Where to Find Overmassive Brown Dwarfs: New Benchmark Systems for Binary Evolution

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Abstract

Under the right conditions, brown dwarfs that gain enough mass late in their lives to cross the hydrogen-burning limit will not turn into low-mass stars, but rather remain essentially brown dwarf–like. While these objects, called either beige dwarfs or overmassive brown dwarfs, may exist in principle, it remains unclear exactly how they would form astrophysically. We show that accretion from AGB winds, aided by the wind Roche lobe overflow mechanism, is likely to produce a substantial population of observable overmassive brown dwarfs, though other mechanisms are still plausible. Specifically, we predict that Sun-like stars born with a massive brown dwarf companion on an orbit with a semimajor axis of order 10 au will likely produce overmassive brown dwarfs, which may be found today as companions to the donor star’s remnant white dwarf. The identification and characterization of such an object would produce unique constraints on binary evolution, because there is a solid upper limit on the brown dwarf’s initial mass.

Unified Astronomy Thesaurus concepts: Brown dwarfs (185); Stellar evolutionary types (2052); Stellar evolution (1599); Binary stars (154); Asymptotic giant branch stars (2100); White dwarf stars (1799); Low-mass stars (2050)

1. Introduction

Brown dwarfs were predicted on theoretical grounds by S. Kumar in the early 1960s (Kumar 1962a, 1962b, 1963a, 1963b, 2003). It took several decades before searches for brown dwarfs (e.g., Latham et al. 1989) yielded a definitive discovery (Nakajima et al. 1995; Oppenheimer et al. 1995). In the intervening decades, surveys have identified thousands of brown dwarf candidates, particularly in the infrared and taking advantage of proper motion measurements (Kirkpatrick et al. 1999; Lucas & Roche 2000; Gizis et al. 2002, 2000; Cruz et al. 2003; Close et al. 2003; Faherty et al. 2009; Kirkpatrick et al. 2011; West et al. 2011).

Brown dwarfs have proved enigmatic as the “missing link” between planets and low-mass stars, with some ambiguity remaining about whether brown dwarfs tend to form like scaled-up planets (Stamatellos & Whitworth 2009), or scaled-down stars (Reipurth & Clarke 2001; Bate et al. 2002). The atmospheres of brown dwarfs have also proven incredibly challenging to model as the result of chemistry and cloud physics (Marley et al. 1996; Burrows et al. 1997; Allard et al. 1997, 2011, 2012), which in turn affects their evolution (Chabrier & Baraffe 1997, 2000; Chabrier et al. 2000; Burrows et al. 2001; Baraffe et al. 2003) and hinders the inference of basic properties of field brown dwarfs (Filippazzo et al. 2015).

Around the time of their discovery, brown dwarfs and even brown dwarfs exceeding the hydrogen burning limit (HBL) were proposed as constituents of dark matter (Salpeter 1952; Hansen 1999; Lynden-Bell & Tout 2001), but stringent limits on massive compact halo objects from microlensing (e.g., Alcock et al. 1993, 1997) have made this explanation for dark matter untenable. Nonetheless, the possibility that brown dwarfs more massive than the HBL exist remains intriguing but unrealized thus far observationally. Recently, Forbes & Loeb (2019, hereafter FL19) rediscovered this possibility as a consequence of the diagram of equilibrium hydrogen burning as a function of a low-mass star’s central entropy and mass (their Figure 1). Brown dwarfs with masses exceeding the HBL need to wait to cool down after their formation, which likely takes several Gyr at least, in order to prevent their cores from igniting when they cross the HBL. In the formulation of FL19, their core entropy needs to be lower than the abscissa of the minimum of the curve in core entropy–mass space that coincides with the HBL.

In this paper, we discuss whether these objects can be produced under specific scenarios, and if so, where observers can find them. We rely heavily on simulations conducted with the Modules for Experiments in Stellar Astrophysics (MESA) (Paxton et al. 2011, 2013, 2015, 2018, 2019). In Section 2, we show that the favored scenario from FL19, namely a brown dwarf–brown dwarf binary evolving under gravitational wave radiation to a Roche lobe overflow phase is unlikely to work, because of the very small initial semimajor axis required for this scenario. Then, in Section 3, we turn to a more promising scenario, namely wind mass transfer from an evolved donor star. We discuss the challenges and implications of finding overmassive brown dwarfs in Section 4, and we conclude in Section 5.

