I present a scenario for the production of low-mass, degenerate dwarfs of mass greater than 0.1 \(M_\odot\) via the mechanism of Lenzuni, Chernoff, & Salpeter. Such objects meet the mass limit requirements for halo dark matter from microlensing surveys while circumventing the chemical evolution constraints on normal white dwarf stars. I describe methods to observationally constrain this scenario and suggest that such objects may originate in small clusters formed from the thermal instability of shocked, heated gas in dark matter halos, such as suggested by Fall & Rees for globular clusters.

Subject headings: accretion, accretion disks — cooling flows — galaxies: formation — Galaxy: halo — stars: formation

1. INTRODUCTION

The detection of microlensing in the direction of the Large Magellanic Cloud (Alcock et al. 1993; Aubourg et al. 1993) has stimulated investigations into the nature of baryonic dark matter. In particular, the lack of short timescale events (Alcock et al. 1997; Aubourg et al. 1995) appears to favor objects more massive than brown dwarfs. This mass limit, combined with direct observational constraints, favors white dwarfs more than main-sequence stars (Bahcall et al. 1994; Graff & Freese 1996; Hansen 1998). However, the problems associated with the chemical pollution from prior evolutionary stages (e.g., Gibson & Mould 1997) makes attempts to salvage the brown dwarf hypothesis worthwhile. Some have invoked dark clusters of brown dwarfs (Carr & Lacey 1987; Kerins 1997; De Paolis et al. 1998) or spatially varying mass functions (Kerins & Evans 1998) to explain the lack of short timescale events. In this letter I will address another possibility, namely the creation of a population of cold, degenerate dwarfs with masses \(\sim 0.1-0.3 M_\odot\), which do not burn hydrogen by virtue of their unusual construction.

In § 2 I will describe the formation and evolution of said dwarfs and the possibilities for their detection. In § 3 I will present a cosmological context for their formation.

2. BUILDING A BIGGER DWARF

Traditionally, star formation occurs via the inside-out collapse of a gas cloud in which radiative cooling and ambipolar diffusion remove the pressure support, allowing rapid contraction to stellar dimensions. What determines the cessation of accretion (and thus the final mass) is a matter of some debate, be it the onset of nuclear fusion, competition for gaseous resources, or back-reaction from protostellar outflows. At the end of this contraction, the protostar ignites nuclear burning in the core if the density and temperature are high enough. Otherwise it becomes a degeneracy-supported brown dwarf and cools rapidly to invisibility. The dividing line between these outcomes is a mass of \(-0.08 M_\odot\) (Burrows et al. 1993).

However, Lenzuni, Chernoff, & Salpeter (1992) and Salpeter (1992) demonstrated that one could raise the hydrogen-burning limit by accreting material onto a brown dwarf \((-0.01 M_\odot\)) at low enough \((\sim 10^{-11} \text{ to } 10^{-9} M_\odot \text{ yr}^{-1})\) rates that the material settles onto the dwarf with low entropy. In principle, this procedure is limited only by the pyconuclear burning rate, and the hydrogen-burning limit could be raised to \(-1 M_\odot\). However, the small but finite entropy of the accreted material is likely to limit this mass to somewhat less than this (Salpeter 1992 estimates a mass limit \(-0.15 M_\odot\)). The limiting entropy of accreted metal-free material in spherical geometry is determined by the opacity minimum in the settling layer above the star, at \(-3000\text{ K}\) where the competition between H and H\(_2\) opacity is approximately equal (Lenzuni et al. 1992). The addition of metals will raise the opacity and will eventually lower the hydrogen-burning limit to original levels. On the other hand, the accretion of material from a disk (possible if the accretion is from an inhomogeneous medium) may serve to increase the limiting mass, depending on conditions at the inner edge of the disk.

To explore this scenario further than the semianalytic analysis of Salpeter, I have constructed a sequence of brown dwarf models using the same atmospheric and evolution codes used to describe old white dwarfs (Hansen 1998, 1999) while incorporating the degeneracy corrections to the nuclear burning from Salpeter (1992). I do not model the accretion process onto the dwarf as done by Lenzuni et al. (1992). Given the uncertainty in the state of material accreted from a disk, I prefer to address the question in another fashion, namely; how hot can a dwarf of given mass be before nuclear burning turns it into a star? For each mass, I have constructed a cooling sequence without including nuclear burning. I then consider the effect of switching on nuclear burning at various points on the cooling sequence. For each mass there is a transition point on the sequence above which there is a slow runaway and the dwarf becomes a normal hydrogen-burning star. Below the transition, nuclear burning is not strong enough to overwhelm the cooling luminosity and the star fades as a brown dwarf. Thus, I determine the range of parameter space which can accommodate brown dwarfs of varying mass. This represents the range of dwarf configurations which can potentially be constructed by the slow accretion of low entropy material.\(^1\)

