Brown Dwarf Formation: A Review

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Abstract

Brown dwarfs are a kind of astrophysical middle child, existing in a mass range between giant Jupiter-like planets and very low mass stars. We will explore the theory of brown dwarf formation, as well as a few of the formation mechanisms that have been proposed (primarily core accretion and disk fragmentation) and simulations. There has yet to be a consensus as to the primary mechanism for brown dwarf formation, but additional simulations and observations using new observatories such as JWST will allow further insight into the origin and life of BDs.

1. Introduction

Brown dwarfs (BDs) were first theorized by Shiv S. Kumar in 1962 as stars with mass less than 0.05 solar masses (we will use $M_{\odot}$ as an abbreviation for solar masses, as is standard) which become degenerate - that is, the force of their radiation cannot support their mass, so they are held up by some other mechanism such as electron degeneracy pressure or Coulomb pressure - and fail to reach the main sequence. These objects would then cool, becoming gradually dimmer until they eventually stop emitting light altogether, thus the original name “black” dwarfs (Kumar 1962). The first discovery of a probable BD happened in 1988 with the discovery of GD 165B (Becklin & Zuckerman 1988), a companion to a white dwarf, and the first member of the spectral classification of L dwarfs, which are objects cooler than M dwarfs. Teide 1, discovered in 1994, was the first object definitively shown to be a BD, and shared a spectral class with M dwarf stars (Rebolo et al. 1995).

BDs have been observed to exist both as free-floating objects and as companions to other objects such as stars as well as other BDs (Luhman et al. 2007). A disproportionate portion (27%) of the transiting companion BD population orbit M-dwarf stars (Carmichael et al. 2022). The variety of environments in which BDs are found makes pinning down their origin more difficult. We will discuss the environments in which BDs are found in a later chapter.

The mechanisms responsible for the formation of giant planets and stars are well known and have been studied extensively. Giant planets form from the circumstellar disks of their host stars, and stars form through the collapse of molecular clouds, but the formation of Brown Dwarfs, which exist in a mass range between these two classes of objects, remains a topic of debate. A number of mechanisms have been proposed as the primary formation channel for BDs, but there is still not a consensus on the primary mechanism.

2. Gray (Brown?) Area

Brown dwarfs exist in a gray area somewhere between large gas planets and very low mass stars (VLMSs). They are typically defined as objects in a mass range of around 0.015-0.08 solar masses($M_{\odot}$), or roughly 15-80 Jupiter masses (M_J) (however, the precise mass range varies from paper to paper), lacking the mass required for the fusion of hydrogen so are held up by electron degeneracy pressure (Whitworth 2018) and sometimes by pressure from deuterium fusion. While giant planets, brown dwarfs, and stars are certainly three separate classes of objects, defining the boundaries between these three populations can be difficult, and has been a topic of debate essentially since the advent of modern astronomy (Basri & Brown 2006). In this chapter we will further discuss the similarities and differences between the three populations, as well as techniques for distinguishing between them.

2.1 Very Low Mass Stars

While no BD is hot enough to burn hydrogen, some young BDs have hot enough cores to burn deuterium. This means that early in their lives, BDs radiate quite brightly, then as they age, they cool down and consequently dim (Rebolo et al. 1995). Spectral classes are used to describe both BDs and stars observationally, which means that it is relatively easy to mistake a BD for an M-dwarf star or vice versa if one is only paying attention to the spectral class a given object falls into. This coupled with the fact that at least some of the BD population is thought to form via the same mechanisms as stars calls into question whether or not BDs are actually a separate population from stars, or simply a different type of star.

Young BDs have surface temperatures and luminosities which are continuous extensions of those of VLMSs, which makes distinguishing between the populations difficult. Luhman et al. (2006) went so far as to say making the distinction was often not possible. Thies et al. (2015), however, concluded that BD and stellar populations must be treated separately, as simulated BD populations were consistently lower than the observed population, suggesting that there must be additional formation mechanisms other than core accretion contributing to BD populations.

One way to determine whether an object is a brown dwarf or a very low mass star is through the so-called "Lithium test". Lithium is burned in the cores of stars once they reach a temperature of around 2.5 million Kelvin (Rebolo et al. 1992), a temperature easily reachable by even low-mass M-dwarf stars, but unreachable by BDs. This means that the presence of a lithium line in the spectrum of an object means it is either a star young enough to have not burned through all of its lithium yet, or it is a brown dwarf (Rebolo et al. 1992). This is an important tool that allows us to make an almost certain distinction between BDs and VLMSs.

2.2 Giant Planet Overlap

Given that BDs are necessarily less massive than stars, it would be logical to try to define the barrier between giant planets and BDs using mass, as BDs are almost always the more massive of the two. However, it has been shown that there exists mass overlap between giant planets and BDs (Chabrier et al. 2014), and that some giant planets show signs of deuterium burning at their cores, while some BDs do not. This eliminates two proposed boundaries between the two populations, blurring the line between Jupiter-like planets and BDs. This makes it seem hopeless to make a concrete distinction between the two populations, and indeed, Chabrier et al. (2014) suggest that formation mechanism may be the best method for defining the exact boundaries between them. This highlights one of many reasons why studying the formation mechanisms for objects in this mass range is so important.

Despite the difficulty of determining an exact boundary between the populations of giant planets and brown dwarfs, we can look to population statistics to at least give us an idea of how they differ and make inferences about what population a given object likely falls into. Upon evaluating a sample of giant planets and BDs, Bowler et al. (2020) found a significant difference in eccentricity distribution between the two populations. They found that giant planets have eccentricities fairly tightly packed around a very low average (<0.2), while BDs have a much wider probability density distribution with an average above 0.6. This implies that the two populations either have distinct formation mechanisms or have orbits which evolve in different ways.