5 Called variously overmassive brown dwarfs, to emphasize their similarity to brown dwarfs in all aspects but their mass, or beige dwarfs, to emphasize their simultaneous similarity to brown dwarfs and white dwarfs, or pristine white dwarfs, since they may be thought of as hydrogen-rich white dwarfs.
2. Brown Dwarf Binary

FL19’s preferred scenario for creating overmassive brown dwarfs was a brown dwarf–brown dwarf binary evolving under gravitational wave emission. They argued that overmassive brown dwarfs must be created slowly, i.e., with a very low accretion rate, to avoid igniting the core of the brown dwarf. In addition to being slow, the mass transfer must occur after several Gyr of evolution of the accretor brown dwarf so that the core can become sufficiently degenerate that additional mass would not simply place the star into the ordinary pre-main-sequence region of a diagram in central entropy versus mass ([FL19]’s Figures 1 and 2). Gravitational wave-driven orbital evolution of a binary brown dwarf system where the accretor had a mass of \( \approx 0.07 \, M_\odot \) and the donor \( \leq 0.05 \, M_\odot \) provided a promising avenue for each of these requirements. The mass transfer occurs over several Gyr, and is stable because the mass ratio, \( q < 0.05/0.07 \), is less than the classical critical value of \( \approx 5/6 \). ([Hjellming & Webbink 1987; Soberman et al. 1997])

Additionally, the evolution would not occur immediately, but rather only once the binary had lost enough angular momentum for the donor object to begin overflooding its Roche Lobe. Over several Gyr, this system could transfer \( \sim 0.02 \, M_\odot \) from the donor brown dwarf to the accretor, clearly bringing it from below the HBL to above it.

In order for the Roche Lobe overflow to occur, the binary brown dwarf system needs to end up with a semimajor axis, \( a \), comparable to the equivalent Roche lobe radius of the donor object, namely \( R_{\text{donor}} \approx R_{L,\text{donor}} \), where the Roche lobe radius is given by \( R_{L,\text{donor}} = aG(q) \) with

\[
G(q) = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}
\]

given by the Eggleton formula ([Eggleton 1983]). Here, \( q = M_{\text{donor}}/M_{\text{accretor}} \).

Under evolution by gravitational wave emission, the initial and final separations, \( a_0 \) and \( a_f \), of a binary are related by

\[
a_0 = \left( a_f^4 + \frac{256G^3}{5c^5}M_1M_2(M_1 + M_2)t \right)^{1/3},
\]

with component masses \( M_1 \) and \( M_2 \), and \( t \) the amount of time evolved (e.g., Paczyński 1967, FL19). For a final orbital separation of \( a_f = R_{L,\text{donor}} \approx 0.19R_\odot \), assuming \( q = 5/7 \) and \( R_{\text{donor}} = 0.1R_\odot \), Equation (2) implies that the initial separation should be \( a_0 \sim 0.35 \, R_\odot \) for \( t = 5 \) Gyr. Comparing this separation to the evolution of a set of brown dwarfs simulated with MESA\(^6\) (Paxton et al. 2011) suggests (Figure 1) that, for this scenario to work as imagined in FL19, the orbital evolution dominated by gravitational waves could only begin after the brown dwarfs were \( \gtrsim 10^7 \) yr old. If it began any earlier, the brown dwarfs would collide. Note that the radius evolution depicted here is in good agreement with the recently discovered and well-characterized transiting brown dwarf TOI-811b ([Carmichael et al. 2021]).

This delay is possible, e.g., if the brown dwarfs are initially separated by a larger distance and lose angular momentum via a different channel, e.g., magnetic braking ([Rappaport et al. 1983]), tidal evolution ([Hurley et al. 2002]), Kozai–Lidov oscillations combined with tidal circularization (see [Naoz 2016, for a review]), or some other dynamical assembly process. The binary fraction for brown dwarfs is not intrinsically high ([Fontanive et al. 2018]), so while the assembly of these systems may be possible, we expect it is not the primary channel by which one might form overmassive brown dwarfs.

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\(^6\) All of the inputs for the MESA runs presented in this work are available at https://github.com/dorsa1376/Ombd.
3. AGB Binary and Creation of an Overmassive Brown Dwarf

A key motivation for FL19’s focus on the binary brown dwarf scenario was the requirement that the accretion proceed slowly. In general, accreting gas will heat the surface of the brown dwarf, which may in turn be transferred to the core. However, it may also be the case that the accretion energy is quickly radiated away (Nomoto & Sugimoto 1977; Nomoto 1982; Townsley & Bildsten 2004). Paxton et al. (2013) argue that the relevant timescales in a thin layer of mass $\Delta M$ near the surface are the thermal time, $t_{th} = C_p T \Delta M / L$, and the accretion timescale $t_{acc} = \Delta M / M$. To understand whether the accretion luminosity $L_{acc} = GMM/R$ can be radiated away faster than more mass is added, we need to estimate the dimensionless ratio

$$t_{th} / t_{acc} \approx C_p TR / GM \sim 6 \times 10^{-5} \left( \frac{T}{1000 K} \right) \left( \frac{R}{0.1 R_*} \right) \left( \frac{0.07 M_\odot}{M} \right) \ll 1.$$  

(3)

Even if the accretion luminosity can easily be radiated away, additional mass added to the surface of the brown dwarf will require additional pressure support, which can compress and heat the interior. This process is discussed in detail in Townsley & Bildsten (2004) in the context of white dwarfs, and implemented numerically in MESA, even in the limit of rapid accretion where $t_{th} / t_{acc} > 1$.

