The Lower Mass Limit

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1 History

The existence of brown dwarfs was first postulated by Kumar in 1963 [Kumar (1963)], who noticed that there was a lower mass limit below which the central temperatures of a stellar core would not reach high enough temperatures to sustain Hydrogen fusion. At the same time, as noted by Stevenson [Stevenson (1991)], there is no reason to expect the mechanisms that cause star formation know anything about the minimum final mass that becomes a star. To quote directly: "the history of astronomy suggests that we adopt an Ecological Principle: All imaginable physical niches are probably occupied." There is a sizeable gap between planets like Jupiter and stars like the sun; surely these processes can form objects sitting somewhere in the middle. These failed stars were deemed to be called 'black dwarfs' to contrast them from 'red dwarfs'; the names were later amended to 'brown dwarf' by Jill Tarter in 1976 ([Tarter (1976)]) in recognition of the fact that these stars should be somewhat luminous, and to avoid confusion with ancient and dim white dwarfs, the surviving meaning of the term.

Most interpretations of the Salpeter mass function slope to higher and higher values at lower masses. The objects near the lower mass limit were therefore commonly assumed to be exceptionally numerous, to the point where many assumed they would measurably contribute to the total mass of the galaxy. Some even held that they could be the mysterious dark matter that comprises most of the baryonic matter in the universe.

Attempts to actually find such objects were fraught with difficulty and uncertainty for years. Contenders were frequently discovered and proposed on the basis that their current luminosities are so small that they could conceivably be brown dwarfs still in the process of cooling down past the end of the main sequence. Finally, Gl229B was discovered in 1994 by [Nakajima et al. (1995)] and proved to be an unambigiously sub-stellar object with a peculiar spectrum. In the years since then, many more brown dwarfs have been discovered and great (though not completely satisfying) strides have been made in the analysis of brown dwarfs, and getting models to more accurately reproduce their behavior.

At around the same time, the first extrasolar planets were discovered, eventually amounting to the hundreds of extrasolar planets now suspected and known. These techniques, despite being more sensitive to more massive objects, have thus far failed to turn up enormous amounts of brown dwarfs. The so-called "brown dwarf desert" is adding fuel to the debate about how these stellar-like objects form, and now more importantly how they don't seem to form.

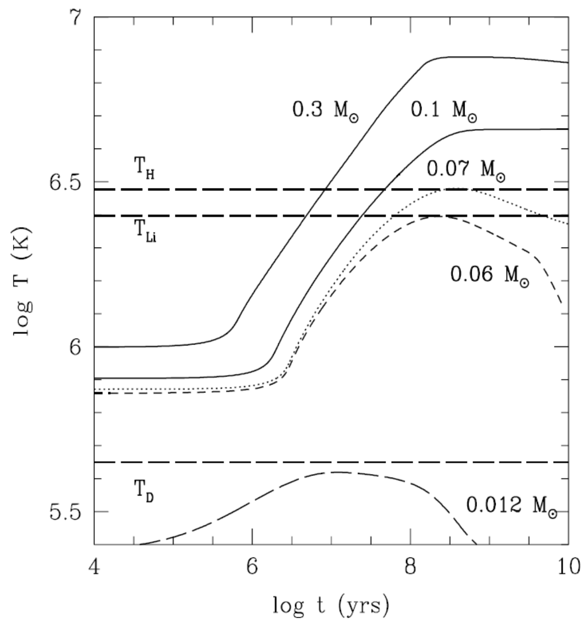

Figure 1: Temperature as a function of time for stars of different masses, from Chabrier & Baraffe (2000). Note that the 0.07 $M_\odot$ brown dwarf does actually burn some hydrogen, briefly.

2 The Burning Limits

2.1 The Hydrogen Burning Minimum Mass

The stellar lower mass limit is defined as the mass point at which objects will reach degeneracy pressure before they get to high enough temperatures to sustain hydrogen fusion. In this sense, brown dwarfs are defined as 'stellar-like objects that do not fuse hydrogen into helium in their cores' while at the same time defining stars as objects that do. This depends on what you consider hydrogen burning; [Chabrier & Baraffe (2000)] point out that for stars less than 0.15 $M_\odot$, the $^3He + ^3He \rightarrow ^4He + 2p$ reaction of the (then-dominant) PPI reaction chain occurs on very slow gigayear-length timescales, and that ^{3}He is far more long-lived than it is in stars like the Sun. [Chabrier & Baraffe (2000)] cite the Hydrogen Burning Limit as in some sense being no more important than the distinction between fusion by Proton-Proton Chain and CNO bi-cycle, except that the eventual destinies of PPI and PPII/III and CNO-cycle stars are far more similar than those of the brown dwarfs. The most massive brown dwarfs will actually also burn hydrogen in their cores, but are never fully supported by it and do not sustain the process for terribly long (See Figure 1).

