A DEFINITION FOR GIANT PLANETS BASED ON THE MASS–DENSITY RELATIONSHIP

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ABSTRACT

We present the mass–density relationship (log \(M - \log \rho\)) for objects with masses ranging from planets (\(M \approx 0.01 M_{\text{Jup}}\)) to stars (\(M > 0.08 M_\odot\)). This relationship shows three distinct regions separated by a change in slope in the log \(M - \log \rho\) plane. In particular, objects with masses in the range 0.3 \(M_{\text{Jup}}\)–60 \(M_{\text{Jup}}\) follow a tight linear relationship with no distinguishing feature to separate the low-mass end (giant planets) from the high-mass end (brown dwarfs). We propose a new definition of giant planets simply based on changes in the slope of the log \(M\) versus \(\log \rho\) relationship. By this criterion, objects with masses less than \(\approx 0.3 M_{\text{Jup}}\) are low-mass planets, either icy or rocky. Giant planets cover the mass range 0.3 \(M_{\text{Jup}}\)–60 \(M_{\text{Jup}}\). Analogous to the stellar main sequence, objects on the upper end of the giant planet sequence (brown dwarfs) can simply be referred to as “high-mass giant planets,” while planets with masses near that of Jupiter can be called “low-mass giant planets.”

Key words: brown dwarfs – planets and satellites: fundamental parameters – stars: low-mass

1. INTRODUCTION

The nature of stellar and sub-stellar objects is determined by their mass. A star is defined as an object with sufficient mass to ignite hydrogen fusion in the core. Sub-stellar objects, on the other hand, have masses below that needed to ignite hydrogen burning (\(M \approx 80 M_{\text{Jup}}\)). Like their stellar counterparts, sub-stellar objects encompass a wide range of properties from those that are accepted as planets, with masses of a few \(M_{\text{Jup}}\), to objects often considered to be brown dwarfs with masses of a few tens of \(M_{\text{Jup}}\). The exact boundary in mass between what one considers a “planet” and what one considers a “brown dwarf” is blurred and is still the subject of debate.

One definition of a giant planet is that it is a sub-stellar object that has not undergone deuterium burning anytime during its life. By this criterion, the boundary between planets and brown dwarfs should be about 13 \(M_{\text{Jup}}\) (Burrows et al. 2001). However, this distinction seems arbitrary as the mass distribution for companions below 25 \(M_{\text{Jup}}\) show no characteristic features at this mass limit (Udry 2010). Furthermore, the phase of deuterium burning is relatively short (less than \(\approx 100\) Myr), and it has little influence on the future evolution of the brown dwarf. This is contrary to stars where hydrogen burning under hydrostatic equilibrium significantly alters the future evolution of the object. Chabrier et al. (2014) argued that deuterium burning, or the lack thereof, plays no role in either giant planet or brown dwarf formation. Chabrier et al. (2014, p. 619) also pointed out that these two types of objects “might bear some imprints of their formation mechanism, notably in their mean density and in the physical properties of their atmosphere.”

On the other hand, the intersection of the mass distributions of sub-stellar objects appears to have a distinctive dip around \(M \approx 25–30 M_{\text{Jup}}\) (Udry 2010). Schneider et al. (2011) attributed this dip as the boundary between the mass spectrum of planets, which is decreasing with increasing mass, and the distribution of sub-stellar and low-mass stars, which is increasing beyond this point. The dip is also coincident with a possible break in the mass–radius relationship for low-mass and sub-stellar objects (Pont et al. 2005; Anderson et al. 2011), which suggests a difference in the physical natures between objects on either side of this boundary (Schneider et al. 2011). For these reasons, Schneider et al. (2011) arbitrarily (our emphasis) assigned a maximum mass of 25 \(M_{\text{Jup}}\) as the limit for including objects in the Exoplanet Encyclopedia (http://www.exoplanet.eu). However, if an object lies near this 25 \(M_{\text{Jup}}\) boundary, we still do not know its nature, i.e., to which distribution (planets or brown dwarfs) it actually belongs. The mass distribution may, however, tell us something about the formation, if not the nature of the object.