This means that there may still be a limit to how quickly or how much mass can be added before igniting the brown dwarf. We will return to this point below after seeing the results of a binary MESA run that takes this compressional heating into account. Before that, we need to decide which area of parameter space to focus on.

The unimportance of the direct accretion luminosity $GMM/R$ opens up the possibility of scenarios with much slower characteristic timescales than the gravitational-wave-driven case. These include accretion in AGN disks (Cantiello et al. 2021; Dittmann et al. 2021; Jermy et al. 2021) and accretion from winds captured gravitationally by a brown dwarf orbiting a stellar companion. Given the uncertainties of stellar evolution in AGN disks and the difficulty of observing brown dwarfs in these distant environments, we focus on the case of wind capture.

To begin, we consider the case of Bondi–Hoyle accretion (Bondi & Hoyle 1944; Hoyle & Lyttleton 1939) from the wind of a star losing mass at a rate $M_{\text{donor},w}$. The wind has some approximately constant velocity $v_w$, meaning that the density of the wind, $\rho_w$, at any radius away from the star $r$ can be determined by $M_{\text{donor},w} = 4\pi r^2 \rho_w v_w$. The Bondi–Hoyle formula then implies that the brown dwarf companion accretes at a rate (Hurley et al. 2002)

$$\varepsilon_{BH} = \frac{M_{BD}}{-M_{\text{donor},w}} = \left[ \frac{GM_{BD}}{v_w^2} \right] \left( \frac{\alpha_w}{2\alpha_w^2 + 1} \right) \left( \frac{1}{\sqrt{1 + \frac{v_{orb}^2}{v_w^2}}} \right)^{3/2}.$$  

(4)

where $a$ is the semimajor axis of the orbit, and $v_{orb}$ is the orbital velocity $\sqrt{GM_{tot}/a}$ where $M_{tot} = M_{BD} + M_{\text{donor}}$. The $\alpha_w$ parameter is set to 3/2 following Hurley et al. (2002) and Boffin & Jorissen (1988). The wind velocity $v_w$ is taken to be proportional to the escape velocity at the surface of the donor star,

$$v_w^2 = 2\beta_w \frac{GM_{\text{donor}}}{R_{\text{donor}}}.$$  

(5)

Again following Hurley et al. (2002) and the wind mass transfer implementation in MESA, we set $\beta_w = 1/8$, as appropriate for the cool supergiant winds where most of the mass transfer takes place (Kučinskas 1998; Lamers et al. 1995). Note that the mass rates of change can be negative, i.e., $M_{\text{donor}} < 0$ as mass is lost from the donor star, but in our case $M_{BD} \geq 0$. For the purposes of the simple calculation in this section, $M_{\text{donor}} = M_{\text{donor},w}$, i.e., the donor’s mass is only changing due to its winds.

As a result of mass transfer between the stars, the angular momentum of the system changes, resulting in the following evolution equation for the semimajor axis,

$$\dot{a} / a = - \frac{M_{\text{donor}}}{M_{tot}} - \left( \frac{2}{M_{\text{donor}}} + \frac{1}{M_{tot}} \right) M_{BD},$$  

(6)

which is adapted from Hurley et al. (2002) with the simplifying assumption again that $e = 0$.

We evolve Equations (4) and (6) jointly, starting from a brown dwarf mass of $0.07 M_\odot$ and a varying initial separation $a(t = 0)$. To specify the evolution, we need to know $M_{\text{donor}}(t)$, and $R_{\text{donor}}(t)$, which could in principle come from any grid of stellar evolution calculations so long as the brown dwarf companion does not substantially affect the donor star’s evolution. Using the MIST tracks (Dotter 2016; Choi et al. 2016), themselves calculated with a previous version of MESA, we survey the space of initial $M_{\text{donor}}$ and $a(t = 0)$ in Figure 2.