A fairly instructive analysis of the Hydrogen Burning Minimum Mass (HBMM) was carried out by [Dantona & Mazzitelli (1985)], where they computed the fraction of internal energy derived from nuclear and from gravitational contraction. The main sequence, as stated, is the point at which the total luminosity of the star is due to nuclear reactions, $L_{total} = L_{nuclear}$. As given by their models, objects of 0.09 $M_\odot$ contract as they heat up, pausing briefly to fuse deuterium into helium at temperatures of 7–8$\times10^5$, followed by a further contraction and increase in temperature until

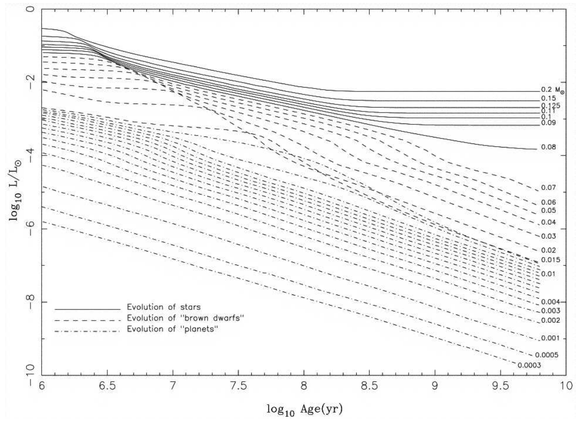

Figure 2: The putative waterfall, from Burrows et al. (1997). Note how long it takes the 0.08 $M_\odot$ star to reach equilibrium (steady luminosity)

they reach $L_{total} = L_{nuclear}$ at an age of 3.9 Gyr. On the other hand, their 0.06 $M_\odot$ model pauses briefly to fuse deuterium into helium, but the temperature reaches a maximum shortly thereafter and declines, leaving the star to forever contract and cool as degeneracy pressure takes over. After a "short" while longer, all nuclear reactions stop and the brown dwarf is left as a thermally radiating object. The more interesting cases are of the 0.08 $M_\odot$ model and the 0.075 $M_\odot$ model, sitting right on the hairy edge of the HBMM line. Their 0.08 $M_\odot$ model does indeed become a star, but it does so only after a period of 12 Gyr, nearly the age of the galaxy (see Figure 2). The 0.075 $M_\odot$ model is 80% supported by hydrogen fusion at the 10 Gyr mark, but by the time their model series terminated at 1.9×10^{10} Gyr, that luminous support had dropped to 70%. They took this as evidence that the cutoff was somewhere just above 0.075 $M_\odot$.

There are a few things to note from this work. First of all, [Dantona & Mazzitelli (1985)] is an older paper, published before Gl229B was discovered and it became apparent exactly how accurate these low-mass stellar models had to be. Secondly, D'Antona and Mazzitelli themselves note that their results are highly dependent on proper treatment of opacities. In a previously published paper using a different set of opacities, the 0.09 $M_\odot$ model failed to switch on as a star. Though the exact value is still not entirely resolved, their results are quite close to the best current estimates of the HBMM: 0.075 $M_\odot$.

[Burrows et al. (1997)] find similar results in their more rigorous analysis (though unlike D'Antona and Mazzitelli they do not include grain opacity, which is an extremely important factor in atmospheres). Actually, models of barely-subsolar objects have been saying things in the vicinity of 0.07 $M_\odot$ since the very earliest research done by [Kumar (1963)]; this limit is merely in need of fine-tuning.

One particularly important consequence of this research, particularly for observers, is that brown dwarfs resemble low-mass stars extremely well in both external and internal properties, and can do so for periods approaching a Hubble Time. Other models may differ on specifics, but the fact generally remains that the very lowest mass stars and highest mass brown dwarfs act like members of the same class of object for long periods of time.

2.2 The Deuterium Burning Limit

The other end of the brown dwarf distribution is commonly taken to be the limit of deuterium burning, separating objects that have at least had some form of fusion from those that exhibit none. The production of energy through the $^2D + p \rightarrow {}^3He + \gamma$ process can occur for temperatures of $T_D = 4 \times 10^5 K$ or higher, which leaves Deuterium fusion open as a source of energy for a much wider range of objects than can fuse ^1H. This is one form of fusion that is common to objects both above and below the Hydrogen burning limit. and is the closest brown dwarfs come to nuclear support. Beyond deuterium fusion, both classes of objects will follow extremely similar tracks down toward the main sequence, though only one will reach hydrogen fusion before degeneracy pressure sets in.