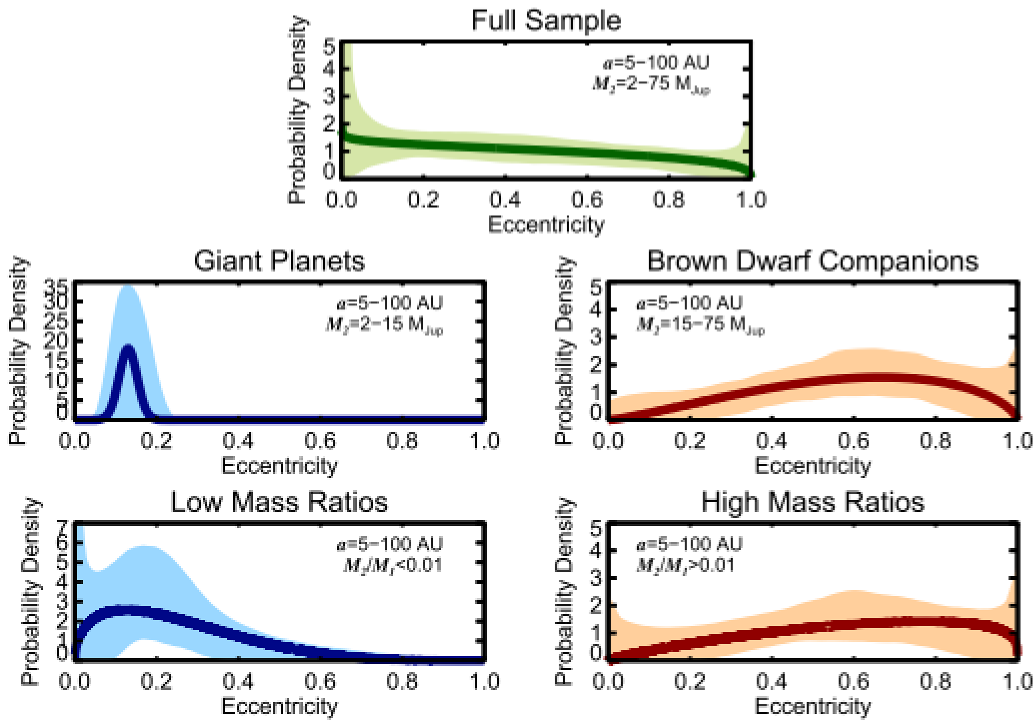

Figure 1. Subset of Figure 22 from Bowler et al. 2020. In the top plot, the probability density for the eccentricity of the full sample considered in Bowler et al. 2020, showing that the combined population of giant planets and BDs have a relatively flat distribution. The plots in the second row show the probability density distributions of the giant planet and BD populations separately (with giant planets defined as having masses between 2-15 Jupiter masses, and BDs defined as being between 15-75 Jupiter masses) , displaying the dichotomy present between giant planet and BD orbital eccentricities. The plots in the bottom row separate the population by the mass ratio of the systems rather than the mass of the companion, showing that objects in systems with low mass ratios tend to have lower eccentricities, and vice versa.

3. Mechanisms

In its simplest form, the mechanism that causes the formation of BDs is gravity, a cloud of gas condenses and forms a self-gravitating object with a mass between ~15 and 80 M_J. The proposed mechanisms for Brown Dwarf formation fall into two major regimes: star-like formation via the contraction of gas in star forming regions (which we will refer to as core accretion), and planet-like formation via the fragmentation of a circumstellar disk around a companion star (this will be referred to as disk fragmentation). In this chapter, we will discuss both of these regimes in further detail, along with the overarching processes which allow BDs to form.

3.1 The Jeans Mass

Despite the variety of different proposed mechanisms, one crucial concept central to every formation mechanism for brown dwarfs is the Jeans mass. The Jeans mass is named after James Jeans, who proposed that clouds of gas could collapse under their own gravity into one or more masses and the Jeans mass is the mass at which this happens. When a gas cloud of a certain density and temperature reaches its Jeans mass, inward pressure from gravity overcomes the outward pressure of a gas, and it begins contracting. As the gas contracts, local Jeans masses within the cloud can decrease, allowing fragmentation into smaller pieces, forming stellar and substellar objects.

The Jeans Mass for a cloud of gas with uniform density can be quite simply derived using the Virial Theorem, giving the following result:

$$M_{Jeans} = \left(\frac{5k_B T}{Gm}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2} \tag{3.1}$$

A derivation of the Jeans mass can be found in the appendix in chapter 5. The important takeaways from this equation for the purpose of this review are the proportionalities. The Jeans mass is proportional to $T^{3/2}$, $m^{-3/2}$, and $\rho^{-1/2}$, and consequently the cooler and more dense a gas cloud is, the lower its Jeans mass, and therefore the smaller the minimum mass for a self-gravitating object to form. This will be crucial to understanding many of the formation mechanisms we will be discussing, most of which focus on mechanisms for increasing the density of a region significantly enough for gravitational collapse to occur.

3.2 Core Accretion

The core accretion theory for brown dwarf formation posits that BDs form similarly to stars, beginning life as small pre-stellar bodies in star forming regions, which accrete material from the surrounding space, but fail to reach masses necessary for hydrogen burning.

There are several different possible ways in which core accretion could happen; one of these is through turbulent fragmentation, a process in which turbulence in molecular clouds causes a non-uniform density distribution of the gas, with some areas decreasing in density and others increasing.This allows lower-mass objects such as BDs to form in the higher density areas, even if the average density of the region would be too low for them to otherwise form (Padoan & Nordlund 2004). Filament fragmentation is another proposed variety of core accretion in which BDs form within the filaments of material that feed star forming regions, and then are ejected from the region and halt accretion before collecting enough matter to begin hydrogen fusion (Bate et al. 2002).

3.2.1 Turbulent Fragmentation

In a typical star forming region, the Jeans mass is much higher than the mass of BDs, which brings into question how the BDs we observe in these regions come to be (Padoan & Nordlund 2004). Padoan & Nordlund propose that this BD abundance may be explained by the turbulent flow of gas in star forming clouds. In these conditions, gas is compressed by shocks, and the simple relation for the Jeans mass discussed previously - which takes into account only gravitational and thermal kinetic energy - does not apply, and there is not necessarily a minimum mass for dense self-gravitating objects to form. Padoan et al. (2005) found that in numerical simulations of turbulent clouds in star forming regions using adaptive mesh refinement (AMR), the density peaks at high enough values to form BD-mass objects.

