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Karla M. Rojas
Amsterdam University College

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KARLA M. ROJAS, AMSTERDAM UNIVERSITY COLLEGE
MENTOR: LOTTE TAVECCHIO

Abstract

Brown dwarfs, objects within the mass range of 13–80 M_J, exhibit similarities with both low-mass stars and giant planets. Despite great progress in both detection and theory in the past few years, the main formation mechanism of brown dwarfs remains unclear. To understand their origin, I tested whether low-mass (≤42.5 M_J) and high-mass (≥42.5 M_J) brown dwarfs came from distinct populations, as has been claimed in the literature. I collected all the available data on brown dwarfs from the NASA Exoplanet Archive and the Extrasolar Planets Encyclopaedia. Then, using SPSS Software, I performed nonparametric tests to analyze their statistical properties. Finally, I compared the results to the theories of gravitational collapse, core accretion, and disk instability.

Results showed that the two mass groups did not come from distinct populations. In fact, inside the brown-dwarf desert, stellar and planetary processes met and produced almost indistinguishable objects. Despite the hybrid origins of brown dwarfs, disk instability seems to be their main formation mechanism.

Brown dwarfs, starlike objects, are common yet mysterious. The Milky Way contains about 25–100 billion brown dwarfs (Mužić et al., 2017) and approximately 60 billion stars (McMillan, 2011), suggesting that there might be one brown dwarf for every star in the Milky Way—perhaps even more. Despite the frequency of brown dwarfs, their origin is still unknown. Kumar theorized their existence in 1963, but not until 1995 did Oppenheimer and colleagues observe the first brown dwarf. Unlike stars, brown dwarfs are unable to fuse hydrogen (Nakajima et al., 1995), but they do share several characteristics with stars (Luhman, 2012), such as radial velocity dispersions, spatial distributions in young clusters, and outflows.

Because of this overlap, Chabrier et al. (2014) argued that stars and brown dwarfs must have a common origin; still, a clear consensus is lacking in the literature. For instance, Mollière and Mordasini (2012) reasoned that brown dwarfs and planets could form correspondingly. Since 1995, at least seven theories for formation have been proposed, ranging from turbulent fragmentation (Padoan &

Nordlund, 2002) to accretion-ejection (Reipurth & Clarke, 2001); however, because the formation process in each of these theories can be classified as a variation of either a stellar or planetary process, I simplify the scenarios by discussing only the major theory of star formation—gravitational collapse—and the two main theories of planetary formation—core accretion and disk instability—the latter two operating at different distances.

Debate is still underway to determine which of the three is the main mechanism responsible for brown-dwarf formation. The theory of gravitational collapse argues that a molecular cloud, which consists of gas and dust atoms bound together, collapses under its gravity to create a star (Bodenheimer, 2011). On the one hand, in the theory of core accretion, small particles collide to form a solid core that then gathers or accretes mass and thus eventually grows into a planet (Armitage, 2010). On the other hand, in the theory of disk instability, the gaseous disk surrounding a star gravitationally fragments into a planet (Armitage, 2010). While core accretion is associated with close companions, disk instability can effectively produce wide companions (Luhman, 2012). The answer might also be closely related to the brown-dwarf desert—the theorized absence of brown dwarfs that have low orbital periods (≤100 days) within short separations (≤3 AU) of their main-sequence stars (Carmichael et al., 2019)—as the desert is seen as evidence not only of different mechanisms in operation (Maldonado & Villaver, 2017) but also of the boundary between them.

If we succeed in understanding the nature of brown dwarfs, we will improve our knowledge of galaxies and their composition, determine the minimum stellar mass (Pinochet, 2019), and reassess the boundary between stars and planets. To serve this aim, this paper collects all the available data about brown-dwarf binaries (i.e., systems in which a brown dwarf orbits a host star or another brown dwarf) in the NASA Exoplanet Archive and the Extrasolar Planets Encyclopaedia. Next, it divides the sample into low-mass and high-mass groups to test the hypothesis that these, particularly inside the brown-dwarf desert, come from different populations. Then, the results are compared with the theories of gravitational collapse, core accretion, and disk instability. Finally, based on these results, this paper suggests the main formation mechanism of brown dwarfs.