[Chabrier et al. (2000)] note that by their calculations, all objects more massive than 0.012 $M_\odot$ should be massive enough to fuse Deuterium, but such that they will exhaust the primordial supply on timescales of 1-50 Myr. According to their calculations, based on more accurate 'NextGen' atmospheres, by 1 Myr all stellar-mass objects should have fused appreciable amounts of their deuterium, while 0.07 $M_\odot$ objects will have only burned an indistinguishable amount. The authors find that this should accomodate the deficiency in the lithium burning limit at early ages. Unfortunately, this reveals no new internal physics.

2.3 The Lithium Burning Limit

One of the more popular tests for whether an object is a young and hot brown dwarf or an actual star is the so-called lithium test. The test stems from the fact that the required temperature for the $^7Li + p \rightarrow {}^4He + \alpha$ is around $10^{6.4} K$, temperatures that will not be reached in objects with starting masses less than 0.06 $M_\odot$. Any object more massive and yet still fully convective (as stars at the cool end of the main sequence are thought to be) will quickly exhaust its entire lithium supply from both core and outer atmospheric layers; any smaller object will still exhibit all its original lithium. This makes lithium burning a rather attractive test of the stellar/nonstellar nature of an object, with a few caveats.

Firstly, Lithium burning is not instantaneous. [Chabrier et al. (2000)] cite a depletion timescale of 10^8 years. While this is fairly brief in an astrophysical sense, it makes distinguishing between the lowest-mass stars and their equally-luminous brown dwarf imposters impossible at young ages when brown dwarfs are easiest to spot. Several papers have actually been written proposing the lithium test as a probe of age for clusters. The Lithium test is thus more accurate as an age test within star clusters, and only outside does it become an accurate probe for fusion in the core.

Secondly, the limit of hydrogen fusion as mentioned above is believed to be closer to 0.075 $M_\odot$. Any object with lithium must be a brown dwarf, but the lack thereof is not an indicator of anything.

2.4 Metallicity

One general outcome of the previous generations of brown dwarf models are that the correct opacities matter a great deal in terms of the actual values of the Hydrogen Burning Minimum mass. [Chabrier & Baraffe (2000)] note that for Z=0.02 $Z_\odot$ their calculations of the minimum mass goes from 0.075 $M_\odot$ to 0.083 $M_\odot$. Decreased metals means decreased opacity, and more energy production (which requires more mass) is needed to support the object against collapse. Metallicity is therefore a vital quantity to know before we talk about the minimum burning mass for *any* atomic species.

3 Interiors

3.1 State Parameters

As mentioned above, most of the formulae for the internals of brown dwarfs are still relatively in their infancy. The general picture, however, is that central densities peak at 0.4 $M_\odot$, where the stars become fully convective and approach an n = $\frac{3}{2}$ polytrope. Above that line, stars tend toward solar-like polytrope indicies. Below, they remain n = $\frac{3}{2}$ polytropes all the way down to Saturn-mass objects. Central densities range from $\rho_c = 10^3 gcm^3$ for the peak of the n=$\frac{3}{2}$ distribution at 0.4 $M_\odot$, and reach as low as $\rho_c = 10 gcm^3$ for Saturn-sized objects. Central temperatures T_c also vary from 10^7–10^4 , between sunlike stars and Saturn.

While stars are capable of holding off degeneracy (either in the case of a white dwarf or neutron star) for extended periods of time by the processes of nuclear fusion, brown dwarfs have no such internal energy source, are only saved from degeneracy by the thermal pressure of their continuing collapse. [Stevenson (1991)] notes that in this absence of nuclear energy generation, the internal pressure is best approximated by $P = P_F + P_{th,ion} + P_{th,el}$. For an object that is under adiabatic collapse for nearly all of its lifetime, this works out to a total pressure of $10^{13} \rho^{\frac{2}{3}} \left(1 + \psi + \frac{\psi^2}{1+\psi}\right) \mu e^{\frac{-5}{3}}$, and with a radius of $R = R_0 \left(1 + \psi + \frac{\psi^2}{1+\psi}\right)$. An interesting result of these calculations, also noted by Stevenson based on even earlier work by Zapolsky and Salpeter, is that with the addition of small yet finite Coulomb and exchange pressures to these equations, these pressures stabilize the star such that there is a maximum radius $2.2 \times 10^9 \left(\frac{M_\odot}{M}\right)^{\frac{1}{3}} \left(1 + \frac{M}{0.0032 M_\odot}^{\frac{-1}{2}}\right)^{\frac{-4}{3}}$ at about 6×10^9 cm, roughly the radius of Jupiter.