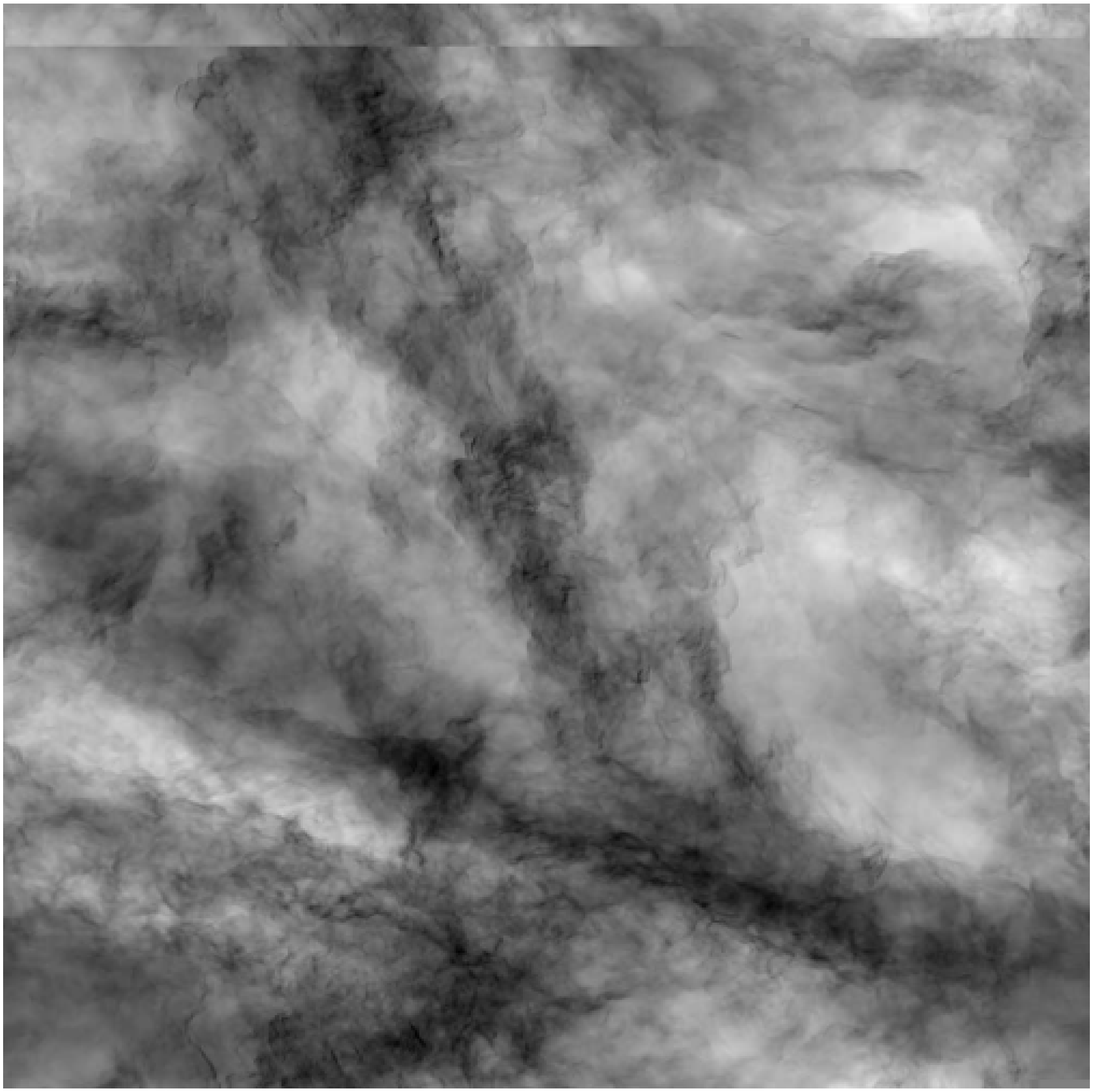

Figure 2. Figure 2 from Padoan et al. 2005, logarithmic density field from their simulation of turbulence in a molecular cloud.

Lomax et al. (2016), however, performed Smoothed Particle Hydrodynamics simulations in order to constrain the conditions required for isolated BDs to form as a result of turbulent fragmentation. They found that while it is *possible* for BDs to form in these environments, they appear to only form when gas flow is essentially converging to a single point, which is unlikely to be common enough to make a significant contribution to the observed population of brown dwarfs. Figure 3 below shows three different simulations with different initial velocity distributions. In the left and middle columns, the simulation failed to produce a self-gravitating object, as material escaped outward after gas with opposing velocities met and “bounced ” off of each other. Only in the simulation in the third column, where all velocities were directed inward, did an object dense enough to begin accreting material form.

This simulation brings into question whether or not turbulent fragmentation is a common formation mechanism, or one which only contributes to the BD population in areas where the conditions meet very specific environments. Further simulations will likely be needed to definitively determine the prevalence of BDs formed via this mechanism.