Methodology

This paper considers objects within the mass range of 13–80 M_J (M_J is the mass of Jupiter, or = 1.898×10^{27} kg) as brown dwarfs (Sahlmann et al., 2011). I obtained the brown dwarf data by accessing the NASA Exoplanet Archive and the

Extrasolar Planets Encyclopaedia and then filtering the search for the indicated mass range. This generated 184 results, all checked against the literature. The variables obtained for each object included mass or m*sin(i), in Jupiter masses; eccentricity; orbital period, in days; semimajor axis, in astronomical units; effective temperature, in Kelvin; and the stellar host mass, in solar masses.

I divided the brown dwarfs into low-mass (13–42.5 M_J, $N = 142$) and high-mass (42.5–80 M_J, $N = 42$) groups to assess the claim that these objects belong to different populations (Ma & Ge, 2014). Then, I used the SPSS software to perform various tests. I began by checking the normality of the distribution with a Shapiro-Wilk test because of the small sample size. None of the variables were normally distributed ($p > .05$), so the rest of the tests were nonparametric to avoid the requirement of normality in the data. I next performed the Mann-Whitney U, Kruskal-Wallis H, and Kendall's tau-b tests, the first two of these tests identifying statistically significant differences between groups, and the third providing an indication of how strongly two variables are monotonously correlated. Lastly, I produced three scatter plots and two bar graphs to summarize these data.

Results

The Mann-Whitney U test exhibited two significant differences between the low-mass (13–42.5 M_J, $N = 142$) and high-mass (42.5–80 M_J, $N = 42$) groups (Figure 1). First, the mean rank orbital period was dissimilar (U = 587, $p = .029$), with values of 54.75 and 38.95, respectively; hence, the low-mass group had a higher mean orbital period compared to the high-mass group. Second, the mean rank temperature varied significantly (U = 278, $p = .11$), with values of 43.16 and 26.53, respectively. The high-mass group had a lower mean temperature than the low-mass group. Besides these, the other measured variables of the sample—eccentricity, semimajor axis, and stellar mass—did not show a significant difference; therefore, while the low-mass group was related to hot and close objects, the opposite was true for the high-mass group.