In addition to showing $M_{\text{accreted}} = \int M_{BD} dt$, i.e., the total mass gained by the brown dwarf over the course of the donor star’s evolution, we also mark contours where the initial conditions lead to the brown dwarf being engulfed directly by the donor star at some point during the evolution (light pink lines), or the donor star overflows its Roche lobe (orange lines), which itself will lead to unstable mass transfer and a common envelope evolution because the mass ratio $q \equiv M_{\text{donor}}(t)/M_{BD} \gg 1$. We also highlight donor masses whose ages correspond to 13.7 Gyr and 3.5 Gyr. Donor stars with lifetimes longer than the former have yet to undergo the red giant and AGB phase where nearly all of the mass transfer takes place, while donor stars with lifetimes shorter than the latter will donate their mass to a brown dwarf that is not yet degenerate enough to avoid ignition of its core. This implies that overmassive brown dwarfs formed through this AGB accretion channel live preferentially in a region where the donor star’s initial mass is $\sim 1 M_\odot$, and the initial separation of the binary is $\sim 10$ au.

To the right of the yellow line, i.e., for donor stars that evolve so quickly that the brown dwarf has not yet cooled, it is likely that objects pushed above the HBL by mass transfer will become low-mass stars. Meanwhile, below the orange line, the common envelope phase may itself involve substantial mass transfer or evolution in angular momentum. It is clear that low-mass brown dwarfs can survive a common envelope phase
Figure 2. Mass gained by a brown dwarf from wind capture. In this case, we assume simple Bondi–Hoyle accretion, and evolve Equations (4) and (6) jointly assuming $R(t)$ and $M(t)$ from the MIST stellar evolution tracks. Systems with separations closer than the orange line undergo a common envelope phase, and systems outside of the yellow lines transfer their mass too early (i.e., the brown dwarf’s core is not yet degenerate enough to avoid igniting), or too late (i.e., the donor star’s evolution has not had time to occur within the current age of the universe). The pink contours show values of $M_{\text{accreted}}$ of $10^{-3} M_\odot$ and $10^{-4} M_\odot$.

(e.g., Maxted et al. 2006; Casewell et al. 2018), but it is not clear what would happen to a brown dwarf just below the HBL.

An additional source of uncertainty is the assumption of Bondi–Hoyle accretion. Winds whose velocity is comparable to the escape speed of the system at the Roche lobe set by the binary’s potential experience more complex dynamics than is captured by the Bondi problem, as shown in a series of idealized simulations with fixed wind launching velocity and binary configuration (Mohamed & Podsiadlowski 2007) in which the accretion rate can exceed the Bondi–Hoyle estimate by up to two orders of magnitude. This effect is referred to as the Wind Roche lobe overflow (WRLOF) mode.

These simulation results were fit to a quadratic formula for accretion efficiency in Abate et al. (2013), namely

$$\epsilon_{\text{WRLOF}} = \frac{\dot{M}_{\text{accreted}}}{M_{\text{donor},w}} = \min \left[ 0.5, \max \left( \epsilon_{\text{BH}}, f(q') \right) \right] \times \left( -0.284 x^2 + 0.918 x - 0.234 \right),$$

where $x = R_d/R_{\text{L, donor}}$, the ratio of the radius where dust forms and hence drives the acceleration of the stellar wind, and the Roche radius of the donor star. The quadratic in $x$ is bound from below by the Bondi–Hoyle efficiency $\epsilon_{\text{BH}}$ and above by 0.5, though the exact upper bound is highly uncertain. Following Abate et al. (2013), we adopt a dust radius $R_d$ from Höfner (2007) of $(1/2)R_{\text{donor}}(T_{\text{eff}}/T_{\text{cond}})^{2.5}$. We adopt a condensation temperature $T_{\text{cond}} = 1000$ K appropriate for oxygen-rich dust with $C/O < 1$, and note that now, in addition to $R$ and $M_w$, we need to also know the donor star’s $T_{\text{eff}}$ as a function of time. We use $q' = 1/q$ in this formula to account for the opposite mass ratio conventions in Eggleton’s and Abate’s work. The function $f(q')$ must be 1 for $q' = 0.6$, since the Mohamed & Podsiadlowski (2007) simulations are all carried out for $q' = 0.6$, but otherwise its functional form must be guessed.

Abate et al. (2013) note that, for fixed $M_{\text{donor}}$, the Bondi–Hoyle accretion efficiency $\epsilon_{\text{BH}} \propto q'^2$ or $q'^{2(1 + q')^{-3/2}}$, depending on the ratio of $v_w$ to $v_{\text{orb}}$. Abate et al. (2013) argue that $f(q')$ should therefore be approximately bounded by $(25/9)q'^2$ from below and 1 from above. However, for a brown dwarf orbiting an AGB star, $q' \ll 1$, meaning that in either limit of the Bondi–Hoyle accretion efficiency, $\epsilon_{\text{BH}} \propto q'^2$. However, we emphasize that the dynamics of the flow around the brown dwarf could in principle be quite complex, in which case $f$ may not have such a simple dependence on $q'$, and indeed may depend not just on $q'$ but on other details of the system as well. Nonetheless, we adopt $f(q') = (25/9)q'^2$ as a reasonable guess.