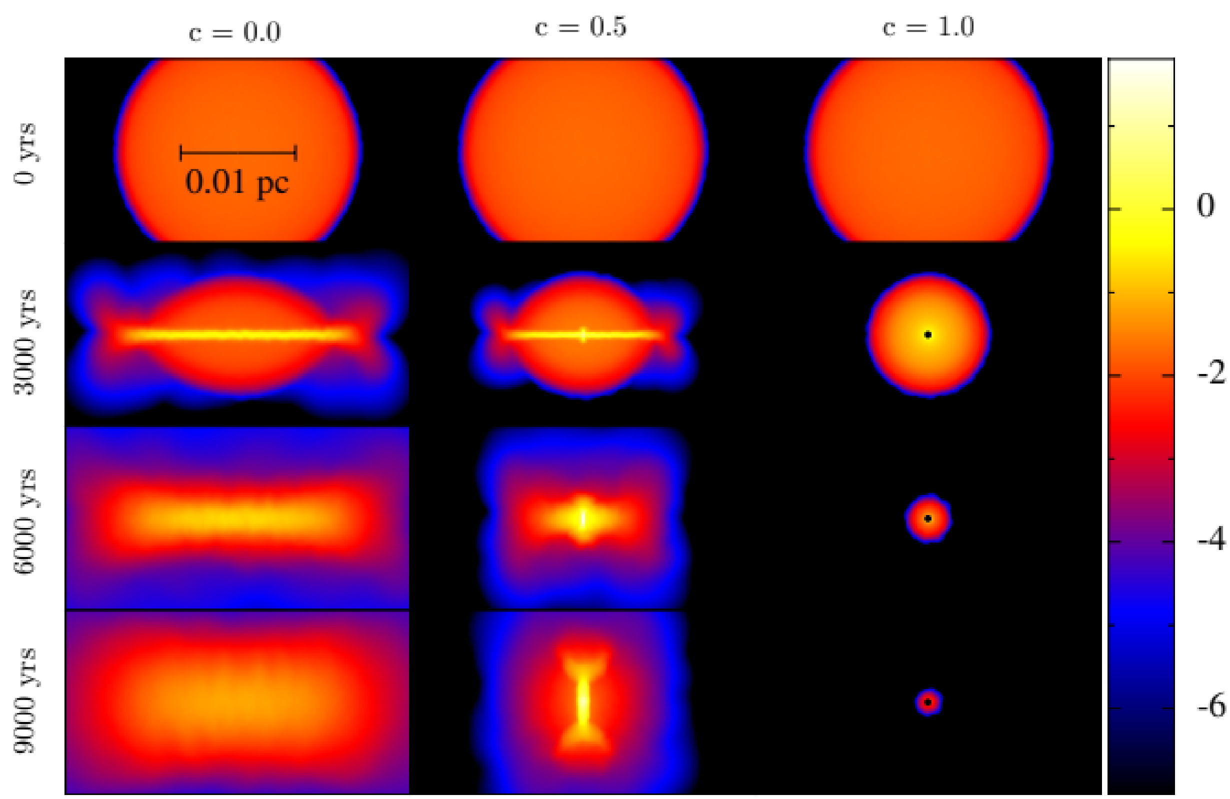

Figure 3. Figure 2 from Lomax et al. 2016, showing the evolution of three simulations with varying values of c, a convergence parameter which essentially measures how much of the initial velocity of the gas is directed toward the center. With c=0, velocities are split into two colliding hemispheres, and with c=1, all velocities converge to a single point. The black circles on the bottom three images of the right column are sink particles, where an object has formed and begun accreting material.

3.2.2 Filament Fragmentation

Brown dwarfs that form via filament fragmentation form the high density filaments that feed material into star forming regions. Bate et al. (2002) performed a simulation of this process, beginning with a spherical cloud of gas with a uniform density and a gaussian velocity distribution, containing 50 solar masses of gas. According to the simulations carried out by Bate et al., approximately a quarter of all brown dwarfs are formed in this manner, and the rest form via disk fragmentation, which will be discussed later.

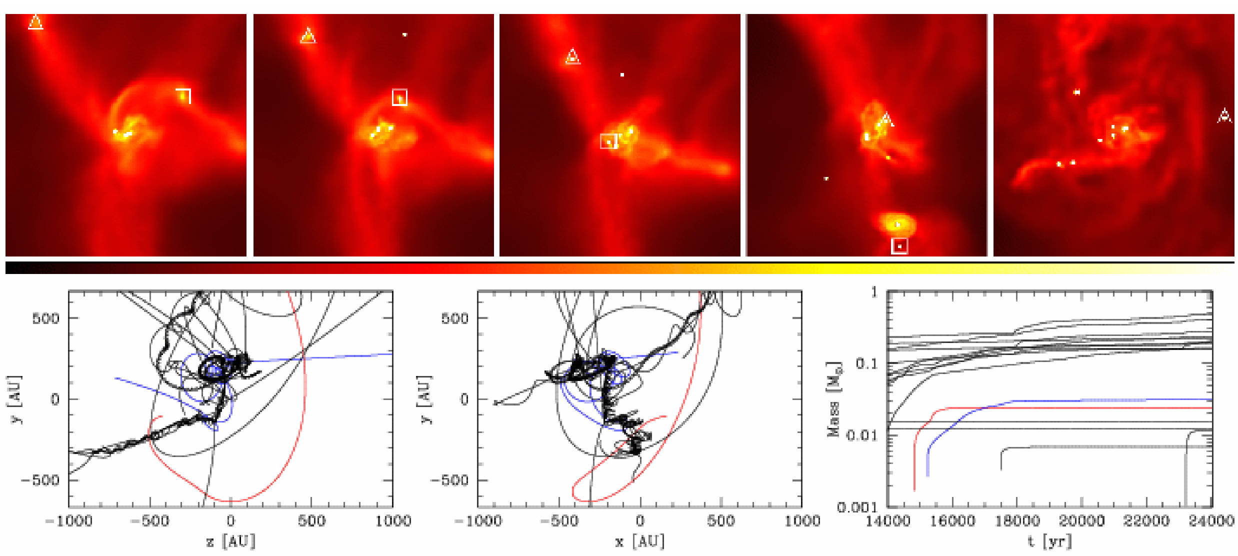

Figure 4. Figure 2 from Bate et al. 2002: Results of a simulation of filaments in which BDs fragment out of the gas in the filaments, fall into a system with multiple bodies, and then are ejected and stop accreting matter before they can reach stellar masses. Panels 1,2,3,4, and 5 are at times of 14300, 14870, 15440, 17150, and 23710 years respectively. The BDs are outlined with a triangle and square.. Each plot is 1000 AU on a side, and the color bar is log column density from $3X10^{-1}$ to $3X10^{3}$ g cm^{-2}. The bottom row of plots show the positions over time of all of the simulated objects, with the lines representing BDs colored red for the square and blue for the triangle. The positions are represented with two separate plots showing y vs z and then y vs x in order to show all three spatial dimensions. The third plot on the bottom row shows the mass over time of all simulated objects, with the BDs once again in red and blue.