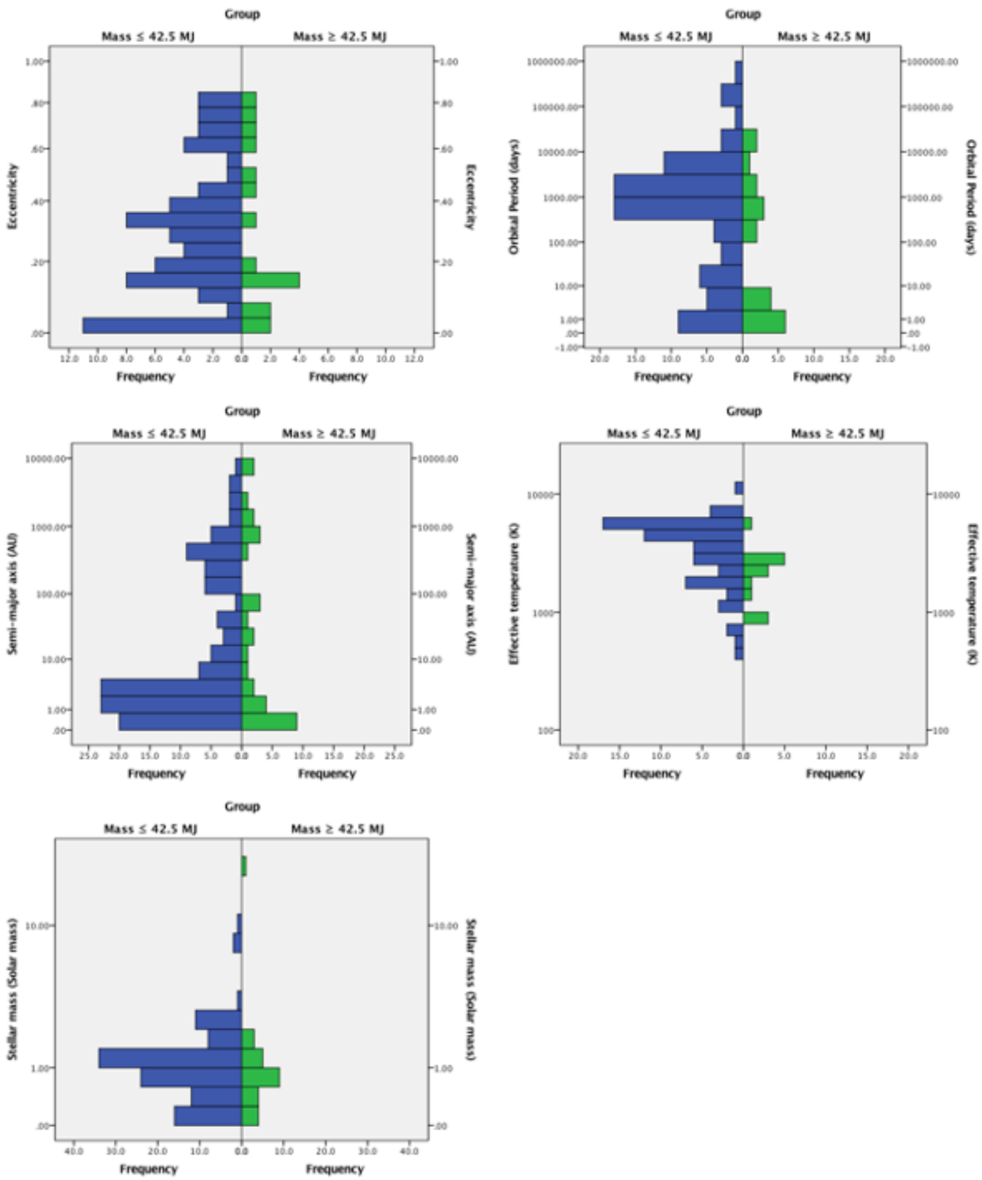

Figure 1 Comparison Between the Low-Mass (≤42.5 M_J) and High-Mass (≥42.5 M_J) Brown-Dwarf Groups

Although eccentricity is not statistically different between the low-mass and high-mass groups, I would like to highlight two things. First is the paucity of brown dwarfs with high eccentricities (≥0.60) within a mass range of 25–55 M_J (solid line,

Figure 2) as well as across all eccentricity values within a narrow mass range of 42.5–49 M_J (dotted line, Figure 2). Second is that a Kendall's tau-b test revealed a positive medium correlation, between the orbital period and the eccentricity, that was statistically significant (τb = .318; p = .000025). Figure 3 shows that this correlation holds for both groups.

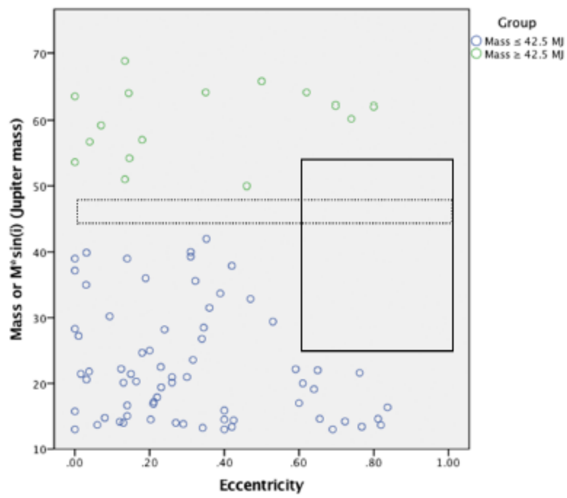

Figure 2. Mass Distribution of Brown Dwarfs Depending on Eccentricity
Note. The dotted and solid rectangles are the identified gaps of brown dwarfs.