The mean density versus mass relationship for planets shows a broad minimum around a mass of 0.3 \(M_{\text{Jup}}\) (Rauer et al. 2014; Laughlin & Lissauer 2015) that separates the H/He-dominated giant planets from low-mass planets (LMPs) of Neptune-mass or smaller. The different slopes in the density–mass plane of the two objects highlight the differences in structure between the two classes of planets. We extend the density–mass relationship through sub-stellar and stellar objects and show that this also exhibits a change in the slope marking the differences in structure between giant planets/brown dwarfs and stellar objects where the onset of hydrogen burning has an impact on the structure. We propose a definition of giant planets based on this mass–density diagram.

2. THE DENSITY VERSUS MASS RELATIONSHIP

We constructed a mass–density diagram for the full range of masses covering planets through main-sequence stars. Due to the fact that these are transiting/eclipsing systems, they are all relatively close pairs. In this sense, they can be treated as a “pseudo-homogeneous” sample. These systems also have known orbital inclinations, so we have the true companion mass. This has a distinct advantage over single objects (e.g., free-floating brown dwarfs) for which the masses rely on evolutionary tracks and are thus more uncertain.

For the giant planet data, we largely restricted our sample to transiting planets from the space-based missions CoRoT and Kepler. These space missions provide light curves with the best photometric precision for producing the most accurate planet radii. This is particularly important since the radius enters as...
the third power in the density. Besides using space-based transit discoveries that provide the best photometric precision, it is important to use transit light curve analyses that were done in a consistent manner. Various investigators may use different limb-darkening laws or apply different methods to filter out intrinsic stellar variability that may introduce more scatter in the results. For this reason, we took radius and mass values for the planets from the web-based TEPCat catalog (http://www.astro.keele.ac.uk/jkt/tepcat/tepcat.html and references therein) as these were derived from a uniform analysis (see Southworth 2010, 2011, 2012).

There are few mass and radius measurements for brown dwarfs or “super planets,” mostly because of the paucity of such objects, so we had to include ground-based results. Along with the Kepler discoveries (Bouchy et al. 2011; Diaz et al. 2013, 2014; Moutou et al. 2013), we included ground-based results (Johns-Krull et al. 2008; Hellier et al. 2009; Joshi et al. 2009; Anderson et al. 2011; Siverd et al. 2012; Triaud et al. 2013). For completeness, we also included the brown dwarf eclipsing binary system 2MASS J05352184–0546085 even though this is a young system still in the earliest stages of gravitational contraction (Stassun et al. 2006).

Stellar masses and radii for most main-sequence stars were taken from Torres et al. (2010). A variety of sources were used for the parameters of stars from the low-mass end of the main sequence (Pont et al. 2005, 2006, 2008; Demory et al. 2009; Ofir et al. 2012; Tal-Or et al. 2013; Zhou et al. 2014). Figure 1 shows the resulting mass–density relationship for our sample. There are two major inflections in the curve. The maximum density occurs at a mass of approximately 60–70 $M_{\text{Jup}}$, the boundary between core nuclear burning stars and degenerate core brown dwarfs. The second inflection is a minimum in density at $M \approx 0.3 M_{\text{Jup}}$, roughly the boundary between H/He-dominated planets and LMPs. The two outliers in the “giant planet” region are the components of the young eclipsing brown dwarf system 2MASS J05352184–0546085. The densities of these two objects are anomalous because of their large radii and the fact that they are still undergoing gravitational contraction.

Fits were made to the data in these regions in order to better define the boundary between low-mass stars, giant planets/brown dwarfs, and stars. Although the stars show an approximately linear relationship in the mass range 0.08–1 $M_{\odot}$, the relationship is best fit by a second-order polynomial shown by the curved line. For low-mass stars in the range 0.08–1 $M_{\odot}$, the log $M - \log \rho$ relationship can also be fit by a line resulting in $\rho \propto M^{-1.2 \pm 0.16}$. This follows from the mass–radius relationship on the low-mass end of the main sequence where $R \propto M$, thus $\rho \propto M^{-2}$.

