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## CURRENT UNCERTAINTIES IN THE INTERIOR PHYSICS OF BROWN DWARFS AND GIANT PLANETS

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# CURRENT UNCERTAINTIES IN THE INTERIOR PHYSICS OF BROWN DWARFS AND GIANT PLANETS

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The thermodynamics of brown dwarfs (BDs: substellar objects with masses less than about 80 Jupiter masses but greater than about 10 Jupiter masses) and giant planets (GPs) are dominated by the equations of state of liquid metallic hydrogen. However, the distribution and high-pressure properties of elements with $Z > 1$ are a dominant source of uncertainty in the structure and evolution of these objects.

Because of its high cosmic abundance, helium plays an important role in the energetics of GPs where hydrogen-helium immiscibility can occur; temperatures are generally too high in BDs for H-He phase separation. We have recently incorporated an accurate helium equation of state in BD/GP models, but, except for the phenomenon of immiscibility with hydrogen in the GP mass range, its gross effect on the models is minor. A much greater source of uncertainty comes from the "metals" (elements with $Z > 2$), which have a dominant influence on atmospheric and interior photon opacity. As a limiting case, we have investigated the effect of a total absence of metals in a suite of BD models (Saumon, D., P. Bergeron, J.I. Lunine, W.B. Hubbard, and A. Burrows, 1994, Astrophys. J., **424**, 333). Not only do such models simulate a putative primordial low-mass, low-metal, low-luminosity galactic halo population (some of which may have been recently detected via microlensing surveys), but they could also stand for a population of normal-composition BDs in which the atmospheric metals abundance has been greatly suppressed by sequestration of metals in the deep interior, via a hypothesized immiscibility of metals with metallic hydrogen.

Very little work has been done on immiscibility of metals in metallic hydrogen, and it is not known whether cooler BD atmospheres can be made extremely metal-poor by this process. However, if it occurs, it can have a dramatic effect in changing the evolutionary timescale and spectral properties of such BDs.

Our group has also investigated the effect of various initial deuterium abundances on the evolution of BDs and GPs. The marginal mass for deuterium fusion, using standard reaction rate theory, is 13 $\times$ Jupiter, depending little on metals abundance. If the initial deuterium abundance is as high as $2 \times 10^{-4}$, a deuterium main sequence develops, and lasts about $6 \times 10^{7}$ years.

## I. INTRODUCTION

The equation of state of most of the mass of BDs and GPs lies in the range of parameter space $Z \sim 1$, $\Gamma \sim 1$ to 30, and $r_e \sim 0.1$ to 1. Here $Z$ is the atomic number, $r_e$ is the usual electron spacing parameter defined in terms of the electron number density $n_e$ by $4\pi a_o^3 r_e^3/3 = n_e^{-1}$, and $\Gamma$ is the usual electron plasma coupling parameter defined by $\Gamma = e^2/r_e a_o k_B T = (3.16 \times 10^5 \mathrm{K})/r_e T$, where $e$ is the electron charge, $a_o$ the Bohr radius, $k_B$ Boltzmann's constant, and $T$ the temperature. The composition of the material is for the most part hydrogen, with an admixture of $\sim 25\%$ helium by mass, and (for solar-composition material), $\sim 1$ to 2% by mass of material with $Z > 2$. In accordance with astrophysical usage, we denote the mass fraction of hydrogen by $X$, the mass fraction of helium by $Y$, and the mass fraction of all elements heavier than helium (the so-called "metals" in astrophysical parlance) by $Z$. The latter $Z$ will always be expressed as a percentage in this paper so that it will not be confused with the atomic number.

The equation of state of pure hydrogen is well understood for this range of parameters (Ichimaru, 1994), and there is little likelihood that any of the thermodynamic variables important for the structure and evolution of BDs and GPs are in error by more than a few percent within most of their mass range. With the exception of the details of the so-called plasma phase transition (PPT; Saumon and Chabrier, 1992), the pressure range under which metallization of hydrogen occurs is noncontroversial and understood to be in the vicinity of $\sim 1$ to 3 Mbar (depending on $T$); this phase transition may have important observable consequences for GPs but not for BDs.

However, the equation of state of a dense mixture of hydrogen with other species is less well understood, and uncertainties in the behavior of the mixture strongly limit our understanding of the evolution of BDs and GPs. There are two types of mixtures of concern in this context: (1) a mixture of hydrogen with helium with $Y \approx 25\%$; (2) a mixture of hydrogen, helium, and metals, with $Y \approx 25\%$, and $Z \leq 2\%$. The H-He mixture has been studied extensively (Stevenson, 1975; Hubbard and DeWitt, 1985; Klepeis et al., 1991), and it is commonly believed that limited miscibility of helium in metallic hydrogen in the giant planets Jupiter and Saturn has led to formation of a helium-enriched inner region in Saturn (and possibly in Jupiter), with a corresponding depletion in the observable outer layers. Because helium is a major component of the mass of both Jupiter and Saturn, it could provide a significant gravitational energy source should it commence to unmix from the hydrogen via immiscibility in liquid metallic hydrogen (Stevenson and Salpeter, 1977). The temperature range under which helium develops limited solubility in metallic hydrogen does not appear to exceed $10^4$ K according to most calculations (Stevenson, 1975; Hubbard and DeWitt, 1985), and thus unmixing of helium from hydrogen would be in an intermediate stage in Saturn and only incipient in Jupiter. In contrast, the calculations of Klepeis et al. (1991) predict a maximum phase-separation temperature of about 40000 K at a pressure of 10.5 Mbar, and for solar-composition hydrogen and helium, insolubility would commence at $T \leq 15000$ K. This phase-separation temperature is about a factor of two higher than that predicted by the other calculations, and would imply very strong separation in both Jupiter and Saturn. This is not supported by observations.