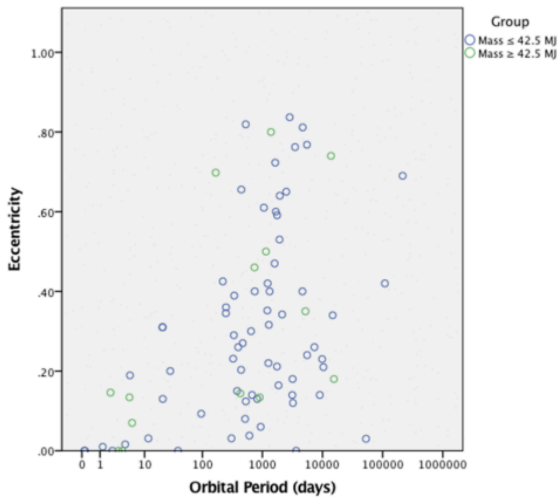

Figure 3. Positive Correlation Between Orbital Period and Eccentricity

As Figure 4 shows, 10 objects within the brown-dwarf desert were classified: EPIC 219388192 b, WASP-128 b, PSRJ2055+3829 b, 2M1510A b, Kepler-492 b, 2M1510A a, SDSSJ1411+2009 b, EPIC 212036875 b, TOI-503 b, and AD 3116 b. Sixty percent (60%) of these objects were in the low-mass group, and the remaining 40% were in the high-mass group. A Kruskal-Wallis H test revealed that, apart from mass, there is an insignificant difference ($p > 0.05$) in the orbital period, eccentricity, semimajor axis, effective temperature, and stellar mass of the brown dwarfs inside the desert.

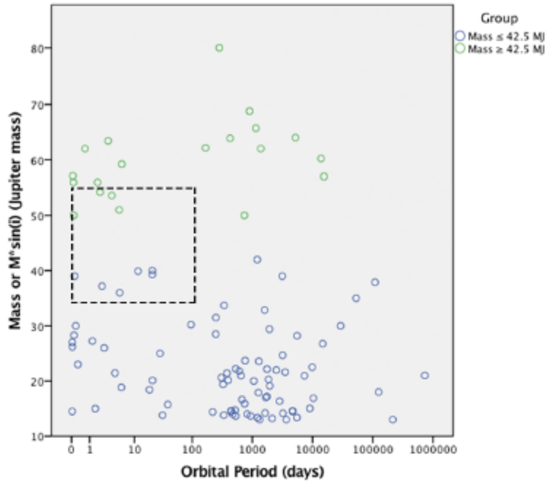

Figure 4. Mass Distribution Depending on Orbital Period
Note. The dashed rectangle represents the brown-dwarf desert.

Discussion

This study identified two types of brown dwarfs: hot, close, low-mass objects, and cold, distant, high-mass objects. Between these two groups, the orbital period and effective temperature were significantly different, but the eccentricity, semimajor axis, and stellar mass were not. As Figure 5 suggests, the temperature variation could be explained through the dependence of the brown dwarf's temperature on its distance from the host star (Kutner, 2003); thus, the key difference lies in the orbital period. This pattern was even stronger inside the brown-dwarf desert, where the 10 brown dwarfs, located in the driest region of mass range of 35–55 M_J (Ma & Ge, 2014), did not show statistical differences in orbital period, eccentricity, semimajor axis, effective temperature, and stellar mass. This study thus rejects the hypothesis that the low-mass and high-mass groups belong to completely distinct populations.