Effective temperatures for stars reach down to around 2000 K, and for brown-dwarf and other related substellar objects reach down to 100 K. These lower temperatures are suitable places for the formation of all kinds of complex and highly absorbing molecules, requiring more complicated non-stellar models of atmospheres and in the coolest cases, interiors. Nevertheless, when dealing with the actual lower mass limit and objects in that range, [Chabrier & Baraffe (2000)] find that treating the interior as a fully ionized gas of $H+$ and $He++$ is still a reasonably accurate assumption.

3.2 The Core

Stars with masses less than roughly 0.35 $M_\odot$ are widely agreed to exhibit fully convective interiors, allowing for mixing of all the material within the star. This general effect also separates low mass stars, interior-wise, from the higher mass stars up through F5 (where the surface becomes radiative). For the kind of interior densities and pressures they exhibit, within the cores of very low mass stars T_{eff} approaches the Fermi Temperature, and the degeneracy parameter $\psi = \frac{kT}{kT_F}$ hovers around 1. Combine the polarizeable partial classical and quantum degeneracies mentioned in [Chabrier et al. (2000)] with the pressure ionization that are believed to become important around those temperatures, and the computational problems become extremely challenging.

In brown dwarfs, the process is much the same except that rather than teetering on the edge of degeneracy for trillions of years, their core collapse fails to sustain fusion and degeneracy dominates in a much shorter time. Apart from residual thermal energy, brown dwarfs are electron degenerate and will essentially remain so for the rest of eternity while their envelope slowly collapses. These stars are still not fully degenerate, and worse, the effects of *conductive* flux are increasingly important. The addition of sizeable conductive flux is currently understood to cause older brown dwarfs to slow their cooling processes and appear less luminous but hotter than relations would predict.

One unanswered question about the cores of these objects is directly related to their formation. One of the competing theories of how these very low mass objects form suggests that brown dwarfs and very small stars may form as planets do, accreting around a central rocky core. While the decision has been made to consider both a stellar core-collapse produced object *and* its giant planet cousin as brown dwarfs (or stars) on the basis of observable properties, it remains an unanswered question just what kind of residual properties the original rocky (therefore higher metallicity) core may have–are they observable at all?. The physics behind the cores of both of these classes of objects are still not all that well known.

3.3 Magnetic Fields

Lower mass stars are fairly well known for having powerful magnetic fields given their small size, judging by frequent reports of powerful stellar flares observed in X-ray and radio wavelengths, or with Zeeman splitting of various spectral lines [Reiners (2007)]. Based on measurements of the sun it has long been assumed that flares are coupled with magnetic activity, with the dynamo at the interface between the convective and radiative zones in the star [Reiners & Basri (2006)], and highly dependent on the rotation of the star (the so-called $\alpha\omega$ model). As discussed above, below masses of 0.35 $M_{\odot}$ the interiors of stars are believed to be convective all the way down into the core, which leaves some question as to the exact mechanism used for energy production. Objects without this change between radiative and convective regions clearly require a different dynamo, seeing as even though there is some sort of dropoff toward the end of the main sequence.

The peak of this X-ray flux measurement is around the M4-M5 stars (See Figure 3), which would seem to imply that fully convective stars have more powerful magnetic fields. [Reiners (2007)] suggests that this is rather due to the fact that convection dampens rotational braking, leaving more massive M stars rotating much slower than the sun, and smaller ones (around M4-M5 again) rotating much faster. The exact mechanism by which these magnetic fields are generated is still poorly understood, but nevertheless fully convective M dwarfs have kiloGauss magnetic fields. One mechanism described in [Reiners (2007)] is simply that magnetic fields may not actually require the tachocline (boundary between convection and radiation) to produce magnetic fields, and rotational mixing will do the job instead, with magnetism generated by smaller scale disturbances.

This trend, with the dropoff at the end of the main sequence, seems to continue into the brown dwarf stars, although [Reiners (2007)] raises the question of whether nor not this is observational bias toward younger, brighter dwarfs who have yet to lose a residual field. Unfortunately, brown dwarfs cool as they age and their atmospheres change beyond the possibility of comparing like spectral features against like.