Under these assumptions, we rerun our integrations of $\dot{a}$ and $M_{\text{BD, inc}}$, still using the MIST stellar evolution tracks, resulting in the distribution of $M_{\text{accreted}}$ shown in Figure 3. As might be expected, substantially more mass is transferred in this WRLOF scenario, with the region expected to be able to produce overmassive brown dwarfs increasing $M_{\text{accreted}}$ from $\lesssim 10^{-3} M_\odot$ to $\sim 10^{-2} M_\odot$. To understand one of these systems in more depth, we employed MESA’s binary evolution capabilities (introduced in Paxton et al. 2015) to simultaneously simulate the brown dwarf’s and the donor star’s evolution, along with the evolution of the binary parameters. This requires enabling the WRLOF accretion efficiency with MESA’s run_binary_extras feature, and some slight modifications to the default runtime parameters to aid the donor star’s passage through the RGB and He flash phases of its evolution. In particular, we set the stellar wind coefficients for the Reimers (1975) and Bloxekker (1995) scaling laws to 0.7.

The donor star begins at $1.05 M_\odot$ and the brown dwarf at $0.069 M_\odot$, with an initial period of $10^4$ days, corresponding to an initial semimajor axis of about 9.4 au. The evolution of the
binary during the vast majority of the mass transfer is shown in Figure 4. The mass transfer is dominated by extremely short periods of time where the donor star reaches a radius of around $100 R_\odot$, which correspondingly decreases $v_w$, and dramatically increases the accretion efficiency $\epsilon_\text{WRLOF}$, as evidenced in the decrease in the separation between the wind mass-loss rate and the brown dwarf’s accretion rate in the upper right panel. The brown dwarf in this scenario clearly crosses the boundary corresponding to the hydrogen-burning limit in our version of MESA with a fixed set of atmospheric, opacity, and other physical parameters. The nuclear luminosity does increase modestly as a result of the new mass, slightly changing the long-run evolution of the brown dwarf’s long-run cooling (see Figure 5 for the long-run evolution of the brown dwarf’s luminosity), but clearly this object remains essentially a brown dwarf, in that it never burns hydrogen at a high enough rate to supply its surface luminosity.

The MESA run’s sudden increase in nuclear luminosity as a result of the mass transfer from the donor star’s wind strongly suggests that there are limits to how much mass can be transferred before the brown dwarf, now above the hydrogen-burning limit, has its core “jump-started” to produce enough nuclear luminosity to supply the surface luminosity, thereby becoming an “ordinary” low-mass star, albeit with an unusual history. We find that, within a particular short period of accretion, i.e., the AGB or RGB phase of the donor star, the brown dwarf’s central density and temperature both increase. In particular, $d \ln T_e / dt \approx d \ln M / dt$ and $d \ln L_i / dt \approx 2 d \ln M / dt$. This is not dissimilar to the case of compressional heating in a white dwarf, for which Townsley & Bildsten (2004) showed that, in the isostructural core, compressional heating follows $d \ln T_e / dt \approx (6A/\alpha) d \ln M / dt$, where $\alpha$ is a constant of order unity related to the structure of the white dwarf’s core. We defer an exact accounting of the maximum mass obtainable by an overmassive brown dwarf before it becomes a star to future work.

While the binary MESA run is promising, in that it shows how the entire binary system evolves together to allow the brown dwarf to exceed the HBL without igniting as a low-mass star, including the effects of compressional heating, we note that there is a discrepancy between this particular MESA run and the corresponding integration we carried out using the MIST stellar tracks. Rather than gaining a mass of $0.0034 M_\odot$, the integration predicts about twice the mass gain, $0.0066 M_\odot$. This difference appears to arise from a difference in the evolutionary path of the 1.1 $M_\odot$ star according to MIST and the path taken by the present MESA simulation. In the MIST track, the star loses a much higher proportion of its mass in an AGB phase where it reaches a much larger radius. This is likely the result of the higher wind scaling factors we employed in the present run, to allow it to “survive” the helium flash without crashing. We expect that, especially for properties like $T_{\text{eff}}(t)$, $R(t)$, and $M(t)$ that are observable with only limited model-dependence, the MIST track is more realistic, since the parameters were tuned to match a variety of observations.

4. Discussion

Having found the conditions under which overmassive brown dwarfs may form, we now turn to the questions of how common they may be, how they may be detected, and why they may be of interest beyond their novelty.

4.1. Occurrence Rate

Brown dwarf companions of Sun-like stars, i.e., the putative progenitors of overmassive brown dwarfs, are known to be rare, an observation referred to as the brown dwarf desert.