The first important point to note is that, for dwarfs of primordial composition, the normal hydrogen-burning limit is raised to \(-0.1 M_\odot\) as noted by Nelson (1989), a consequence of the change in boundary condition resulting from the lower atmospheric opacity. As the mass increases, the transition tem-

\(^1\) Deuterium burning during construction may change the adiabat for a given object, but it is not strong enough to change this bound (Salpeter 1992).
perature drops rapidly as we pass through the range of masses 0.13–0.17 $M_\odot$. The effective temperatures for models at the transition point are $\sim$1500 K. At masses of more than 0.17 $M_\odot$, electron degeneracy in the center leads to formation of an isothermal core where energy transport by electron conduction dominates convection. This results in lower central temperatures than the adiabatic case and the effective temperature at the transition point remains essentially constant in the range $\sim$1200–1500 K for masses 0.17–0.3 $M_\odot$. Thus, if we allow material to be accreted with entropies appropriate to $T_{\text{eff}} \sim$ 1500 K atmospheres, the mass limit can be raised considerably above the 0.15 $M_\odot$ estimated by Salpeter (1992). These stars represent a configuration containing elements of both brown dwarfs (in terms of composition and lack of nuclear burning) and white dwarfs (in terms of mass and internal structure). Thus, for the purposes of clarity later, I shall refer to these (>0.1 $M_\odot$) objects as “beige dwarfs.”

Once formed, these dwarfs will fade slowly, radiating what little thermal energy they possess, just as brown and white dwarfs do. The cooling of the various models is shown in Figure 1. The watershed nature of the 0.15 $M_\odot$ model is apparent. For smaller masses, the evolution is similar to that of a traditional brown dwarf, with a rapid fading to insignificance within 5–6 Gyr. The 0.15 $M_\odot$ model retains a significant contribution from nuclear burning for several Gyr after birth, so that it takes longer to cool and therefore is the brightest model after $\sim$15 Gyr. For more massive models, the central transition temperatures are low enough that the dwarfs essentially begin life in a cool, white dwarf–like configuration and do not cool significantly further within a Hubble time. Also shown is a 0.6 $M_\odot$ carbon/oxygen white dwarf with hydrogen atmosphere from Hansen (1999). Thus, the larger radii of the beige dwarfs mean they are $\sim$1 mag brighter (since they have similar effective temperatures to the white dwarfs). For masses $\sim$0.3 $M_\odot$ the beige dwarfs will be superficially similar in appearance to white dwarfs.

Figure 1 shows the colors calculated for the HST WFPC bandpasses of Holtzmann et al. (1995). Furthermore, a population of such objects can be distinguished from a white dwarf population by the very different cooling sequence. Beige dwarfs are born with effective temperatures $\sim$1500–3000 K, in which molecular hydrogen is already a strong source of opacity (e.g., Borysow, Jorgensen, & Zheng 1997), so that they cannot populate a region equivalent to the upper part of the white dwarf cooling sequence (i.e., the initial redward evolution of the white dwarf track), which occurs for temperatures greater than 4000 K.

3. COSMOLOGICAL CONSIDERATIONS

This particular mode of star creation requires fairly special conditions to be important. The accretion rate must be in a narrow range $\sim$10$^{-11}$ to $\sim$10$^{-9}$ $M_\odot$ yr$^{-1}$ to yield both significant mass accretion while allowing the accreted material to retain only low entropies (Lenzuni et al. 1992). Furthermore, such rates are well above the $\sim$10$^{-18}$ $M_\odot$ yr$^{-1}$ experienced in the local ISM, implying that such rates must be related to the initial conditions for the formation of such objects.

Let us assume that brown dwarfs form in small clusters. Unless the process is highly efficient, there will be a substantial amount of gas present as well. For a cluster of mass $M$ and radius $R$, the ambient density $\rho \sim 0.25M/\pi R^3$ and velocity $V^2 \sim GM/R$ yield a Bondi-Hoyle accretion rate for a 0.01 $M_\odot$ brown dwarf of

$$\dot{M} \sim 6.4 \times 10^{-11} M_\odot \text{ yr}^{-1} \left(\frac{M}{10^2 M_\odot}\right)^{-1/2} \left(\frac{R}{0.1 \text{ pc}}\right)^{-3/2}. \quad (1)$$

Such an estimate lies within the acceptable range for transformation of brown dwarfs into beige dwarfs. But we need to know what size clusters and collapsed objects do we expect from primordial star formation.