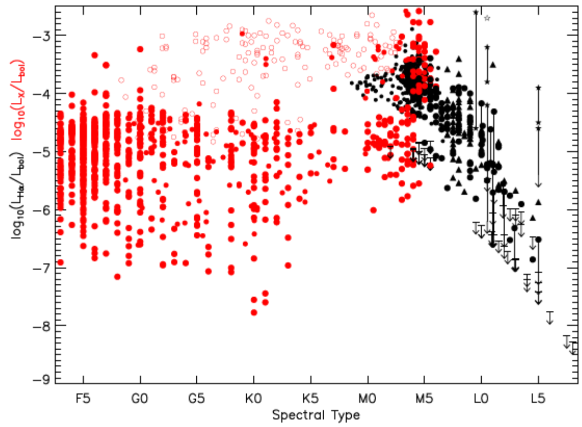

Figure 3: Normalized activity vs. spectral type. X-ray and Hα emission are shown on the same scale. Lines connect observations of identical objects. X-ray measurements (red) are from Voges et al., 1999 (field stars, filled circles) with spectral types from the Hipparcos catalogue (ESA, 1997). Open circles are cluster stars from Pizzolato et al. 2003, field stars from the same publication are plotted as filled circles. Hα (black): small circles from Reid et al., 1995 and Hawley et al., 1996; large circles from Mohanty & Basri, 2003, Reiners & Basri, 2007, Reiners & Basri, in prep.; triangles from Schmidt et al., 2007; stars from Burgasser et al., 2002 and Liebert et al., 2003.

Figure 3: Note the peak activity, which theoretically correlates with rotation

4 Atmospheres

The lowest-mass stars (classiffied as M) are generally defined by the appearance of titanium oxide bands in their upper atmospheres (though such features can be discerned in K star spectra as well), rendering them unlike other stars both in the presence of molecules in their atmospheres, and the way those molecules render the stellar spectra completely unlike blackbodies. Less specific treatments of low-temperature stellar atmospheres have failed to reproduce the behavior properly [Jao et al. (2007)], and it's only with more recent work such as the Phoenix code for GAIA [Brott & Hauschildt (2005)], though these do not even go down below 2700K) that models have started reproducing, in earnest, the behavior of the lowest mass stars.

The spectra of brown dwarfs are an even more complicated matter. Indeed, somewhere between stars and giant planets, the atmospheres must shift from having coronae (M stars) to having clouds (Jupiter). In reality, the shift to molecule-dominated spectra has already begun by the M stars. M star spectra show signs of increasing amounts of high-temperature molecules like titanium oxide, vanadium oxide, and calcium hydroxide, which dominate the spectrum and carve huge chunks out of it. Brown dwarfs continue this trend, with even more complicated sources of opacity.

The brown dwarf range (designated as spectral type L) is distinguished spectrally by extremely infrared colors and the sudden depletion of the heavier elements [Chabrier et al. (2005)] as they condense out of the atmosphere into more complicated molecular grains (eg. TiO into $CaTiO_3$, aluminum into complex molecules like corundum (Al_2O_3), and so on). Their effects are replaced by grain opacity from those molecules, while water lines and other species mentioned above dominate the spectrum, obliterating visible flux and greatly enhancing the infrared flux of these objects.

Grain sizes are thought to reach somewhere around 0.5 μm, and complicate the atmospheric and internal physics by requiring estimates of cloud heights and where within the star the grains will reach sublimation temperatures. One particular irony of grain formation in these regions is that the computed opacities generated as a function of temperature cause the spectrum to actually loop back to slightly bluer (but still heavily infrared) wavelengths in some models for objects less than 0.072 $M_{\odot}$. Even hydrogen begins to have significantly different effects, with powerful H_2 collisionally induced absorption in the outer atmospheres- a powerful effect missing in more massive stars that are fully ionized out to their coronae.

The major portions of the paper by Burrows [Burrows et al. (1997)] detailed their attempts to model brown dwarfs. The model they arrived at contained many non-starlike features, such as treatments of metallic hydrogen and helium (metallic hydrogen is thought to be at the center of Jupiter, and thus should appear at some transition point), and scattering and absorption opacities for chemicals like H_2O, CH_4, NH_3, N_2, and H_2. They actually noted in their explanation that large portions of their technique were adapted from attempts to form temperature profiles of the outer planets. Their model, at various points, contains up to 2×10^8 lines per hydrostatic atmospheric slice, perhaps explaining why such analysis was avoided before Gl229B demonstrated its necessity.