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Figure 3. Mass gained by the brown dwarf as a function of the donor star’s initial mass and the initial separation of the binary in the WRLOF scenario. Contours and colorbar have the same meanings as in Figure 2. In this case, the mass transferred in the AGB phase is substantially larger than in the Bondi–Hoyle case, and almost constant at values approaching $10^{-2} M_\odot$, provided that the brown dwarf is initially between about 5 au and 30 au and the donor star is initially $\lesssim 6 M_\odot$. 

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8 This value of the HBL was determined by running a series of low-mass star/ brown dwarf models with the same physics, altering only the initial mass, and zeroing in manually with the bisection method by choosing a new mass based on whether a given run lived for $\sim 10$ Gyr before the model cooled (as a brown dwarf) or lived for $\sim 10^{11}$ yr before undergoing post-main-sequence evolution.
While there is a particular lack of brown dwarfs on short orbits, as demonstrated in radial velocity searches, direct imaging and interferometric searches (e.g., Gizis et al. 2001; Metchev & Hillenbrand 2009; Tanner et al. 2010; Kraus et al. 2011; Evans et al. 2012), and much longer-baseline radial velocity searches (e.g., Kiefer et al. 2019), find a somewhat higher fraction of stars to have brown dwarf companions. Taken together, these results suggest that on the order of 1% of Sun-like stars appear to have a brown dwarf companion between \( \sim 5 \) and \( \sim 30 \) au. Gaia is expected to dramatically reduce the uncertainty of this fraction by greatly expanding the sample of brown dwarfs around Sun-like stars (Holl et al. 2022). The mass function of companions to Sun-like stars is fairly steep (e.g., Grether & Lineweaver 2006), implying that the brown dwarf companions in question will be preferentially close to the hydrogen burning limit (as opposed to the middle of the brown dwarf mass range), meaning that comparatively little mass transfer may be necessary to bring the brown dwarfs over the HBL into the overmassive brown dwarf regime. Despite the brown dwarf desert, therefore, we expect that only somewhat less than \( \sim 1\% \) of white dwarfs whose progenitors

![Figure 4. AGB binary results. Starting with the upper left plot, the donor star significantly expands its radius at at around 10.25 and 10.37 Gyr. Yet, the binary separation increases only by a very small distance at the same age. Therefore, we would expect the most mass transfer to happen at those periods. Looking at the lower left panel, we can confirm this idea by observing the sharp peaks in BD’s mass at the same ages of \( \sim 10.25 \) Gyr and \( \sim 10.37 \) Gyr. These results are also consistent with the two plots in the right panel. In the upper right plot, the highest mass accretion rates are at those ages, and in the lower right plot, the peaks in the accretion, total, and nuclear luminosity are also at the same times.](image-url)
are Sun-like stars to potentially have an overmassive brown dwarf companion.

The key uncertainty, more so than the statistics of the population of the progenitor systems, is the physics of the WRLOF mechanism. Setting aside uncertainties in the original Mohamed & Podsiadlowski (2007) simulations themselves, our results are extremely sensitive to guesses made by Abate et al. (2013) for how this mechanism should scale to mass ratios far from the original $q' = 0.6$. This provides an interesting opportunity for hydrodynamic simulations of binary evolution (e.g., MacLeod et al. 2018) to make predictions in the extreme mass ratio regime of the WRLOF mechanism, which may be confirmed or falsified with the future detection of overmassive brown dwarfs.

### 4.2. Search Methods

While the statistics of Sun-like stars on the main sequence and their companions can tell us a great deal about the frequency with which we may hope to find overmassive brown dwarfs, actually finding them requires seeking out the companions of the white dwarfs left behind after the evolution of a Sun-like star through the AGB phase. The long period of the orbits, faint intrinsic brightness of the primaries, and small radii of the primaries make detection via transits and radial velocity methods difficult. To date, many low-mass companions to white dwarfs have been detected via multiband photometric searches (Steele et al. 2011; Girven et al. 2011; Rebassa-Mansergas et al. 2019) that take advantage of the white dwarf’s and brown dwarf’s dramatically different spectra, peaking in the UV/blue and IR, respectively. These candidate systems may then be followed up with direct imaging, which benefits from the reduced contrast between the two objects relative to the main-sequence star—brown dwarf case, and spectroscopy (e.g., Hogg et al. 2020) to characterize at least the nature of the companion object, though perhaps not the orbit. Timing variability in pulsating white dwarfs may have also been used to find candidate companions (Mullally 2007; Winget et al. 2015). Intriguingly, of the known white dwarf binary systems, few have been reported to have brown dwarf companions, but there are some objects with masses just above the HBL (Farihi et al. 2005) (though we caution that the steep mass function of companions in this regime and the spectral-type classification used to estimate these masses makes it a priori unlikely that these objects are overmassive brown dwarfs).