In contrast to the outer metallic-hydrogen layers of GPs, the metallic-hydrogen layers of BDs do not cool below $10^4$ K within the age of the Galaxy, and so helium-hydrogen immiscibility is of potential relevance only to GPs (even if Klepeis et al. are correct).

In BDs of solar composition, the abundance of metals is so low that only an insignificant amount of gravitational energy is released if some of these elements have limited solubility. However, even trace amounts of metals dominate the photon opacity in the ideal-gas envelope of a BD. It is this outermost skin which regulates the rate of escape of the BD's heat into space, and therefore a significant change in its photon opacity will have major repercussions on the evolution history of a BD (as well as, obviously, on the emergent spectrum). Thus the commencement of limited miscibility of metals in a BD's interior regions is likely to lead to observable consequences.

Stevenson (1986) pointed out that Fe may become partially insoluble in BDs, and that this effect might have an influence on grain opacity in such BDs. However, he did not quantify the effect. At present, the synthesis of wavelength-dependent atmospheric opacities for BDs is an ongoing project of several groups (Saumon, et al., 1994; Allard, 1990), and is not yet solved in general. Our group has computed BD evolution trajectories for two limiting cases: solar-composition metallicity ($Y \approx 25\%$ and $Z \approx 2\%$), and zero metallicity (pure hydrogen and helium, with $Y \approx 25\%$ and $Z = 0\%$). We argue that these limiting cases bound the possibilities for BDs which gradually lose atmospheric metallicity due to development of a metal-rich core as a consequence of limited solubility of the metals in metallic hydrogen, and we discuss these possibilities in the following.

Finally, although deuterium is of course a fully soluble trace species in BDs and GPs, it serves as a brief but important nuclear energy source in BDs owing to its vulnerability to thermonuclear processing at much lower temperatures ($T \sim 5 \times 10^5$ K) than those for which the p-p reaction chain can proceed. In this paper we also report on some of our recent calculations of the marginal mass for deuterium burning in low-mass BDs.

## II. EVOLUTION OF BROWN DWARFS

Figure 1 shows luminosity $L$ in units of the solar luminosity $L_\odot$, as a function of time $t$ for two ensembles of BDs. The first ensemble (dashed lines) is computed for zero metallicity, while the second ensemble (solid lines) is computed for solar metallicity ($\odot$); these ensembles correspond to the sequences of models presented by Saumon et al. (1994). It is important to note that in both of the ensembles, the models are fully convective, and that the interior trajectories of pressure $P$, mass density $\rho$, and temperature $T$ follow an isentrope. The entropy corresponding to the isentrope is established by the atmospheric boundary condition, which depends on the opacity of the atmosphere. Thus the differences between the two ensembles of evolutionary tracks are entirely caused by the composition of the ideal-gas atmosphere. Equation of state differences in the deep interior are entirely due to the presence or absence of metals and are negligible.