Tafalla & Hacar (2015) analyzed the Taurus L1495/B213 complex and found chains of, on average, three dense cores, and suggest a process they call “fray and fragment” in which the collision of supersonic gas flows create filaments, which then split due to turbulence and gravitational interactions. If the filament was able to accumulate enough matter, some of these smaller “fibers” are then dense enough to fragment into multiple dense cores, including BDs.

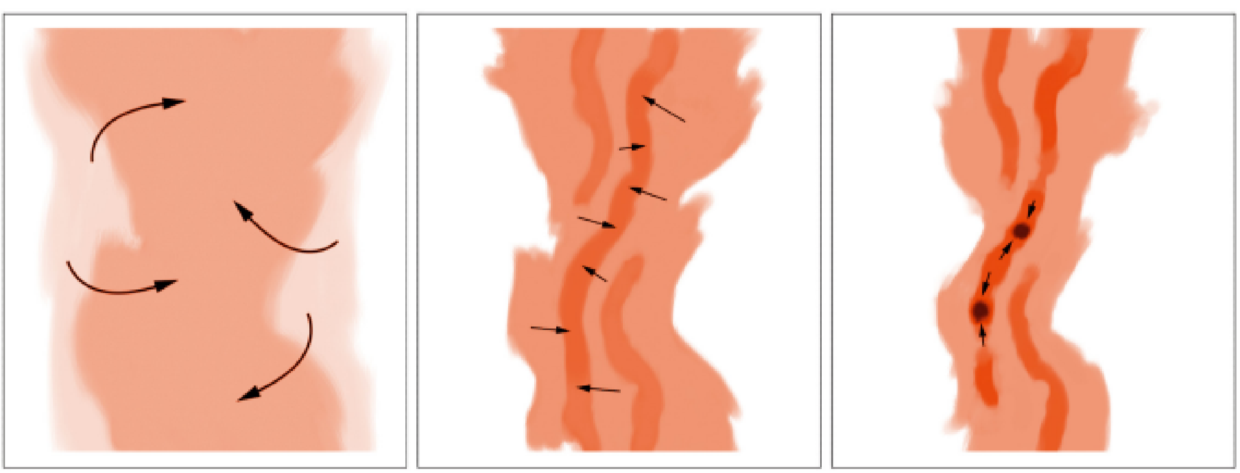

Figure 5. Figure 11 from Tafalla & Hacar (2015), showing a rough evolution of filaments. In the first panel, a filament of dense material is created by the collision of two gas flows, then in the second panel, smaller fibers are formed, and finally in the third panel, some of the fibers are massive and dense enough for self-gravitating cores to form.

3.2.3 Dynamical Ejection

A simpler explanation than turbulent and filament fragmentation is dynamical ejection, a mechanism in which BDs begin life as regular stellar embryos, but are ejected from star forming regions due to some interaction with their surroundings. This cuts them off from their source of material to accrete, and prevents them from reaching masses sufficient for hydrogen burning (Reipurth & Clarke 2001). Consideration of simple Newtonian physics makes it clear that as protostars accrete material and interact with each other, those objects with lower mass will tend to be ejected from the cloud more commonly.

Simulations have found that this is a valid formation mechanism for BDs, however if radiative feedback and magnetic fields are ignored, BDs are overproduced, even outnumbering stars (Bate 2008). Additionally, interactions strong enough to eject BDs would likely strip them of any accretion disk they might have (Reipurth & Clarke 2001), which contradicts observations.

3.3 Disk Fragmentation

When a star forms from a cloud of gas, the gas surrounding the star has a distribution of angular momenta, and if there is sufficient extra angular momentum in the system, a circumstellar disk can be formed by those particles energetic enough to avoid accretion into the star. This disk can then, over time, become sufficiently cool (Lin & Pringle 1987) for a perturbation caused by tidal forces, interaction with a nearby star, or some other source to lead to fragmentation and formation of a variety of companion objects, including planets and brown dwarfs. These fragments can then be ejected entirely from the system, or pushed to eccentric orbits, which agrees with the eccentricity distribution found by Bowler et al. (2020), shown in Figure 1. Simulations seem to show that disk fragmentation is a robust mechanism for the formation of a large portion of the observed brown dwarf population.

3.3.1 The Jeans Mass in a Circumstellar Disk

The Jeans mass as derived in the appendix is a useful estimation tool, but fails to fully describe the criteria for gravitational collapse under more complex circumstances. Forgan & Rice (2011) discuss the various additional factors which must be considered in order to fully understand the criteria for fragmentation in a self-gravitating disk, including viscous heating, radiative cooling, and accretion.

Following is an expression for the Jeans mass in a circumstellar disk, derived in Forgan & Rice (2011):

$$M_J = \frac{4\sqrt{2}\pi^2}{3G} \frac{Q^{1/2} \cdot c_s^2 \cdot H}{(1+1/\sqrt{\beta_c})} \tag{3.2}$$

Where G is the universal gravitational constant, c_s is the local speed of sound, β_c is the cooling time parameter given by:

$$\beta_c = t_{cool} \cdot \Omega \tag{3.3}$$

and

$$H = \frac{c_s}{\Omega} \qquad (3.4)$$

Where Ω is the angular frequency of the disk.

A self-gravitating disk becomes gravitationally unstable when:

$$Q = \frac{c_s \cdot \kappa}{\pi \cdot G \cdot \Sigma} \sim 1 \qquad (3.5)$$

Where Σ is the surface density of the disk, and κ is the epicyclic frequency of the disk.