The log $M - \log \rho$ relationship for giant planets and brown dwarfs (excluding the binary 2MASS J05352184–0546085) shows a very tight correlation (correlation coefficient, $r = 0.976$). A linear fit over the mass range 0.35–65 $M_{\text{Jup}}$ results in

$$\log \rho = (1.15 \pm 0.03) \log M - (0.11 \pm 0.03).$$

This linear relationship of density with mass simply reflects the fact that objects with masses ranging from giant planets ($\sim 1 M_{\text{Jup}}$) up to low-mass stars all have approximately the same radius. Thus, an increase in mass is accompanied by a proportional increase in density. Note that this curve closely follows the mass–density relationship for H/He-dominated giant planets (Fortney et al. 2007), which is shown as the dashed line. At the low-mass end of the giant planet range, the linear fit to the giant planets deviates significantly from the dashed line for planets with Jupiter-like composition. The planets below the dashed line are larger than expected by such models and are called “inflated” planets. The linear relationship intersects the main sequence for stars at $M = 63 \pm 6 M_{\text{Jup}}$.

For simplicity, we shall refer to all exoplanets with masses less than $\approx 0.3 M_{\text{Jup}}$ as low-mass exoplanets. These can be either rocky or ones that have a large fraction of volatiles (i.e., Neptune-like). The LMPs show considerable scatter in their densities. In spite of this scatter, there clearly appears to be a minimum in density around $\sim 0.3 M_{\text{Jup}}$. Indeed, a parabolic fit to the valley of this “V”-shape results in a minimum of the density at this value for the mass. For higher-mass objects, the density increases. We take this as the boundary between the LMP and giant planets.

**Figure 1.** Density and mass of stars (red squares), giant planets and brown dwarfs, and low-mass planets. Triangles represent Kepler discoveries, and dots are CoRoT exoplanets. Ground-based discoveries for high-mass giant planets are shown by pentagons. The line represents a linear fit to the giant planets and brown dwarfs in the mass range $M = 0.35–60 M_{\text{Jup}}$. A second-order polynomial fit (curved line) was made to the lower end of the stellar main sequence. The boundary between the low-mass planets and giant planets occurs at $M = 0.3 M_{\text{Jup}}$. The boundary between the giant planets and stars is at $M = 60 M_{\text{Jup}}$ (0.060 $M_{\odot}$). The dashed red line shows the mass–density relationship for H/He-dominated giant planets taken from Fortney et al. (2007). The two outliers in the “giant planet” region are the components of a young eclipsing brown dwarf binary that are still undergoing gravitational contraction.

**Figure 2.** Points from Figure 1 shown in the mass–radius plane.
Figure 2 shows the more traditional mass–radius relationship with our boundaries shown as the vertical dashed lines. One can also see inflections in this curve at roughly the same boundaries seen in Figure 1, although these are not as striking or well defined, particularly between the low-mass and giant planets.

3. DISCUSSION

The mass–density diagram for all objects with masses ranging from planets to stars are separated by three distinct regions marked by an abrupt change in sign of the slope of the log $M$ – log $\rho$ relationship. Stars show a negative slope, whereas giant planets and brown dwarfs have a positive slope. However, below about $0.3 M_{\text{Jup}}$, objects show considerable scatter in their densities. We shall simply refer to this region of the diagram as the LMP. It is beyond the scope of this paper to discuss this region of the diagram, the origin of such scatter, or any relationship between the mass and density. Instead we will focus on the giant planets, and for the sake of discussion, we shall refer to these regions between the LMP and stars as the “gaseous planet sequence” (GPS). MS will refer to the classic main sequence for stars.

The beginning of the GPS occurs at $M \approx 0.3 M_{\text{Jup}}$, roughly the boundary between planets with a significant amount of volatiles and those dominated by H/He. The boundary between the GPS and the MS occurs at $60 M_{\text{Jup}}$. Laughlin & Lissauer (2015) noted that the distribution of planetary densities had a broad minimum at a planet mass of $M_p \sim 0.1 M_J (30 M_{\text{Earth}})$, which they took as the boundary between giant planets and LMPs (termed “ungiants” in their paper). We propose that this boundary is actually at a much higher mass of $M_p \sim 0.3 M_J$.