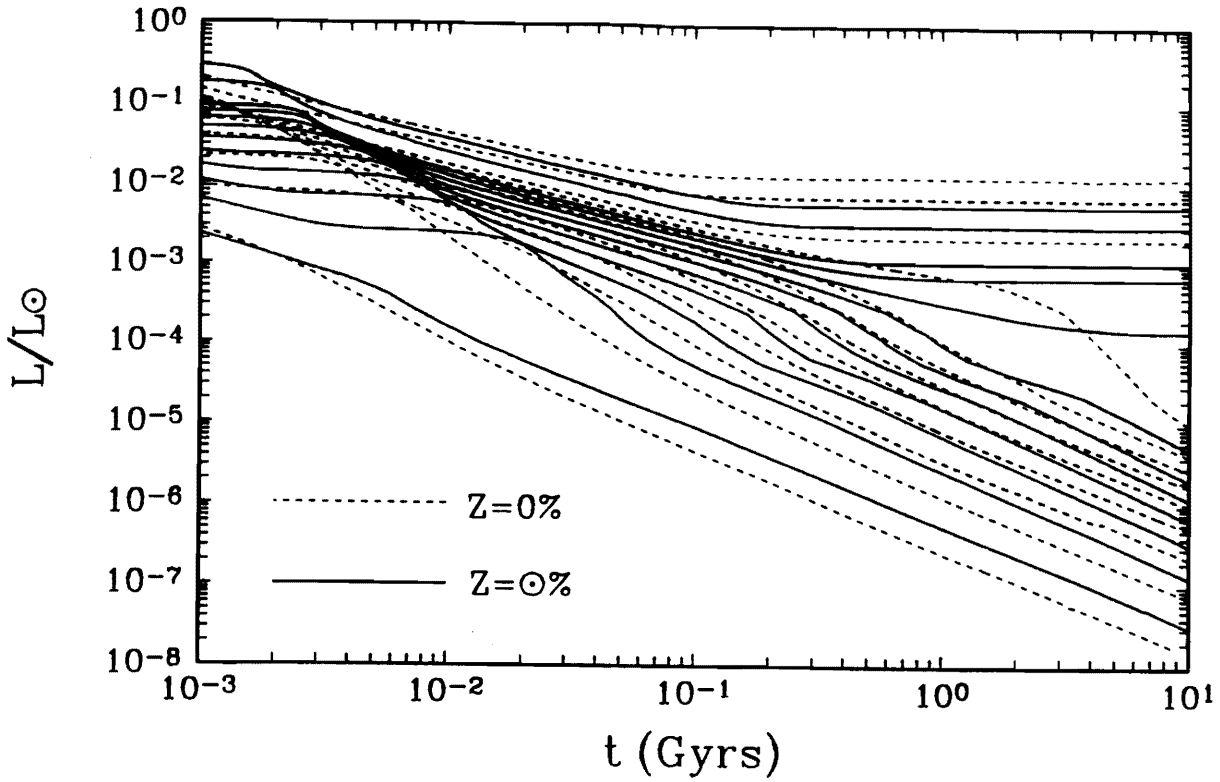


**Fig. 1.** Evolutionary tracks for zero-metallicity and solar-metallicity brown dwarfs and marginal hydrogen burners. The tracks are for (top to bottom) 0.20 $M_\odot$, 0.15 $M_\odot$, and 0.10 to 0.01 $M_\odot$ in steps of 0.01 $M_\odot$.

In Fig. 1, we see that the absence of metals causes the zero-metallicity BDs to cool more quickly than the solar-metallicity BDs, while the objects that are able to reach the main sequence and burn hydrogen via the p-p reaction are more luminous in the absence of metals which increase atmospheric opacity. The "ripple" which appears in the tracks at early phases ($t < 3 \times 10^{-2}$ Gyrs) marks the end of deuterium burning, which is computed for a presumed initial number abundance of deuterium to hydrogen of D/H $= 2 \times 10^{-5}$.

The absence of metals has a dramatic effect on emergent spectra of BDs. Figure 2, taken from Saumon et al. (1994), shows a comparison of black body flux curves and computed nongrey flux curves for BDs with atmospheric effective temperatures of 1500 K (upper curve) and 1000 K (lower curve), and a surface gravity of $10^5$ cm sec$^{-2}$. Note that the nongrey emission profile peaks in red and near-IR, while the corresponding black body curves peak well in the infrared, at wavelengths $\sim 5$ $\mu$m and beyond. The point of this figure is that very strong depletion of metals in the atmosphere of a BD can markedly disguise the true effective temperature of the object, perhaps foiling a search predicated on expected black body emission characteristics.