Forgan & Rice find that this model for the Jeans mass in a disk is consistent with other models, producing mainly objects of BD-like mass, especially when the system is disturbed.

3.3.2 Simulations

Many simulations of the evolution of a circumstellar disk have been carried out, and many of them produce very similar results. Circumstellar disks appear to readily form, and then fragment after interactions with outside objects.

Basu & Vorobyov conducted smoothed particle hydrodynamics (SPH) simulations of the evolution of circumstellar disks with high-resolution models factoring in heating and cooling of the material. They found that disks regularly form from the collapse of gas clouds, and that those disks regularly fragment into "clumps" which are in turn regularly ejected from the system, explaining both the companion BD population and the free-floating BD population (Figure 6). In their simulation, they did not require these ejected clumps to be compact at the time of ejection to be counted as BDs, as their simulation allowed them to continue contracting after exiting the system. This allows for free-floating pre-BDs - which are commonly pointed out as evidence for core accretion - to be created via disk fragmentation. Overall, Basu & Vorobyov claim that their model can account for almost all characteristics of BDs, excluding wide BD binaries, which they admit may well be formed via direct core collapse. Thies et al. (2010) performed similar SPH simulations, specifically studying the effects of perturbations from stellar encounters, and produced very similar results.

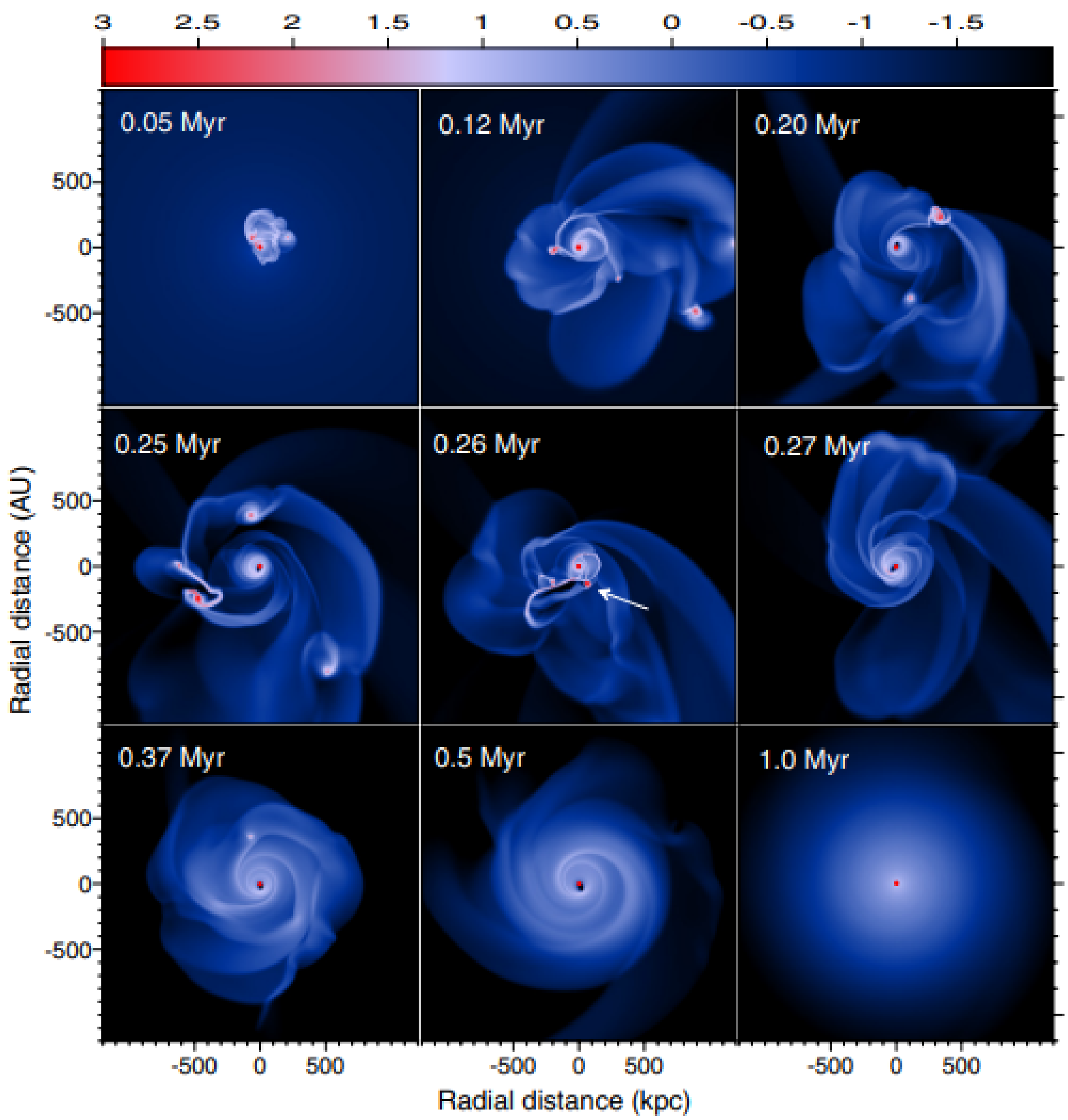

Figure 6. Figure 1 from Basu & Vorobyov (2012) showing the evolution of one of the systems in their model. Over the period of time shown in the figure, the gas contracts into a central solar object, and forms a circumstellar disk. The disk then fragments, and one of these fragments (or clumps) is ejected from the system between 0.26 and 0.27 Myr. After the ejection of one of the fragments, the other merges with the central body, maintaining the angular momentum of the system.

3.4 Population Distribution & the Brown Dwarf Desert

One of the most commonly discussed features of the population distribution of companion BDs is the deficiency of brown dwarfs orbiting close to their host star. This is not a trend shared with planets, and so has been deemed the brown dwarf desert.