The formation of primordial stars is intricately tied to the cooling mechanisms of primordial gas and thus to the formation of molecular hydrogen, the dominant coolant in dense, metal-free media. In the traditional cosmological scenario of hierarchical gravitational collapse, gas falls into the potential well of a cold, nonbaryonic dark matter component, is shock-heated to virial temperatures and cools to form the baryonic component of protogalaxies. Fall & Rees (1985) identified a thermal instability in such hot gaseous halos, in which the gas fragments into cold clumps surrounded by a hot, high-pressure ambient medium. The isobaric collapse of the cold clumps was assumed to halt at $\sim$10$^4$ K where the Lyman edge leads to inefficient cooling. The characteristic mass of such isobaric collapsing clumps was determined to be $\sim$10$^7$–10$^8$ $M_\odot$ and was thereby identified as a possible mechanism for forming globular clusters. However, nonequilibrium calculations of the cooling of shock-heated gas (Shapiro & Kang 1987 and references therein) indicate that cooling progresses faster than recombination, which leads to a residual electron fraction well above equilibrium levels, thereby promoting the formation of H$_2$ and enhancing the cooling rate. The result of this process is that the isobaric collapse is able to continue down to temperatures $\sim$30–100 K. This conclusion is robust unless there is a strong, preexisting source of ultraviolet radiation (such as an AGN) in
the same protogalaxy (Kang et al. 1990); i.e., cooling below 10^6 K cannot be stopped by a UV background alone. The Bonner-Ebert critical mass (Ebert 1955; Bonner 1956) for gravitational instability in high-pressure media is

\[ M_{\text{crit}} = 1.18 \left( \frac{k_B T_{\text{cool}}}{\mu m_p} \right)^2 G^{-3/2} \rho^{-1/2}, \] (2)

where \( \rho \sim n_{\text{H}_2} k T_{\text{vir}} \) is the pressure in the hot, virialized gas phase. The density of the hot phase is such that the cooling time is comparable to the dynamical time (Fall & Rees 1985), so that the pressure is determined entirely by the virial temperature and cooling function. For virial temperatures appropriate to our galactic halo (~10^6 K) the critical mass clusters will range from ~10^2–10^3 \( M_\odot \), depending on the final cooled temperature (assuming a variation between 30–100 K). The appropriate accretion rate is thus

\[ \dot{M} \sim 1.6 \times 10^{-11} \frac{M_\odot}{\text{yr}^{-1}} \left( \frac{M_{\text{bd}}}{10^{-2} M_\odot} \right)^2 \left( \frac{T_{\text{cool}}}{30 \text{ K}} \right)^{-5/2}, \] (3)

where we have assumed a velocity dispersion for the clump appropriate to the cooled gas temperature and \( M_{\text{bd}} \) is the mass of the accreting object. Note that the Bonner-Ebert mass in this situation is an lower limit on the collapsed mass. Larger clumps with lower accretion rates can form also, depending on the spectrum of perturbations in the hot gas phase. Nevertheless, this is exactly the kind of accretion rate we require, low enough to allow accretion of low entropy material but high enough to allow significant mass accretion on cosmological timescales.

Figure 2 shows the expected accretion rates in such cold clumps as a function of halo velocity dispersion (i.e., the virial temperature of the hot confining medium). There is some variation allowed depending on the final temperature to which the clumps can cool and thus the fraction of molecular hydrogen is important. The diagram may be split into three parts, depending on the accretion rate. For rates greater than 10^{-9} \( M_\odot \) yr^{-1}, the accreted material is too hot for the dwarf to remain degenerate and normal hydrogen-burning stars in the mass range ~0.1–0.2 \( M_\odot \) are formed (Lenzuni et al. 1992). For rates less than 10^{-11} \( M_\odot \) yr^{-1}, brown dwarfs will not accrete enough mass to change their character much in 10^9 yr, and so any brown dwarfs formed in such clusters will remain true brown dwarfs. However, between those two extremes, the conditions are appropriate for the transformation of brown dwarfs into the beige dwarfs described above in § 2. Furthermore, these conditions are applicable in the range of 100–300 km s^{-1} that describe the dark matter halos of galaxies. Such conditions may also apply in the case of pregalactic cooling flows (Ashman & Carr 1988; Thomas & Fabian 1990). If one wished to extend this picture to the case of cluster cooling flows (e.g., Fabian 1994), the larger virial temperatures and higher pressures suggest higher accretion rates and thus low-mass star formation rather than beige dwarfs. Thus, it appears that the formation of small gas clusters of appropriate density is a generic feature of gas collapse in CDM halos at moderate to high redshifts. However, there is also a requirement that brown dwarfs be the most abundant initial collapsed object. Once again, the physics of \( \text{H}_2 \) cooling in continued collapse provides the characteristic mass scale, a Jeans mass less than 0.1 \( M_\odot \) (Palla, Salpeter, & Stahler 1983). Although the complexity of star formation prevents a conclusive answer, the preceding provide plausible conditions for our scenario, namely the copious production of brown dwarf mass objects in relatively dense media in which they may grow on timescales ~10^9 yr.