We also fit the density–mass data from Laughlin & Lissauer (2015, Figure 5 of their paper) for planets within the mass range 0.01 to 0.1 $M_J$. The data are well fit by a linear function that intercepts our GPS at $M_p \sim 0.3 M_J (\approx 100 M_{\text{Earth}})$, consistent with our proposed boundary.

The striking feature about GPS is that there is no distinguishing characteristic that separates the low-mass end where objects are clearly planets and the high-mass end where objects are generally considered to be brown dwarfs. The $25 M_{\text{Jup}}$ limit (the arrow in Figure 1) taken by Schneider et al. (2011) to be the boundary between planets and brown dwarfs shows no obvious differences in the GPS on either side of this limit. If anything, the arrow only seems to mark the boundary where the data are sparse. Clearly, the discovery of more objects in this mass range is desperately needed. Possible differences between the giant planets and the “traditional” brown dwarfs may become more apparent with more discoveries. For instance, if no objects can be found that fill the gap marked by $25 M_{\text{Jup}}$ (arrow) and the onset of the MS, then this “gap” might be taken to separate the planets from the brown dwarfs and stars. For now, we note that the few brown dwarfs with masses $\approx 60 M_{\text{Jup}}$ all fall on the GPS.

Figure 1 shows that in terms of density no distinctions can be made between objects on the low- and high-mass ends of the GPS. All objects along the GPS have the same basic structure: a core supported by the electron degeneracy pressure that is surrounded by a H/He envelope. Significant changes in this basic structure occur at the start of the MS where hydrogen burning is ignited in the core and at the low-mass end where the structure of LMPs comes into play. This figure also shows that deuterium burning most likely does not affect the hydrostatic equilibrium of the brown dwarf as shown by theoretical work (Fortney et al. 2007; Baraffe et al. 2014; Chabrier et al. 2014). However, deuterium burning is rather short lived, and the ages for most of the brown dwarfs shown in Figure 1 are unknown. With the possible exception of the binary 2MASS J05352184 –0546085, it is not clear which of these objects is still undergoing deuterium burning.

Chabrier et al. (2014, p. 639) also argued that the mass boundary between giant planets and brown dwarfs given by the present IAU definition was “incorrect and confusing and should be abandoned.” Figure 1 certainly supports this claim. This figure also shows that the density provides us with no obvious hints regarding a different formation mechanism between brown dwarfs and giant planets. Possibly, the differences in the physical properties of the atmospheres may show indications of a different formation mechanism (Chabrier et al. 2014). This may become evident when future data allow a comparison of the atmospheric composition of objects along the GPS.

The large mass range of objects along the GPS should not be a basis for dividing objects into different types. After all, stars along the MS have masses that cover two orders of magnitude, like the GPS, yet the only distinction that is made is between high-mass and low-mass stars. This is in spite of the fact that the structure of a star and its atmospheric composition change considerably along the main sequence. High-mass stars have a convective core and radiative envelope, and as one moves down the main sequence, this structure changes to one with a radiative core and a convective envelope. The lowest-mass stars, on the other hand, are fully convective. The stellar atmosphere changes considerably along the main sequence in terms of effective temperatures and the types of spectral features that are observed. One could argue that even with slight changes in the structure there are no substantial differences between brown dwarfs and giant planets.

One could define planets according to their respective formation mechanisms; however, there is a danger in this as these mechanisms rely on a theory that may be incomplete or, ultimately, may be wrong. The boundary between brown dwarfs and planets may thus vary as the theory changes. One can argue, however, that even a different formation mechanism is no reason to distinguish between the two objects. Again, drawing from the stellar analogy, stars may also have different formation scenarios. Low-mass stars are believed to form from the collapse of a proto-cloud and subsequent accretion (Palla & Stahler 1993). The formation mechanism for high-mass stars is still open to debate. For massive stars, radiation from the core halts the accretion process, thus limiting the mass (e.g., Yorke & Krügel 1977). One hypothesis is that they are formed by the merger of lower-mass stars (Bonnell et al. 1998). Regardless of all these substantial differences, all objects along the MS are considered to be the same general class of objects that is governed by the same physics—nuclear burning in the core under hydrostatic equilibrium. We only make sub-distinctions in the form of “low-mass” and “high-mass” stars.

