasts in V and R of 8 to 15, depending on the lens metallicity. Given sufficient patience, this may be possible. Clearly, a reliable estimate of the detection efficiency of the MACHO lens searches is needed, since photometry may not be up to the task of telling us definitively what this lens population can not be.

CONCLUSION

We have by no means exhausted the list of interesting and current issues that surround the theory and observational status of M dwarfs and brown dwarfs. However, it can be said with little exaggeration that after decades of slow, but steady, progress, there has been in the last five years an efflorescence in this branch of astronomy that shows no sign of fading.

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