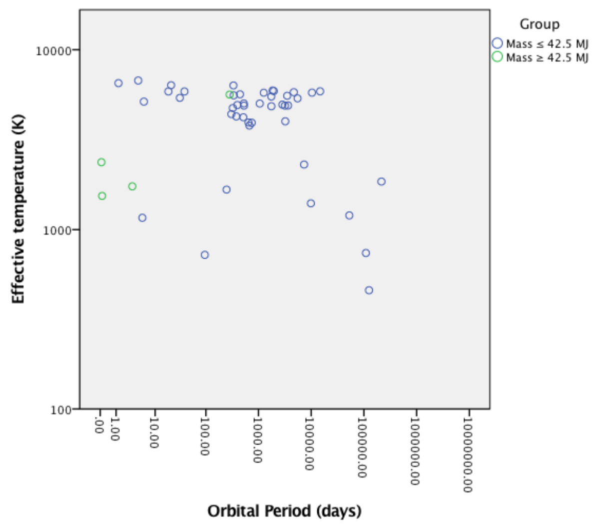

Figure 5. Relationship Between Orbital Periods and Effective Temperatures

Another similarity between the groups was a positive correlation between the orbital period and eccentricity, with the most distant objects having higher eccentricities. This trend, however, is interrupted in a mass range of 25–55 M_J at high eccentricities (≥0.60). This can be explained by the fact that lower-mass companions, with high eccentricities, are more likely to be ejected through dynamical interactions (Chabrier et al., 2014) and can be uncommon. Likewise, there is an absence of brown dwarfs across all eccentricity values in a mass range of 42.5–49 M_J—*w*ithout a clear explanation; this would be an interesting region to explore and in which to further test the formation mechanisms. The previously mentioned gaps have not been reported in the literature yet.

The previous findings should be interpreted using the three major models of brown-dwarf formation: gravitational collapse, core accretion, and disk instability. Luhman (2012) highlighted the similarities in radial velocity dispersions, spatial distributions, and outflows between stars and brown dwarfs. The numerical simulations of Bonnell et al. (2008) support the claim that brown dwarfs can form similarly to low-mass stars. Despite this, only 10% of their objects ended up as brown dwarfs. Stamatellos and Herczeg (2015) pointed out another complication in the theory: to collapse, the low-mass core needs to be very dense and compact. Marks and colleagues (2017) stressed that those conditions are rather unlikely to occur, and they rejected that similarity in spatial distributions, between stars and brown dwarfs, points toward a common origin, because scattering and ejections also come into play. Consequently, gravitational collapse cannot be the only mechanism involved. Mollière and Mordasini (2012) put forward the idea that core accretion can produce brown dwarfs. This theory can explain brown dwarfs at very close separations (Ma & Ge, 2014) and, to a lesser extent, at wide separations (≥ ~10 AU), through outward migration or scattering (Murray-Clay, 2010). Nevertheless, as the numerical simulations of Stamatellos et al. (2007) have shown, disk instability is more effective at producing brown dwarfs at larger separations. In fact, Kratter and Lodato (2016) argued that disk instability is more strongly linked to brown dwarfs than to planets, provided that fragmentation occurs.

Ma and Ge (2014) first proposed to divide brown dwarfs into low-mass (≤42.5 M_J) and high-mass (≥42.5 M_J) groups because of the conflicting evidence and plausibility of both the stellar and planetary models. The division was motivated by the brown-dwarf desert, which was thought to be evidence for the presence of two independent processes. Ma and Ge claimed that two distinct brown-dwarf populations existed: the low-mass, formed by a planetary mechanism, and the high-mass, by a stellar one. Nevertheless, Carmichael et al. (2019) pointed out that their first claim, based on a Kolmogorov–Smirnov test, was flawed. Moreover, the detection of brown dwarfs in that region (Grieves et al., 2017; Nowak et al., 2017; Persson et al., 2019) challenged the mere existence of the brown-dwarf desert. There is increasing evidence for the accuracy of their proposed formation mechanism for each mass group, however (Li et al., 2015; Riaz et al., 2018; Rilinger et al., 2019; Stamatellos and Herczeg, 2015). This denotes that the stellar and planetary mechanisms form objects in the brown-dwarf desert range (35 M_J ≤ mass ≤ 55 M_J, 0 days ≤ orbital period ≤ 100 days, 0 AU ≤ semimajor axis ≤ 3 AU), at the very least, but, as Maldonado and Villaver (2017) suggested, these processes might operate with different efficiencies.