Astrometry is also an extremely powerful tool for identifying and characterizing systems in this regime (Sahlmann et al. 2013; Bowler et al. 2018; Dieterich et al. 2018), with companion masses expected to be reasonably accurately measured in the brown dwarf regime out to hundreds of pc (Andrews et al. 2019) with Gaia. Gaia is expected to dramatically expand the number of known white dwarfs and white dwarf binaries (Toonen et al. 2017), particularly in future data releases that include or allow explicit binary modeling.

### 4.3. Identification of Overmassive Brown Dwarfs

A key obstacle to the discovery of an overmassive brown dwarf is positively distinguishing it from other similar objects, in particular low-mass stars and “ordinary” brown dwarfs. Roughly speaking, an overmassive brown dwarf at the same mass as a low-mass star will be far more compact, cooler, and dimmer (see Figures 3 and 4 of FL19). Meanwhile, the differences between an overmassive brown dwarf and an ordinary brown dwarf are quite modest. This emphasizes the importance of a precise mass measurement through either astrometry or radial velocity measurements (or their combination, e.g., Brandt et al. 2019), both to ensure that the object is above the HBL and to ascertain by how much. Figure 6 shows the result of our orbital integrations with the MIST stellar tracks for the final period of the overmassive brown dwarf—white dwarf binary that is the end state of these systems. Their $\gtrsim 30$ yr periods mean that precisely characterizing these systems via
radial velocities will be difficult in general, especially given that white dwarfs are not commonly included in radial velocity campaigns, owing to their broad lines and intrinsic faintness.

Gaia astrometry seems to be a more promising approach: Andrews et al. (2021) determine a simulation-based empirical estimate for the precision in mass that Gaia may achieve over the course of its lifetime, even for orbital periods far exceeding the time baseline of 5–10 yr expected for the observations. In essence, if an unseen companion causes a given object to deviate from the helical pattern it traces in the plane of the sky, this deviation may be measured even if only a small fraction of a single arc of the helix is traced in Gaia’s lifetime. Their result for the fractional precision \( \xi \) that may be obtained is

\[
\xi \approx 35 \frac{DR}{V^2} \frac{\sigma_G}{\tau_G} \sqrt{\frac{1}{N}},
\]

where the distance to the system from Earth is \( D \), \( R \) is the radius of the orbit of the observed object, i.e., the white dwarf in this case, and similarly \( V \) is the orbital velocity of the white dwarf. The lifetime of Gaia is \( \tau_G \), its precision is \( \sigma_G \), and \( N \) is the number of observations of the system. Note that \( \xi, \sigma_G \) when expressed in radians, and of course \( N \), are dimensionless.

Following Andrews et al. (2021), we adopt \( N = 70, \tau_G = 5 \) yr, and \( \sigma_G = 10 \) mas. For the orbital velocity and radius, we use standard solutions for the two-body problem for circular orbits to find the white dwarf’s orbital velocity and radius—in so doing, we fix the mass of the white dwarf to 0.55 \( M_\odot \), which is typical of the final masses of the white dwarfs for this range of donor masses according to the MIST tracks. We also retain the dependence on the mass gained by the brown dwarf. We then fix \( D \) to three different values, and plot (Figure 6) the resulting curves, which on this scale are nearly straight vertical lines, where \( \xi = 0.1 \). This implies that Gaia should be able to determine the mass of these brown dwarf companions with sufficient precision, out to hundreds of parsecs, to assess whether they exceed the HBL or not. While this is a remarkable and encouraging testament to the power of Gaia, there are several additional caveats that bear consideration.

The HBL itself is uncertain (for a useful compilation, see, e.g., Table 5 of Dieterich et al. 2018). While we can determine what the HBL is for a given set of physics in a particular version of MESA by trial and error, the complex chemistry and cloud physics in the atmospheres of brown dwarfs renders these determinations unreliable. Empirical determinations of the HBL by characterizing transiting systems with a component near the HBL (e.g., Grieves et al. 2021) is a promising avenue forward. An additional complication is that the objects in question may have non-solar metallicities, especially given the old age required to produce overmassive brown dwarfs. To a first approximation, lower metallicities push the HBL to higher masses, meaning that even if an overmassive brown dwarf candidate has a precisely measured mass securely above the solar-metallicity HBL, abundance measurements will need to be made to determine whether the object is a relatively high-metallicity overmassive brown dwarf, or a low-metallicity ordinary brown dwarf.