Most recent observers have observed a further boundary within the Brown Dwarf range, at the approximate point (around $T_{eff} = 1400K$) where the dominant form of carbon in the atmosphere goes from CO to CH_4. Objects below this boundary, like Gl229B, are designated 'T dwarfs'. This region is also suspected to be around the point where clouds begin to form in the atmosphere [Chabrier et al. (2005)], and a further evolutionary step between stars and planets.

Since brown dwarfs never sustain hydrogen fusion, the L and T "spectral" classes actually define an evolutionary sequence. All brown dwarfs will pass through the T dwarf range at some point in their lives. As per the discussion of Hydrogen Burning, the most borderline brown dwarfs will take extremely long times to cool, but such cooling is inevitable. That generality has to be tempered by the fact that L and T, like all spectral classes, is defined by spectra mostly produced by the outer layers of the atmosphere. It remains possible that a few objects with L spectra could actually be stars, while it's already well known that brown dwarfs can masquerade as M dwarfs over non-trivial timescales.

5 Formation (and location)

In the years following the discovery of Gl229B and the recognition of brown dwarf status, many brown dwarf stars have been found. At the same time radial velocity techniques have found gigantic collections of planets. These radial velocity techniques are most sensitive to objects with large masses and short periods; thus they should be picking up extremely high proportions of brown dwarfs. The fact that they do not suggests one of three things: a statistically improbable fluke, a lack of brown dwarfs, or a statistical lack of brown dwarfs in close orbits, pointing to a different physical formation mechanism.

The first possibility can be rephrased in a somewhat more palatable form as this: We're missing something vital and the brown dwarfs have been slipping through our fingers. This idea has been raised before by such authors as [Reid et al. (1994)], writing pre-Gl229B about the possibilities that either brown dwarfs were truly rare, or that scientists were mistaking them for other stars, presumably low mass M stars. While that has been proven to be theoretically possible (and the

Brown Dwarf Archives from Kirkpatrick et al. list many stars with IR or Optical classifications as M stars), this theory does not seem to fit the facts.

The second theory is that there simply aren't as many brown dwarfs. This suggests that the famous Salpeter mass function (general form $N \approx M^{2.35}$) 'turns off' at lower masses. It's already known that better piecewise functions fit the facts better for the other areas of the main sequence, though most of those are still biased toward lower mass stars.

5.1 Multiplicity

The third possibility is there's something fundamentally different about brown dwarfs that they don't show up in close orbits. This is already mentioned in several arguments, most notably ones that take into account the binarity of these objects. [Thies & Kroupa (2007)] cite a distinct lack of brown dwarf-solar type star binaries, suggesting a different mass fraction for the two different kinds of object, and notes research that separately, very low mass stars and brown dwarfs are only about 15 percent in binaries, versus nearly 100% for young clusters, and 50% for field stars. While they note it remains possible that there are binaries whose companions are just farther out, that would still need to be explained, since stars and planets are found at all manner of distributions as far as the physical limits of what we can observe go.

(It's worth noting that [Chabrier et al. (2005)] claim that the binary fraction is very *high*; apparently this particular topic is still open to debate)

5.2 Core Collapse

The first potential theory on their formation is the most obvious one, that they form like stars except with insufficient end mass to start hydrogen fusion. Given turbulent gas clouds or clouds with sufficient metallicity, it's possible to construct models that fragment into objects as small as brown dwarfs. This, an extension of the ecological principle mentioned at the beginning of this paper, would simply lead to formation of objects with smaller scales (down to 0.007–$0.015 M_{\odot}$) [Whitworth & Goodwin (2005)] irrespective of their own unusual nature. Brown dwarfs and very low mass stars are very much like each other, leading to the suspicion that they should form the same way.

There are a few problems with these theories though; the repeated fragmentary collapse method is apparently never actually seen in nature [Whitworth & Goodwin (2005)]. Secondly, if we ascribe the same formation mechanism to very low mass stars and brown dwarfs, we should expect to see the same distribution and multiplicity fractions. As the previous section has indicated, we do not.