Because there is no clear division between these two formation mechanisms in nature, we must acknowledge the hybridity of brown dwarfs. Instead of being classified by their formation processes (Carmichael et al., 2019; Luhman, 2012) or on individual bases (Vorobyov, 2006), brown dwarfs should be placed in a continuum where, depending on their mass, they share characteristics with both stars and planets to a greater or lesser extent. This paper supports this idea because of the lack of significant differences between the low- and high-mass groups within the brown-dwarf desert, even though brown dwarfs in that region must have formed by core accretion/disk instability and gravitational collapse, respectively. From this, it is clear that stellar and planetary mechanisms produce almost indistinguishable objects in the region of the brown-dwarf desert. Only when we compare objects that are far from each other in this continuum—with a mass difference of ≥30 M_J—do significant differences in the orbital period and effective temperature emerge. This raises interesting questions about the boundary between stars and planets. If objects were defined by their formation mechanisms, the boundary between stars and planets would disappear. If we instead acknowledge the hybrid origins of brown dwarfs and define objects depending on their inherent physical properties, we can make a distinction among stars, brown dwarfs, and planets.

Brown dwarfs sit in a continuum between stars and planets, although disk instability seems to be their main formation mechanism. The great majority (77%) of the sample belongs to the low-mass group, which shares a common origin with planets, of which 46% most likely formed through core accretion (≤3 AU) and 54% probably through disk instability (≥3 AU). Moreover, gravitational collapse cannot explain the brown dwarfs with very close separations (≤3 AU), which represent 45% of the total sample, as a system formed in this way would quickly migrate inward and merge with the star (Ma & Ge, 2014). Formation mechanisms might not be mutually exclusive (Rilinger et al., 2019), but gravitational collapse should be relegated to a secondary role.

Nonetheless, these results should be interpreted by taking into account three major limitations. First, although the sample size of this study (N = 184) is considerably larger than usually seen in the literature (N = 65; Ma & Ge 2014), it remains small because the population of brown dwarfs in our galaxy was estimated to be 25–100 billion (Mužić et al., 2017). For this reason, the study considered only nonparametric statistical tests although they are less sensitive, causing small effects to go undetected (Garth, 2008). Second, the two main detection methods—radial velocity and transit—are biased toward observing objects in close orbits (Planetary Society 2002a, 2002b), meaning that wide-orbit objects are underrepresented. Finally, there is a fundamental limit in our capability of inferring from current values the exact primordial conditions and their relationship to formation mechanisms (Chabrier et al., 2014)—for example, due to dynamical interactions (i.e., mergers, ejections, migrations).

Independent studies are required to confirm the statistical difference in the orbital period and effective temperature between the low- and high-mass groups, as well as the homogeneity of brown dwarfs inhabiting the brown-dwarf desert. Additionally, more observational data of brown dwarfs are needed to gather a more robust sample. We can expect major contributions in this area from the upcoming James Webb Space Telescope, Atmospheric Remote-sensing Infrared Exoplanet

Large-survey, and Wide Field Infrared Survey Telescope space missions. As we obtain more data, particularly of high-mass brown dwarfs, the hypothesis that disk instability is the main formation mechanism of the overall population will be tested. Finally, to understand the positive correlation between orbital period and eccentricity, the newly identified gaps need to be explored, including a mass range of 25–55 M_J at high eccentricities (≥0.60) and across all eccentricity values in a mass range of 42.5–49 M_J.

Summary and Conclusions

Determining the main formation mechanism of brown dwarfs is possible only by comparing and contrasting the brown dwarfs' statistical properties with theory. For this paper, I collected all the data on brown-dwarf binaries, available in the NASA Exoplanet Archive and the Extrasolar Planets Encyclopaedia, and divided the sample into low-mass (≤42.5 M_J) and high-mass (≥42.5 M_J) groups to test if they came from the same population. I discovered that the only significant differences between these groups were the orbital period and effective temperature, although the latter is dependent on the distance of the object from the host star. I also classified 10 objects inside the brown-dwarf desert that came, almost equitably, from the high-mass and low-mass groups. I not only challenge the existence of the desert but also prove that, besides mass, all the other properties—orbital period, eccentricity, semimajor axis, and stellar mass—show no significant difference. Because the low-mass group is associated with core accretion and disk instability, and the high-mass group with gravitational collapse, this result suggests that the stellar and planetary processes meet in nature and produce almost indistinguishable objects. This paper therefore calls for the recognition of the hybrid nature of brown dwarfs.

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