Objects along the GPS also have masses that differ by over two orders of magnitudes. Like stars, they certainly have a wide range of effective temperatures, atmospheric features, and possibly even different formation mechanisms. Making an arbitrary distinction between giant planets and brown dwarfs only confuses the central issue that these objects share a similar structure. By considering that these objects belong to the same
class, we may gain a more fundamental understanding of their formation, evolution, and nature.

By comparing the GPS to the MS, one may speculate that the so-called “brown dwarf desert” simply reflects the decrease in number of high-mass brown dwarfs, much in the same way there is a decrease in the number of high-mass stars in the stellar distribution. Compared to low-mass main-sequence stars, O-type stars in our galaxy are extremely rare—it is simply harder for nature to form these higher-mass stars. To our knowledge, astronomers never refer to the “O-star desert.” Likewise, there are relatively few brown dwarf companions to stars simply because it is so much more difficult to form these more massive “giant planets.”

Our conclusions do not address the issue of single or free-floating brown dwarfs (or giant planets, for that matter). Obviously, these were excluded from our study because there are no accurate mass and density measurements for these objects. Furthermore, it is not even clear if free-floating brown dwarfs have the same formation mechanism as those that are close companions to stars. It is probably safe to assume that brown dwarf companions to stars, like those in our sample, at least have a shared formation mechanism.

We propose a new definition of planets, brown dwarfs, and stars based not on arbitrary separation of distributions, or whether short-lived deuterium burning has occurred, or just because we are biased in thinking that giant planets should all have masses close to that of our Jupiter. Rather, our definition is based on the observed inflections in the mass–density diagram that separate regions governed by different underlying physics. Thus,

\[ M < 0.3 M_{\text{Jup}} \Rightarrow \text{Low Mass Planets} \]

\[ 0.3 M_{\text{Jup}} < M < 60 M_{\text{Jup}} \Rightarrow \text{Giant Gaseous Planets} \]

\[ M > 60 M_{\text{Jup}} \Rightarrow \text{Stellar Objects} \]

We note that by our definition Saturn has a mass near the boundary between LMP and gas giant planets. Although we refer to objects with \( M > 60 M_{\text{Jup}} \) as “stars,” the exact boundary between objects supported by electron degeneracy pressure and those with a hydrogen burning core is not well known and can be as high as \( 80 M_{\text{Jup}} \). Possible objects with \( 60 M_{\text{Jup}} < M < 80 M_{\text{Jup}} \) should be considered to be the bona fide brown dwarfs.

Another obvious feature of Figure 1 is the relative paucity of objects in the mass range \( 20 < M_{\text{Jup}} < 100 \). This is in part due to the relative low number of these with respect to lower-mass planets, but may also be due to the fact that Doppler surveys have largely concentrated on confirming transit discoveries of lower-mass planets. Low-mass stars, and objects on the high-mass end of the GPS, are often ignored in favor of getting mass measurements on the more “interesting” planet candidates. However, accurate mass and radius measurements of objects on the low-mass end of the stellar main sequence and the upper end of the GPS, i.e., the boundary between high-mass giant planets and low-mass stars, are also important. Only by studying the full range of objects from high-mass giant planets to the lower end of the main sequence will we obtain a more fundamental understanding of the formation of giant planets compared to low-mass stars.

Currently, the scientific community has yet to agree upon a definition of giant planets versus brown dwarfs and the exact mass boundary between these two types of objects. It is our hope that this Letter starts an earnest discussion on this topic. We are of the opinion that any definition of giant planets versus brown dwarfs should be based on observable quantities. A good analogy is the case of the H–R diagram where plotting luminosity versus temperature showed characteristic features that distinguished different classes of objects such as dwarfs and giants (Russell 1913). Based on the observed quantities of mass and density, all objects with masses of \( 0.3–60 M_{\text{Jup}} \) fall on a linear sequence with no characteristic features to distinguish between objects on the high- and low-mass end. The only distinction is between high- and low-mass giant planets, or alternatively high- and low-mass brown dwarfs. One may arrive at a different definition of giant planets based on other observable quantities. Regardless, the \( M–\log \rho \) diagram can still serve as a powerful tool for understanding planetary structure.

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