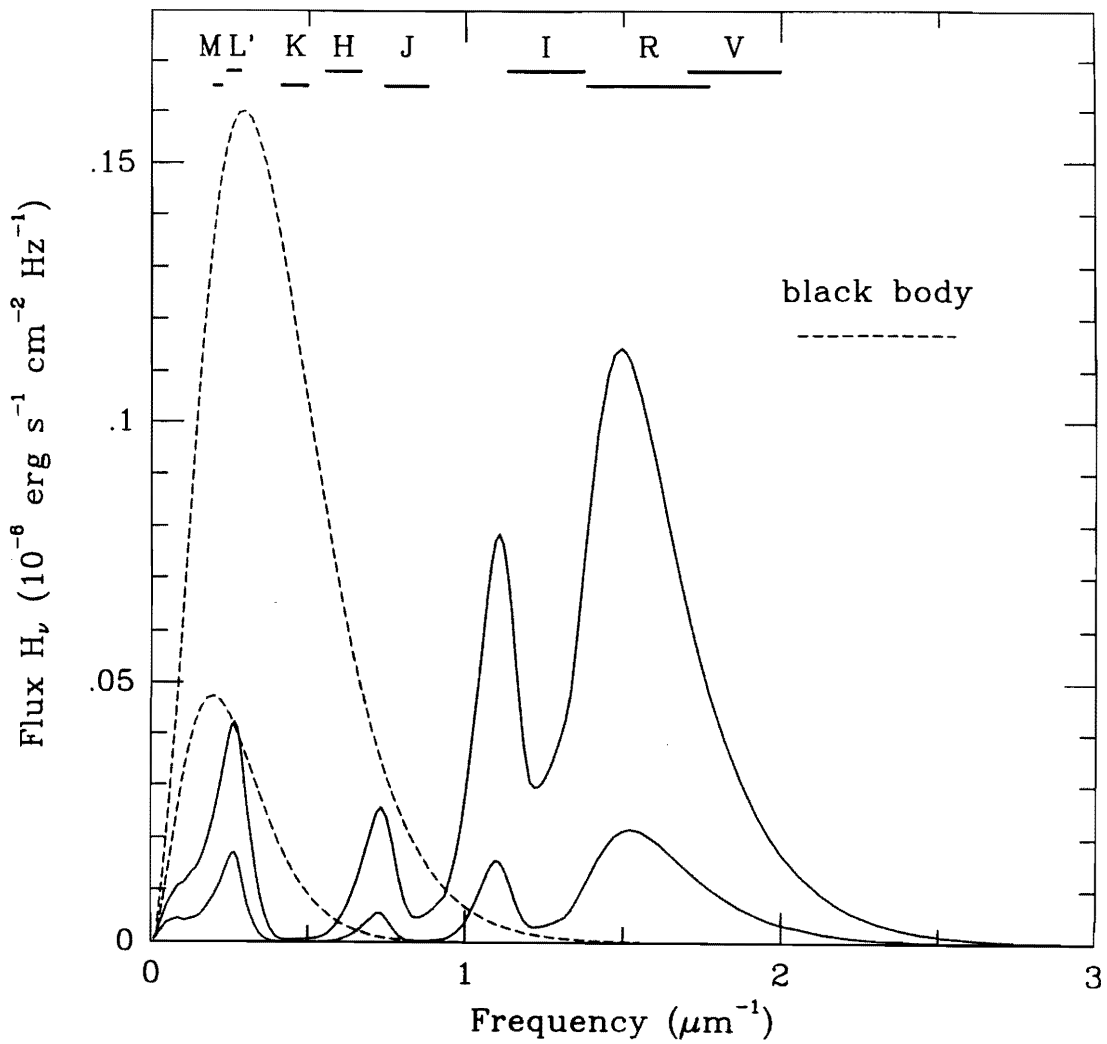


**Fig. 2.** Emitted spectra of zero-metallicity brown dwarfs (solid curves), and black bodies at the same effective temperature (dashed curves). Bandpasses of some standard astronomical filters used to search for brown dwarfs are shown for comparison.

## III. SOLUBILITY OF METALS IN BROWN DWARF INTERIORS

Figure 3 shows, for the same ensembles as in Fig. 1, the trajectories of the central temperatures $T_c$ as a function of $t$. Objects which have masses above the hydrogen-burning limit at $0.0767 M_\odot$ (solar metallicity) or $0.092 M_\odot$ (zero metallicity) reach constant central temperatures and become lower main-sequence stars, while objects below the limiting mass (BDs) cool steadily with time. Figure 4 shows the evolution of the same objects, but on the $T_c$ vs. $\rho_c$ plane, where $\rho_c$ is the central mass density. At the right-hand side of both Fig. 3 and Fig. 4 are shown predicted temperature ranges affecting the solubility of the labeled elements in metallic hydrogen, which we discuss in detail below. Note on Fig. 4 that the finite-metallicity trajectories fall on top of the zero-metallicity trajectories, but do not extend as far. As explained in section II, this

is because the metals do not affect the equation of state to any extent, but do affect how rapidly the object evolves via atmospheric opacity.

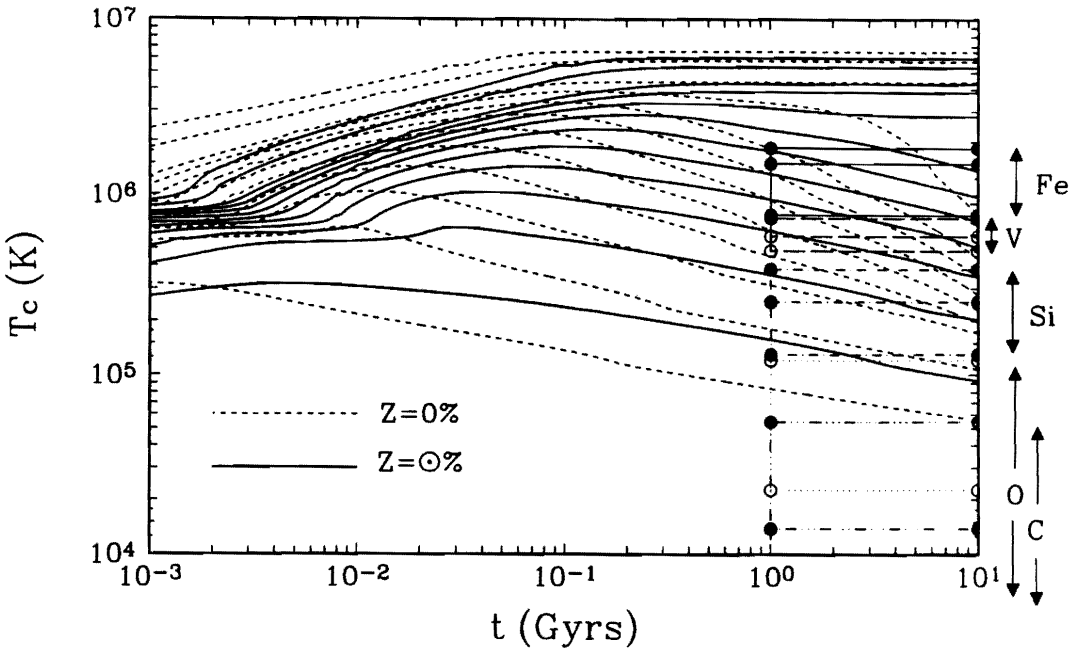


**Fig. 3.** Central temperature vs. time for brown-dwarf and lower main-sequence models. At the right side of the diagram are shown three characteristic temperatures for each element indicated in the right-hand margin.