Some authors (eg. [Chabrier et al. (2005)]) have used this distinction as a definition of a brown dwarf. The high mass limit is still fixed at the lower stellar mass limit, but now *anything* nonstellar that forms from core collapse is a brown dwarf; this potentially includes objects below the deuterium-burning mass limit that would otherwise be classified as giant planets. While it is obviously possible that having accreted matter around a solid rocky core could affect the properties of an object, most researchers maintain the view that the mass and age (and composition, and proximity to a star) will be more important, as "an object's pedigree is not an obvious observable" [Burrows et al. (1997)]. Despite being the more theoretically interesting definition, this does not seem to be the dominant view, and the deuterium limit definition was adopted by the IAU in 2003. [Chabrier et al. (2005)]

5.3 Planetary Accretion

The second theory is that brown dwarf stars form like planets. Planetary accretion processes are well known and reasonably understood from in-depth observations of how our solar system formed. Under this model, the brown dwarf or star would form by accreting gasses around some possibly rocky nucleus, producing some kind of mega gas-giant planet. The only difficulty with this theory is that it doesn't explain the lack of objects in close orbits to the parent stars; the easiest and most common type of exoplanet (indeed, the most detectable) is the hot Jupiter in extremely close orbit of its sun, yet we don't find many close very low mass stars or brown dwarfs. Another startling feature of this distribution is a lack of widely separated binaries; there's a steep dropoff outside of 20 AU indicating that for whatever reason, all the binaries thus discovered are more tightly bound than is usual for a normal higher-mass stellar binary ([Burgasser et al. (2007)]).

One possible variation on this method is to cause this protostellar disk to fragment based on interaction with another nearby protostellar disk [Whitworth & Goodwin (2005)]. This mechanism is more adept at producing singular brown dwarfs of significant masses, and can even give the brown dwarfs their own disks. [Thies & Kroupa (2007)] note that the theoretical distance from the central star at which a brown dwarf could condense from the perturbed disk is very nearly what is observed in the only known cases of wide brown dwarf binaries.

5.4 Photoevaporation by O stars

Another theory is that these lower stellar limit stars may be the products of being too close to O and B stars in their parent cloud. If a potential protostellar cloud strays too near the rather massive HII region around one of those supermassive stars, the cloud will either be blown away or its collapse retarded by the ionizing force adding external pressure. With sufficient ablation of the material off of the cloud, what might have become a K or M star might now be a very low mass star or brown dwarf.

The best place to find massive O and B stars capable of doing this is star forming regions, but as [Burgasser et al. (2007)] note, this is not true of *all* star-forming regions. The Taurus and Cha I star-forming regions are both small and not populated by sufficiently luminous stars to make that argument believable, and yet brown dwarfs have been observed in there. While this could definitely winnow away material and leave only a substellar or barely-stellar core, it can't be the dominant mechanism.

5.5 Binary Ejection

Another way to prematurely cut off the supply of material settling into the protostar is to imagine that it formed as a binary or higher order multiple, but due to complex interactions was ejected from the system while forming. As above, this leaves it with an insufficient source to form an actual star. This explanation does reproduce the curious lack of binarity observed in very low mass stars and brown dwarfs, and might also help to explain why existing binaries are more tightly bound than the average binary system. [Thies & Kroupa (2007)] do debate whether it accurately reproduces the protostellar disks observed around brown dwarfs, though.

Which of the preceeding four mechanisms actually dominates seems to largely depend on whose paper you read; [Chabrier et al. (2005)] favors the turbulent fragmentation method, while

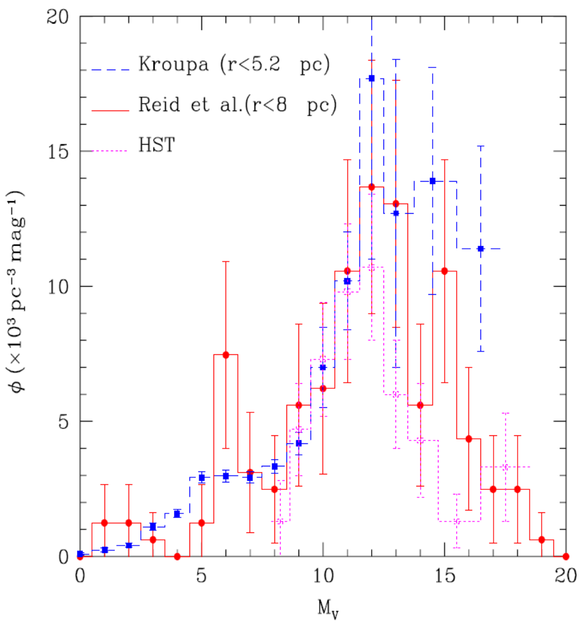

Figure 4: A best-guess luminosity function as of 2000, from Chabrier & Baraffe (2000). Whether the low end behavior is real or observational is unknown.