How long will such accretion episodes last? This is an important question, because Bondi-Hoyle accretion \( \propto M_{\text{bd}}^2 \) and is thus a runaway process. An obvious concern is that, if gas is too abundant, even accretion at rates initially less than 10^{-9} \( M_\odot \) yr^{-1} will eventually lead to sufficient accretion to create a star. The abundance of ambient gas will depend on the efficiency with which one forms brown dwarfs initially. If the efficiency of conversion of gas into ~0.01 \( M_\odot \) objects is ~10%, then few objects will be able to grow by more than a factor of 10, providing a natural limiting mechanism. Furthermore, the formation of copious collapsed objects in a small cluster will result in two-body relaxation on timescales

\[ t_{\text{rel}} \sim 10^9 \text{ yr} \ \epsilon^{-1} \left( \frac{M_{\text{bd}}}{10^{-2} M_\odot} \right)^{-1} \frac{M_\odot^2}{100} \left( \frac{T_{\text{cool}}}{30 \text{ K}} \right)^{-3/2}, \] (4)

where \( \epsilon \) (in units of 0.1 here) is the efficiency of conversion of gas into 0.01 \( M_\odot \) bound objects and \( M_{\text{bd}} \) is cluster mass in units of 100 \( M_\odot \). In fact, \( \epsilon \) and \( M_{\text{bd}} \) may be regarded as dynamically evolving quantities as the characteristic collapsed object mass grows through accretion. Although cluster evaporation takes place on timescales ~300\( t_{\text{rel}} \) (e.g., Spitzer 1987), as more gas mass is incorporated into dwarfs, the cluster potential becomes “lumpier” and two-body relaxation accelerates, so that the cluster disruption time is ~5\( t_{\text{rel}} \) as defined in equation (4) by the time all the gas mass has been accreted onto the original seeds. This is also approximately equal to the timescale
for Bondi-Hoyle accretion runaway to infinite mass (this is not surprising, given that both accretion and two-body relaxation are intimately related to the gravitational focusing cross section). Thus, there is a finely balanced competition between mass accretion and cluster evaporation that may produce a very different mass spectrum than is usually assumed for primordial objects.

4. CONCLUSION

In this paper I have considered the possibility that thermal instabilities in primordial gas collapse favor the creation of small ($\sim 10^2$–$10^3 M_\odot$) gaseous clusters, which are ideal sites for the formation of massive brown (a.k.a. beige) dwarfs by the process of Lenzuni, Chernoff, & Salpeter (1992). This offers a scenario for the formation of baryonic dark matter which meets the requirements of both the microlensing survey mass limits and those of limited chemical pollution of the interstellar medium and production of extragalactic light (two stringent constraints on the currently fashionable white dwarf scenario). The scenario predicts that baryonic dark matter lies predominantly in beige dwarfs $\sim 0.1$–$0.3 M_\odot$, with probably some contribution from low-mass stars ($\sim 0.2$–$0.3 M_\odot$) as well. This mechanism is also peculiar to the early universe because it will become less efficient at constructing beige dwarfs once the accreted material contains significant metallicity (since greater opacity means material is accreted with more entropy). Thus, any present-day analog is more likely to produce low-mass stars. As such, this scenario may also naturally account for the red stellar halos of galaxies such as NGC 5907 (Sackett et al. 1994). Indeed, Rudy et al. (1997) find that the peculiar colors of this halo requires a population rich in red dwarfs ($<0.25 M_\odot$), but of approximately solar metallicity (primordial metallicity stars are not red enough to explain these colors).

Given the many uncertainties inherent in discussing primordial star formation and galaxy evolution from first principles, I have also constructed preliminary models for the evolution and appearance of such objects. Hopefully, deep proper motion surveys will be able to constrain this scenario directly. In particular, such beige dwarfs will be somewhat brighter than white dwarfs and should also occupy a restricted region of the Hertzprung-Russel diagram; i.e., they will not display a cooling track like a white dwarf population would.

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