To explore the possibility of limited solubility of metals in BD interiors, we have used the crude ion-sphere model of Stevenson (1976). In this model, we consider only binary mixtures of hydrogen and elements with $Z > 2$, ignoring the possible influence of helium. As shown by Stevenson, if the pressure is sufficiently high for electron screening to be negligible, then the Gibbs free energy of mixing approaches an asymptotic high-pressure limit given by

$$\Delta G = -\frac{27}{100}(4/9\pi)^{2/3} f(x) + k_B T[x \ln x + (1-x)\ln(1-x)], \tag{1}$$

where $x$ is the number concentration of the metal in hydrogen, and

$$f(x) = \frac{\langle Z^{5/3} \rangle}{\langle Z \rangle} - x Z_2^{7/3} - (1-x) Z_1^{7/3}. \tag{2}$$

Here $Z_1 = 1$ is the atomic number of the hydrogen, which has concentration $(1-x)$, and $Z_2$ is the atomic number of the metallic ions at concentration $x$. The averages are carried out with respect to the concentration.

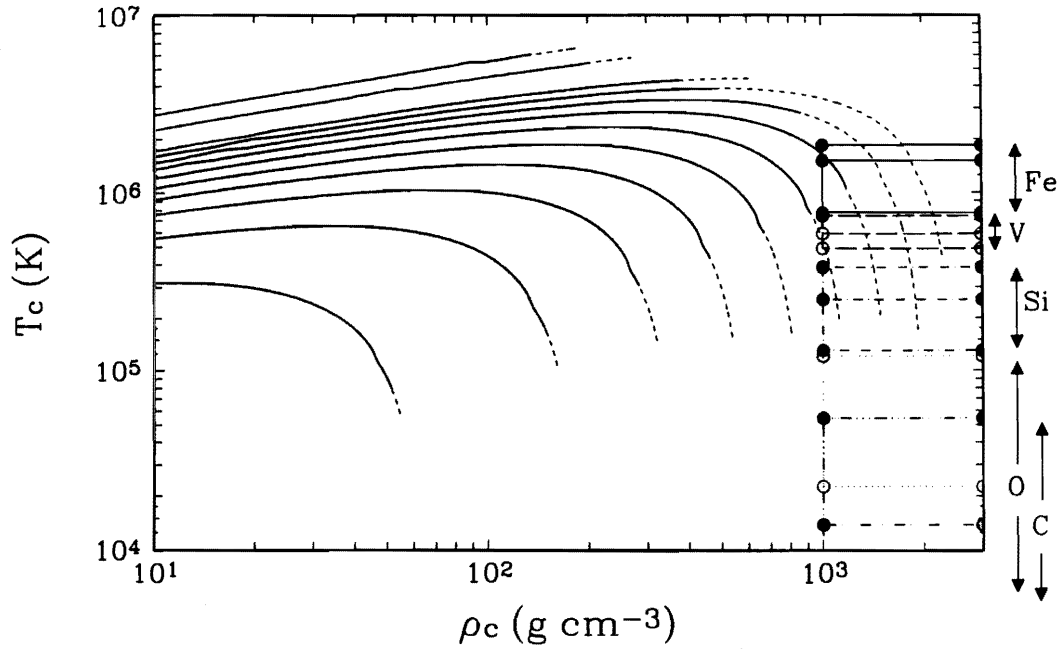


**Fig. 4.** Central temperature vs. central density curves for constant masses. Curves are terminated at an age of 10 Gyrs.

Despite the crudity of Stevenson's model, Hansen (1980) was able to confirm its essential details, and also to explore the pressure-dependence of the results. In this paper, we use Stevenson's simple asymptotic, pressure-independent expression for $\Delta G$ for convenience, while recognizing that Hansen found that metals tended to become *less* soluble in hydrogen with decreasing pressure. Accordingly, we have computed three characteristic temperatures for each of several impurity elements in metallic hydrogen in the asymptotic limit, as follows.

First, we assume that the element is fully pressure-ionized with no screening, so that $Z_2$ represents its full atomic number. We then use the double-tangent construction to $\Delta G$ to compute the temperature at which the concentration $x$ of the element becomes equal to its solar abundance with respect to hydrogen. This temperature then represents the characteristic temperature below which the element would begin to form an enriched core in the BD, depleting the element's atmospheric abundance. This first characteristic temperature is the uppermost of the three temperatures shown for each element in Figs. 3 and 4.

Second, we repeat the calculation by assuming that the element acts like a point ion with charge $Z_2 - 2$, as would be the case if pressure ionization removes all of the bound electron shells except the innermost one, but otherwise does not change the free energy.

In this model, $Z_2$ in Eq. (1) is simply replaced with $Z_2 - 2$. The middle characteristic temperature shown in Figs. 3 and 4 is then the temperature at which the element of atomic number $Z_2$ has a solubility in metallic hydrogen equal to its concentration in solar-composition material, as evaluated using the double-tangent construction to $\Delta G$ with $Z_2 - 2$. Note that the uppermost temperature for carbon is thus identical to the middle temperature for oxygen.