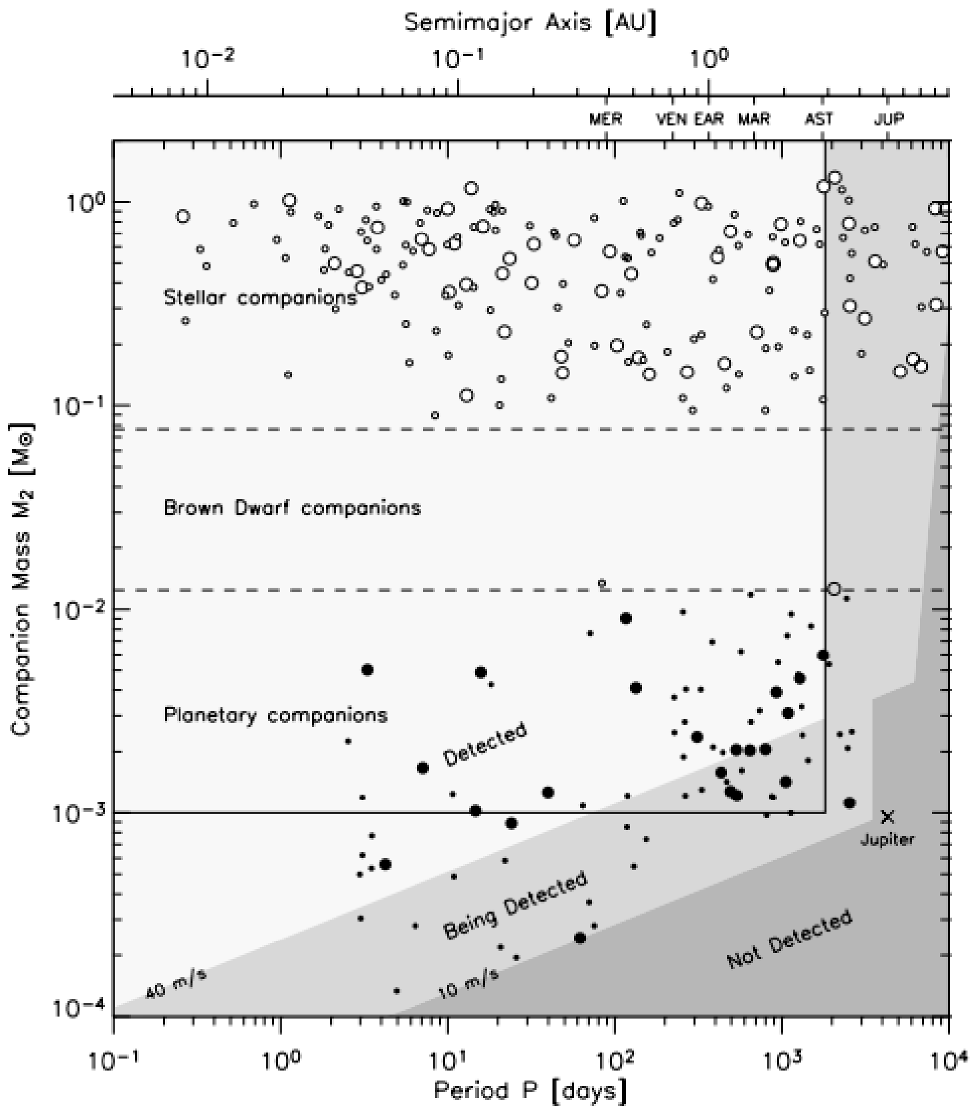

Figure 7. Figure 5 from Grether & Lineweaver (2006), a mass-period diagram of stellar companions, clearly showing the lack of BD-mass objects at short periods.

The brown dwarf desert isn't a universal law and does have exceptions. It has been found that systems with BDs in tight orbits are much more likely to have a binary stellar companion than the general stellar population, indicating that the existence of a binary companion may facilitate or encourage the formation of massive objects such as BDs and massive planets at distances less than 1 AU (Fontanive et al. 2019). This could possibly be due to perturbations caused by interactions between a circumstellar disk and a stellar companion.

Free-floating BDs appear to make up a very small portion of the free-floating (or rogue) object population (Scholz et al. 2022), despite the predictions of a substantial amount of these objects. In order to rectify simulations and observations, more powerful simulations and more extensive observations will be required. JWST in particular, will be a powerful tool for discovering more free-floating BDs and helping determine formation mechanisms.