[Whitworth & Goodwin (2005)] discounts it altogether, and [Thies & Kroupa (2007)] seems to favor embryo ejection. Of course, it's quite possible that all are playing some sort of limited role. [Thies & Kroupa (2007)] find that there's sufficient evidence to support two overlapping mass-generation mechanisms; one for stars and one for brown dwarfs. Some brown dwarfs may form as planets do; perhaps even some stars do.

6 Cosmological Importance

One of the more interesting and exciting possibilities in the study of the lower stellar mass limit is the way that objects in that range may be the source of dark matter. The true nature of the dark matter in the universe has been a hotly contested point since it was first discovered that most of the matter in the galaxy is spread out into a dark halo. Very low mass stars and brown dwarfs fit the criterion of being dark by virtue of their extremely low (10^{-5}) luminosities, and it remains to be seen how many of them there really are. (See Figure 4)

6.1 The Mass Function

For all the reasons mentioned in the introduction to the previous section, the study of the mass function near the lower stellar mass limit may be more interesting than it might first appear. There are ample suggestions that the mass function is actually quite different from the general trends seen in more massive stars. Attempts to actually pin this down have run into severe observational limits due to the faintness (and age, for brown dwarfs) of these objects, but the results they have produced tell a somewhat more interesting story.

[Thies & Kroupa (2007)] looked at the IMFs produced in several papers dealing with the Trapezium, IC 348, the Pleiades, and the Taurus-Auriga star forming region. They found that overall, the power law mass function appears to flatten out at very low masses, with evidence that it may even turn over around the Hydrogen Burning Minimum Mass. Assuming there *are* some minimum and maximum masses for a particular method of object formation, they create fitting functions for binary and single systems. Their results are fit best by allowing stars to have any size companion, while brown dwarf objects were strongly skewed to similar-mass companions, or a rather unusual case where the mass function is not continuous and breaks near the gap between stellar and nonstellar objects. In either case, they take their results as evidence that brown dwarfs and actual stars form two separate populations (as mentioned above, supporting the idea of different formation mechanisms). They find that these mass functions may overlap within the range of 0.07 to 0.2 $M_\odot$, with the two trailing components forming a 'hump' right at the end of the main sequence. The split or double IMFs in [Thies & Kroupa (2007)] have yet to be verified, but the expected appearance is within the noise of currently available data on brown dwarfs and low mass stars.

6.2 Distribution within the galaxy

One attempt to actually probe the collective mass of very low mass stars was carried out by John Bahcall, [Bahcall et al. (1994)] who determined that there were not enough low mass stars in the galactic halo to make a significant dent on the apparent amount of dark matter that's been demonstrated as required to reproduce galactic rotation curves. Bahcall's work used estimates of representative stellar masses and estimated luminosities, combined with the column mass density necessary to produce the observed rotation curves, and determined that, for example, there should have been 65 stars in a field where there were only 5 potential halo stars (some discarded). He also cites evidence of microlensing from proposed MACHOs that are not consistent with the massive compact halo objects being brown dwarfs. Based on this, Bahcall concluded that low mass stars (with V magnitudes ≤ 14, ignoring all dimmer objects via statistical arguments) comprise only a minor fraction of the observed dark matter in the galactic halo.

On the other hand, searches for previously unknown nearby stars remain rather fruitful. In 2006, the RECONS group reported [Henry et al. (2006)] twenty new systems within ten parsecs of the sun, appreciably increasing the known amount of baryonic mass in the nearby parts of the galaxy. This number can be demonstrated as still incomplete, leaving plenty of room for increasingly low-mass stars to be discovered. Exactly how many there are, and how this will impact the general nature of Bahcall's findings remains to be seen. If it turns out the lack of brown dwarfs is *not* due to a second IMF with a power law that turned over, there is still a chance that brown dwarfs will turn out to be the requisite missing mass.

7 Conclusions

What we see here with the lower stellar mass limit is unfortunately a great deal of confusion surrounding the presence or absence of hydrogen fusion, the defining characteristic of a star. These very smallest stars are still poorly understood due to the extra sources of opacity in their atmospheres, the approach (or arrival at) degeneracy pressure in their otherwise fully convective cores, and general uncertainties about how such small objects form. Whether or not they do constitute a large chunk of the mass of the galaxy or not is still unknown. Studies of brown dwarfs are ongoing, and as telescope equipment improves we will increasingly be able to answer the questions about what the lower stellar mass limit is, what the physics are in the transition, how stars form, and what the physical limits of stellar processes are.

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