Finally, we repeat the calculation by assuming that the ions have charge $Z_2 - 2$ and a concentration of $10^{-4}$ of solar. This defines the lowest characteristic temperature shown in Figs. 3 and 4. Thus far no low-mass stars or prospective BDs have been identified with such a low metallicity, but we estimate that such objects would begin to have spectra resembling the ones shown in Fig. 2.

According to the results shown in Figs. 3 and 4, some of the more important metals such as C and O will probably *not* be depleted in the atmospheres of BDs, except possibly for those at the lowest masses, $\sim 0.01 M_\odot$. However other important elements involved in grain formation may become depleted in more massive BDs. And, as Fig. 3 makes clear, as opacity-causing elements are depleted in the atmosphere, the BD's evolution accelerates, resulting in even more depletion.

As Fig. 4 shows, it is possible that even C and O will be depleted in the outer layers of Jupiter. However, this involves an extrapolation of Stevenson's theory from $r_e \sim 0.1$, where it may possibly have some qualitative validity, to $r_e \sim 1$, where it probably does not. This question constitutes a major uncertainty in current research on the interior of Jupiter and Saturn.

## IV. IGNITION OF DEUTERIUM IN LOW-MASS OBJECTS

Deuterium is converted to $^3$He in BDs at significantly lower temperatures than those required to make the thermonuclear p-p reaction proceed. It is interesting that this lowest thermonuclear threshold in astrophysics is reached by objects only about one order of magnitude more massive than Jupiter. The reactions that we consider are

$$p + p \rightarrow d + e^+ + \nu_e, \tag{3}$$

where $Q_p = 1.442$ MeV, and

$$p + d \rightarrow {}^3\mathrm{He} + \gamma, \tag{4}$$

where $Q_d = 5.494$ MeV. Reaction rates are calculated using the theory of Fowler, Caughlan, and Zimmerman (1975), with the intermediate screening algorithm of Graboske et al. (1973). Primordial deuterium is consumed via reaction (4) at temperatures $\sim 5 \times 10^5$ K, and if sufficiently abundant, can even cause the BD's luminosity and interior temperatures to stabilize at constant values for a time. Reaction (3) does not proceed in a steady state in BDs by definition.