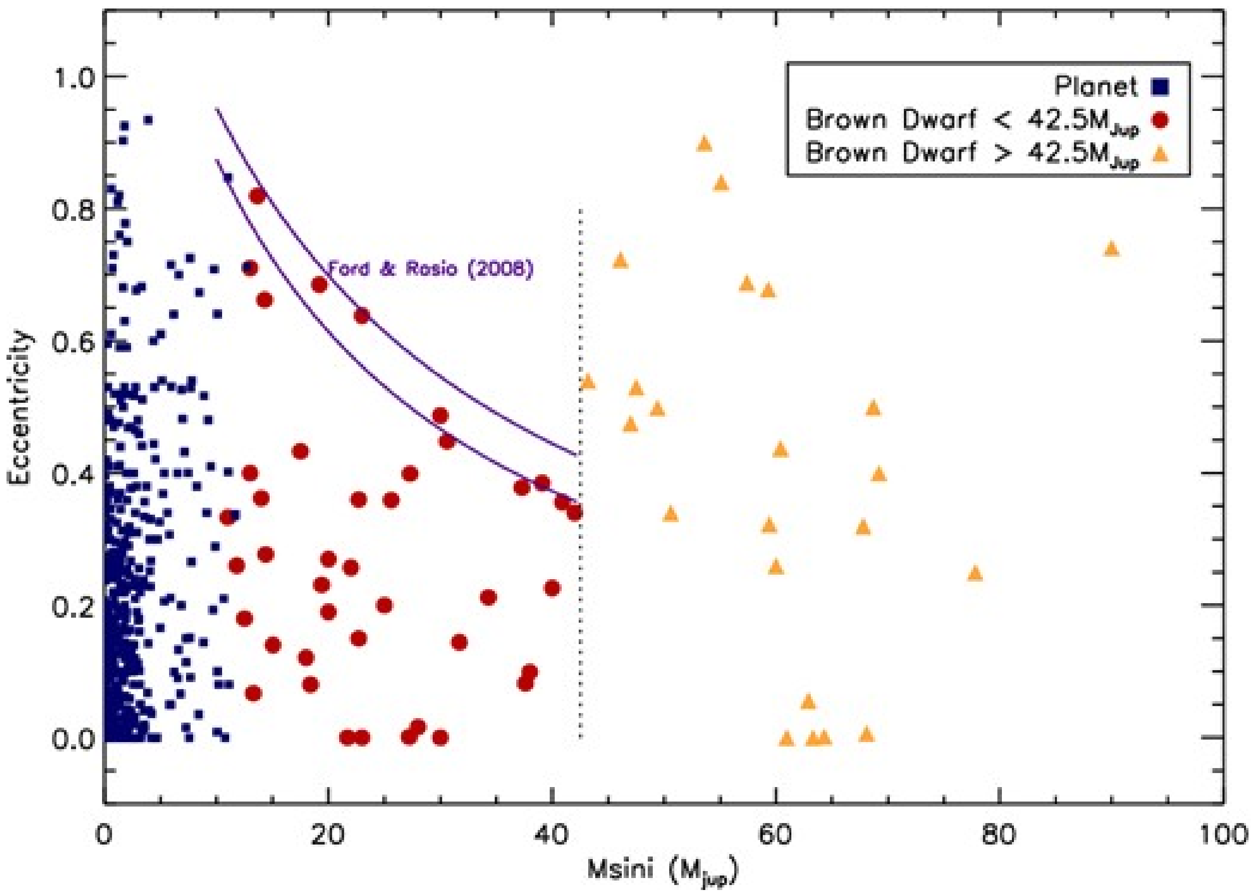

Figure 8. Figure 5 from Ma & Ge (2014): An eccentricity-mass diagram of all known exoplanets (as of 2014) and BDs. A clear dichotomy exists between BDs above and below 42.5 M_J (or roughly 0.041 $M_\odot$)

4. Summary & Conclusion

The exact nature of BDs and how they form has been a topic of debate since they were first theorized in the 1960s. They occupy a gray area between giant planets and small stars and they remain a relative mystery when compared to these two classes of objects they most resemble, which have each been studied extensively and are relatively well understood. The formation and evolution of BDs, in stark contrast to these neighbors, remain without consensus. Many formation mechanisms have been proposed; they were originally thought to form in the same manner as stars, but it has become clear that the gas in star forming regions simply fails to reach the densities necessary to achieve such low mass objects.

One explanation is dynamical ejection, a process in which stellar embryos are ejected from the gas cloud before they accrete enough material to begin hydrogen burning. Additionally, several mechanisms have been proposed for increasing the density in certain parts of a gas cloud sufficiently for BD formation. Among these are turbulent fragmentation (turbulence-caused density fluctuations lowering the local Jeans mass and allowing BD formation) and filament fragmentation (the formation of BDs in filaments of material feeding star forming regions). While these mechanisms likely contribute to the BD population, simulations fail to completely reproduce observations using only these mechanisms. Disk fragmentation is another proposed mechanism in which the circumstellar disk around a host star fragments into one or multiple less massive objects, some of BD-mass, which then interact with each other and their host star, and are often ejected.

Despite a slew of plausible formation mechanisms, the question remains of which, if any, is the primary mechanism for the formation of brown dwarfs. The abundance and distribution of the observed brown dwarf population can give us some clues as to how they were formed. The currently known population of BDs however, is not large enough to make confident determinations of their origins. The next step toward a concrete understanding of the origins of brown dwarfs is more extensive observation, using JWST and other infrared-capable telescopes, in order to better constrain their distribution and characteristics.

5. Appendix: Derivations

Jeans Mass via Virial Theorem

We will derive the Jeans mass for a cloud of ideal gas, assuming constant density. This is clearly not representative of real gas clouds, but the results should give us a good idea of the factors which determine whether or not a cloud of gas will become gravitationally unstable and collapse.

We begin the derivation with the Virial Theorem, setting the total kinetic energy of the gas cloud to half of the total gravitational potential energy:

$$\langle K\rangle = \frac{-1}{2}\langle U\rangle \tag{5.1}$$

Total kinetic energy of the particles in the gas:

$$K = \frac{3}{2}Nk_bT \tag{5.2}$$

Where N is the number of particles in the cloud ($N = M/m$, total cloud mass divided by average particle mass), k_b is the Boltzmann constant, and T is the temperature of the gas.

The gravitational potential energy of the cloud of point masses:

$$U = \frac{-3}{5}\frac{GM^2}{R} \tag{5.3}$$

Where G is the universal gravitational constant and R is the radius of the cloud.

Plugging (5.2) and (5.3) into (5.1) gives us:

$$\frac{3}{2}Nk_bT = \frac{-1}{2}\left(\frac{-3}{5}\frac{GM^2}{R}\right) \tag{5.4}$$

Simplifying and adding an inequality so we are now finding conditions for $U > K$, which is when gravity takes over and the cloud begins to collapse:

$$\frac{k_bT}{m} < \frac{1}{5}\frac{GM}{R} \tag{5.5}$$

We will assume the gas is spherical and has uniform density, given by:

$$\rho = \frac{M}{V} = \frac{M}{\frac{4}{3}\pi R^3} \tag{5.6}$$

Solving for *R* and plugging into (5.5) gives us:

$$\frac{k_bT}{m} < \frac{1}{5}GM\left(\frac{4\pi\rho}{3M}\right)^{1/3} \tag{5.7}$$

Solving for M and simplifying gives us the mass above which gravity takes over, the Jeans mass:

$$M > \left(\frac{5k_bT}{Gm}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2} = M_{Jeans} \tag{5.8}$$

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