4.4. What Could We Learn from a Discovery?

Discovering a bona fide overmassive brown dwarf would be interesting in and of itself, vindicating the fundamental physics of hydrogen burning in degenerate matter and the evolution of stellar structure under accretion. It would also directly verify the WRLOF mechanism without which brown dwarfs would
have a difficult time accreting enough mass from their AGB companions to exceed the HBL. More generally, an overmassive brown dwarf would provide a completely unique constraint on the process of binary mass transfer, because an overmassive brown dwarf must start with a mass below the HBL, meaning that

\[ M_{\text{accreted}} > M_{\text{beige}} - M_{\text{HBL}}. \]

where \( M_{\text{beige}} \) is the mass of the overmassive brown dwarf at the time of observation. As we have seen in our joint orbit and mass-transfer integrations, \( M_{\text{accreted}} \) is sensitive to the wind prescription, which sets not only the instantaneous mass-loss rate but also the subsequent evolution of the donor star, determining how much mass it loses in different phases of its evolution and how much it inflates during the AGB phase (see Willson 2000 and Smith 2014 for a review of uncertainties in the mass-loss phase of AGB stars). The evolution of these extremely bright stars is critical in interpreting the SEDs of distant galaxies (see, e.g., Maraston 2005 and Choi et al. 2016), and may affect the location and size of the putative black hole mass gap (Farmer et al. 2019), the separation in mass scales between low-mass black holes observed electromagnetically and more massive binary mergers seen in gravitational waves.

In addition to these constraints, an overmassive brown dwarf would provide a new approach to constraining the initial mass–final mass relation, i.e., the mapping between a star’s zero-age main-sequence mass and its remnant mass at the end of stellar evolution (Kalirai et al. 2008; Catalán et al. 2008; Andrews et al. 2015). Typically, this is done by estimating a white dwarf’s mass and the time it has spent cooling, and comparing to an independent estimate for the white dwarf’s age. The discovery of an overmassive brown dwarf companion to a white dwarf would independently restrict the white dwarf’s progenitor to a relatively narrow range of initial masses.

5. Conclusion

Overmassive brown dwarfs, or beige dwarfs, are a proposed but not yet discovered type of stellar object that may form when an old brown dwarf gains enough mass to exceed the HBL without igniting its core. This requires that the core be sufficiently cold and degenerate to sustain some compression and heating via the addition of new mass. We have reviewed several astrophysical mechanisms by which overmassive brown dwarfs may be formed, with the key consideration being the long timescale required to allow the brown dwarf to cool and become degenerate.

A brown dwarf–brown dwarf binary evolving via gravitational wave emission as proposed by FL19 remains an intriguing possibility for producing overmassive brown dwarfs, but would require some fine-tuning in that the pair of brown dwarfs would need to begin the gravitational-wave-mediated inspiral at least about 100 Myr after their formation in order to avoid an outright collision. While this may be arranged by having the brown dwarfs form at a wider separation and having some other mechanism act to bring them close later in their evolution, this should be a rare occurrence.

We also considered the case of mass transfer from the slow winds of an AGB star being swept up by a brown dwarf companion. Since nearly all of the mass transfer occurs at the end of the donor star’s life, there is sufficient time for the brown dwarf to cool before the mass transfer takes place. The requirement that the brown dwarf is allowed to cool and that the donor star must evolve within the age of the universe specifies a narrow range in donor star masses around \( 1 M_\odot \), where this mechanism can form overmassive brown dwarfs.

We find that mass is transferred to the brown dwarf most efficiently when its initial semimajor axis around the donor star is around 10 au. For initial separations within a few au, the brown dwarf will likely enter a common envelope phase, the result of which we do not attempt to model. For separations beyond about 30 au, the density of the wind becomes low enough that relatively little mass is transferred.

Taken together, these restrictions single out a very particular type of progenitor system, i.e., a \( 1 M_\odot \) star with a brown dwarf companion at \( \sim 10 \) au, which may result in an overmassive brown dwarf. This overmassive brown dwarf would orbit the white dwarf remnant of the donor star. Candidates for these systems can be identified photometrically by taking advantage of the vastly different SEDs of the white dwarf and its potentially overmassive brown dwarf companion. Characterizing the system well enough to be certain that the brown dwarf is overmassive would require follow-up observations, the most promising of which would be astrometric. Future data releases from Gaia may therefore allow overmassive brown dwarfs to be positively identified and characterized.

Such a discovery would provide a unique constraint on stellar wind and mass transfer in binaries. Typical constraints on binary evolution require population synthesis approaches (e.g., Moe & Di Stefano 2017; Broeggaard et al. 2019; Mandel et al. 2019; Breivik et al. 2020) to construct statistical properties of a synthetic sample of binary progenitor and remnant systems, to be compared with observed populations. In contrast, the discovery of overmassive brown dwarfs could provide meaningful constraints from a single system, because not only would the current state of the system be characterized, but its state prior to the mass transfer is also constrained: the now-overmassive brown dwarf must have been below the HBL when the system formed, and the donor star, now a white dwarf, must have been around \( 1 M_\odot \) on the main sequence.

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