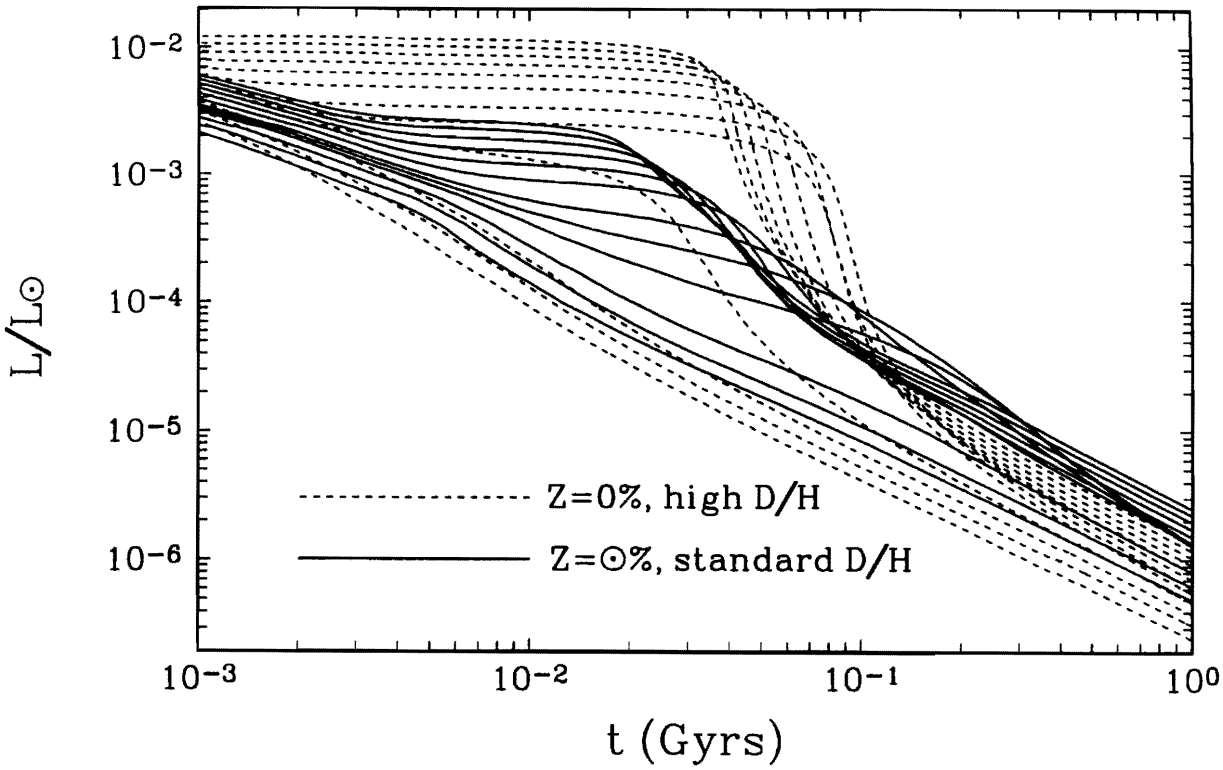


**Fig. 5.** Luminosity vs. time curves for brown dwarfs near the deuterium-burning limit.

Figure 5 shows trajectories of constant mass for ensembles of BDs chosen to clearly illustrate this threshold. The solid curves show the evolution of luminosity with time for standard models with solar metallicity and D/H $= 2 \times 10^{-5}$, for masses ranging from 0.010 $M_\odot$ to 0.020 $M_\odot$ in steps of 0.001 $M_\odot$ (only one Jupiter mass!), plus an extra model with $M = 0.0135\ M_\odot$. As these curves show, there is a phase lasting $\sim 4 \times 10^7$ years when BDs in this mass range stay at luminosities about an order of magnitude larger than normal while they consume their initial stores of deuterium. Also shown in Fig. 5 (dashed curves) are an ensemble of zero-metallicity BDs with the same masses and elevated deuterium fractions (D/H $= 2 \times 10^{-4}$). The increased deuterium abundance is meant to correspond to an elevated primordial value reported by Songaila et al. (1994), and these zero-metallicity BDs thus correspond to hypothetical Population III objects, which might have formed out of low-metallicity, high-deuterium primordial Big Bang material not previously processed in stars. As Fig. 5 shows, the effect of the extra deuterium and reduced opacity is to increase luminosities in the deuterium-burning phase and to prolong lifetimes in this phase to values approaching $10^8$ years.

We have computed sequences of models with extremely small mass steps in order to accurately determine the deuterium-burning limit for low-mass BDs. Figure 6 shows the results for models with solar metallicity and standard deuterium abundance.

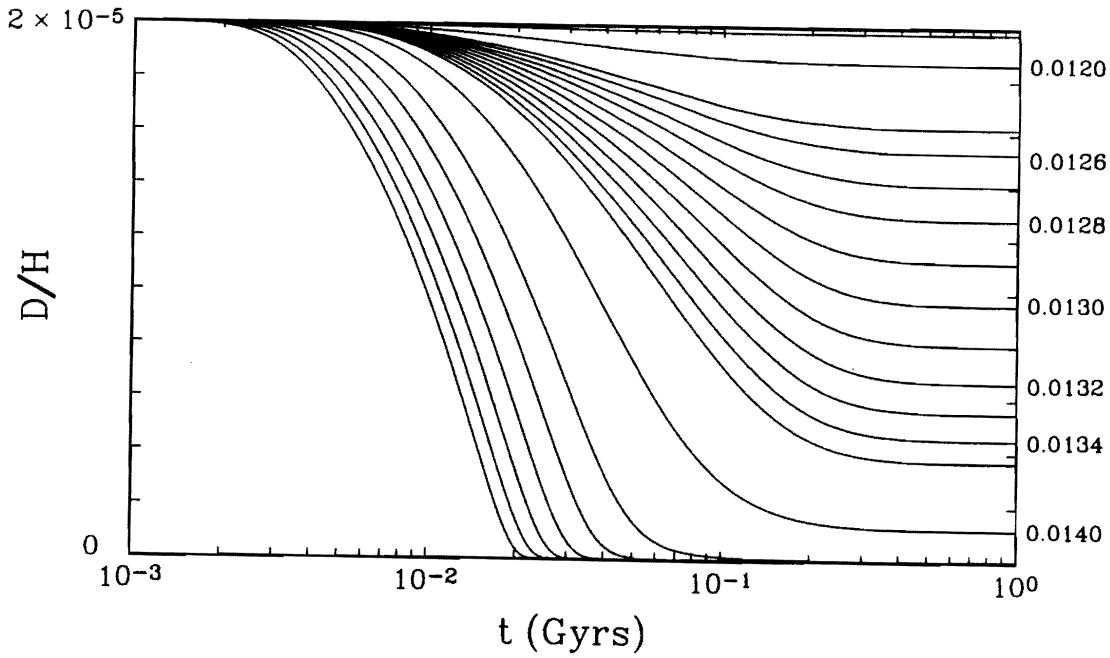


**Fig. 6.** Curves of deuterium abundance as a function of time, for a range of masses. Solar metallicity is assumed.

In addition to the masses shown in Fig. 5, we added a sequence of models with masses ranging from 0.0125 $M_\odot$ to 0.0135 $M_\odot$ in steps of $10^{-4} M_\odot$ (0.1 Jupiter mass!). BDs less massive than 0.0120 $M_\odot$ preserve their primordial deuterium, while by 0.0135 $M_\odot$ most of the deuterium is consumed. Thus the deuterium-burning limit is at 13 Jupiter masses.

Finally, we have repeated the calculation of deuterium consumption, using zero-metallicity models and an initial deuterium abundance one order of magnitude higher. Results are shown in Fig. 7, where we have used a mass interval of 0.005 $M_\odot$. The deuterium-burning limit shifts to a slightly higher mass, but still lies very close to 13 Jupiter masses.

## V. CONCLUSIONS

For the most part, questions involving the interior physics of BDs and GPs, as reflected in the gross properties of the equation of state and thermonuclear reaction rates, are well understood at present and do not present appreciable uncertainties. Thus it is interesting that despite this seemingly satisfactory situation on the theory side, observational surveys have in the main failed to produce large numbers of candidate objects. Although candidate objects have been identified in some relatively young

clusters (e.g., in $\rho$ Oph; age $= 3 \times 10^6$ years; Comeron et al., 1993; Burrows et al., 1993), they presumably have been detected only because of their youth and correspondingly high luminosity (see Fig. 1). The presumably large population of BDs in our galaxy with ages comparable to the age of the sun (5 Gyrs) or the age of the Galaxy ($\sim$ 10 Gyrs) has remained largely undetected (Burrows and Liebert, 1993). However, it is interesting that most attempts to detect BDs have been based on their predicted emitted radiation characteristics, and as yet no reliable synthetic spectra exist for such old BDs with effective temperatures $\sim$ 1000 K, with the exception of the $Z = 0\%$ synthetic spectra of Saumon et al. (1994).

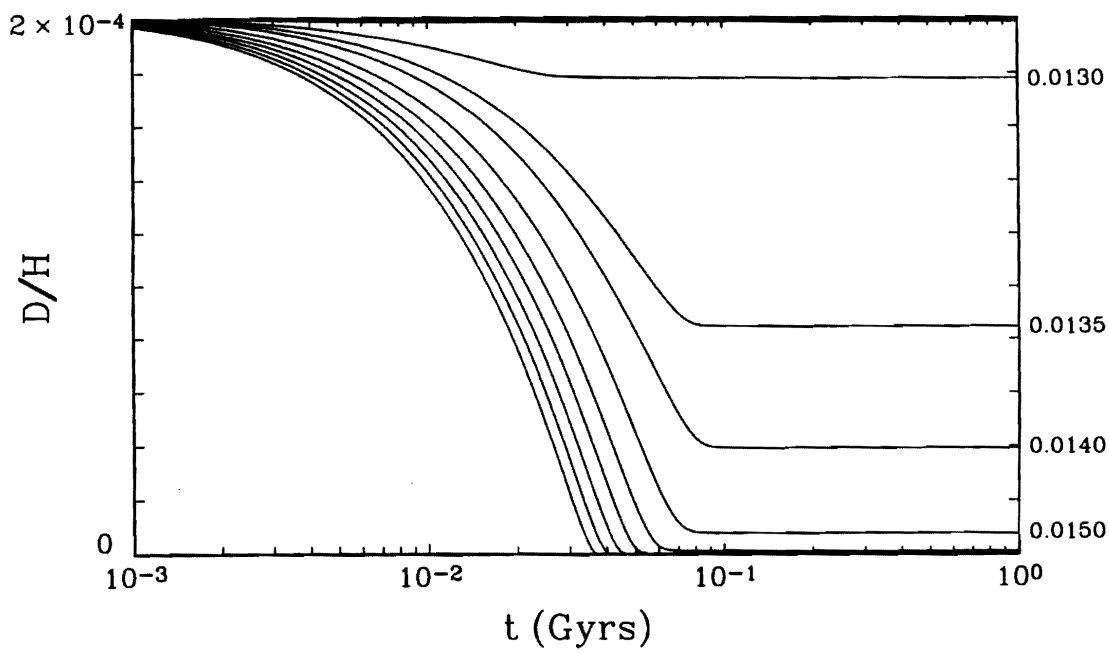


**Fig. 7.** Curves of deuterium abundance as a function of time, for a range of masses, assuming enhanced primordial deuterium abundance (Songaila et al., 1994) and zero metallicity.

Recently, innovative attempts to detect objects in the BD mass range located in the galactic halo have reported some initial successes (Alcock et al., 1993; Aubourg et al., 1993). These experiments are based on the gravitational lensing phenomenon, and rely upon continuous monitoring of a large number ($\sim 10^7$) of background stars in search of a rare event where the gravitational potential of a dark foreground object focuses the light from a background source. The amplitude and temporal scale of the focusing event depend upon the propagation distances, the mass of the focusing object, the miss distance, and the transverse velocity of the focusing object. Clearly not all of

these parameters are known, and so a determination of the mass of the lensing object is only possible in a statistical sense. Nevertheless, this method does not depend upon the emitted radiation from BDs, and so is a prime approach for detecting old, cold BDs. In fact, the preliminary results reported by Alcock et al. and Aubourg et al. involve events in which the lensing objects were probably in the BD mass range, and may be consistent with a significant number of such objects in the galactic halo. More events will need to be observed before definite conclusions can be reached.

We have shown that theoretical calculation of the evolution of old, faint BDs and calculation of their emergent spectra as affected by metals presents great uncertainty in the confrontation between data and theory. Questions involving the limited solubility of metals in dense hydrogen thus assume critical importance for further progress. We also stress that related questions involving the solubility of helium and other elements in metallic hydrogen still loom large in the study of the interior structure and evolution of the giant planets Jupiter and Saturn.

Investigations of the phase diagrams of binary mixtures of liquid metallic hydrogen and traces of cosmically abundant elements, for hydrogen mass densities ranging from $\sim 1$ to $\sim 1000$ g cm$^{-3}$, are badly needed.

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