The 19th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun
Edited by G. A. Feiden

Relation between Brown Dwarfs and Exoplanets

Lauren Melissa Flor Torres[1], Roger Coziol[1], Klauss-Peter Schröeder[1], César A. Caretta[1] and Dennis Jack[1]

[1] Departamento de Astronomía, Universidad de Guanajuato, Guanajuato, México

Abstract

One of the most debated subjects in Astronomy since the discovery of exoplanets is how can we distinguish the most massive of such objects from very-low mass stars like Brown Dwarfs (BDs)? We have been looking for evidences of a difference in physical characteristics that could be related to different formation processes. Using a new diagnostic diagram that compares the baryonic gravitational potential (BGP) with the distances from their host stars, we have classified a sample of 355 well-studied exoplanets according to their possible structures. We have then compared the exoplanets to a sample of 87 confirmed BDs, identifying a range in BGP that could be common to both objects. By analyzing the mass-radius relations (MRR) of the exoplanets and BDs in those different BGP ranges, we were able to distinguish different characteristic behaviors. By comparing with models in the literature, our results suggest that BDs and massive exoplanets might have similar structures dominated by liquid metallic hydrogen (LMH).

1 Introduction

The most accepted interpretation of Brown Dwarfs (BDs) is that they are failed stars (Cushing, 2014), because, although it is assumed they formed like stars, their masses are too small to permit the fusion of hydrogen in their nucleus. This characteristic allows to separate BDs from main sequence stars based on their masses: because a star must reach a critical mass to be able to burn its hydrogen, which varies from $0.07\ M_\odot$ for solar metallicity to $0.09\ M_\odot$ for lower metallicities (Burrows et al., 2001), any star with a mass $< 70\ M_J$ (where M_J is the mass of Jupiter) is a BD (Bate, 2006).

However, determining a lower mass limit for a BD is more difficult. In practice, the consensus to adopt the critical mass for the fusion of deuterium, which is around $13\ M_J$ (Bate, 2006), is arbitrary, because theoretically the lowest mass a BD could have may be just a few M_J (Larson, 1969; Rees, 1976; Silk, 1977a,b; Boss, 1988). Interestingly, this mass is also typical of massive exoplanets, and, since there is no obvious upper-mass limit for an exoplanet, hence, persists the problem of distinguishing between to two objects.

In this poster, using a large sample of "well-studied" exoplanets, and comparing with a large sample of "confirmed" BDs available in the literature, we probe a mass range common to both classes of objects, looking for evidence of a difference between their respective physical structures, as reflected by their mass-radius relations (hereafter MRRs).

Our study concentrates on two questions: 1) At what mass boundary should we expect to see a variation in the MRR that would be consistent with a difference of structure between exoplanets and BDs? 2) Is there a special intermediate mass range where these two classes of objects are likely to overlap in mass? In particular, we propose a lower-mass limit for BDs based on the Self-Gravitating (SG) limit, which marks the moment the self-gravity of matter begins to affect significantly the structure of a body (Padmanabhan, 1993).

In addition to the MRR, the distance of a planet from its host star could also reveal something about its formation process (Lissauer, 1993). For the exoplanets, this last parameter is fundamental to identify Hot Jupiters (Johnson, 2009), while for the BDs, this parameter can be used to test the "BD's desert" hypothesis, which according to some authors (e.g., Grether & Lineweaver, 2006) might be related to different formation processes for exoplanets and BDs.

2 Samples

Our sample of exoplanets consists of 355 entries in the latest issue of the transiting planets catalog available at TEPCat[1], and can be considered as an upgraded version of the sample of well-studied exoplanets used previously in the study of Hatzes & Rauer (2015). Note that because these exoplanets are detected by the transit method, their uncertainties on the inclination of their orbits, i, are relatively low (Winn, 2010; Koch et al., 2010; Batalha, 2014), which reduces significantly the uncertainties on their masses, $M = M_{planet} \sin i$. In our sample, the median uncertainties are 6% for the masses and 5% for the radius.

Our sample of BDs is composed of 87 objects selected from the upgraded compilation produced by Johnston (2015), which is based on published data. For all the BDs in our sample, we double-check their classification as BDs using SIMBAD. Although all these BDs have a mass and radius determined, only 37 have a distance estimate from a companion star. Of the remaining 50 BDs that do not have a distance reported in our list, 14 are part of a binary system with another BD in our list (for which we have the distance), whereas 36 are genuine isolated objects, which already makes them different from exoplanets.

[1]http://www.astro.keele.ac.uk/jkt/tepcat.html

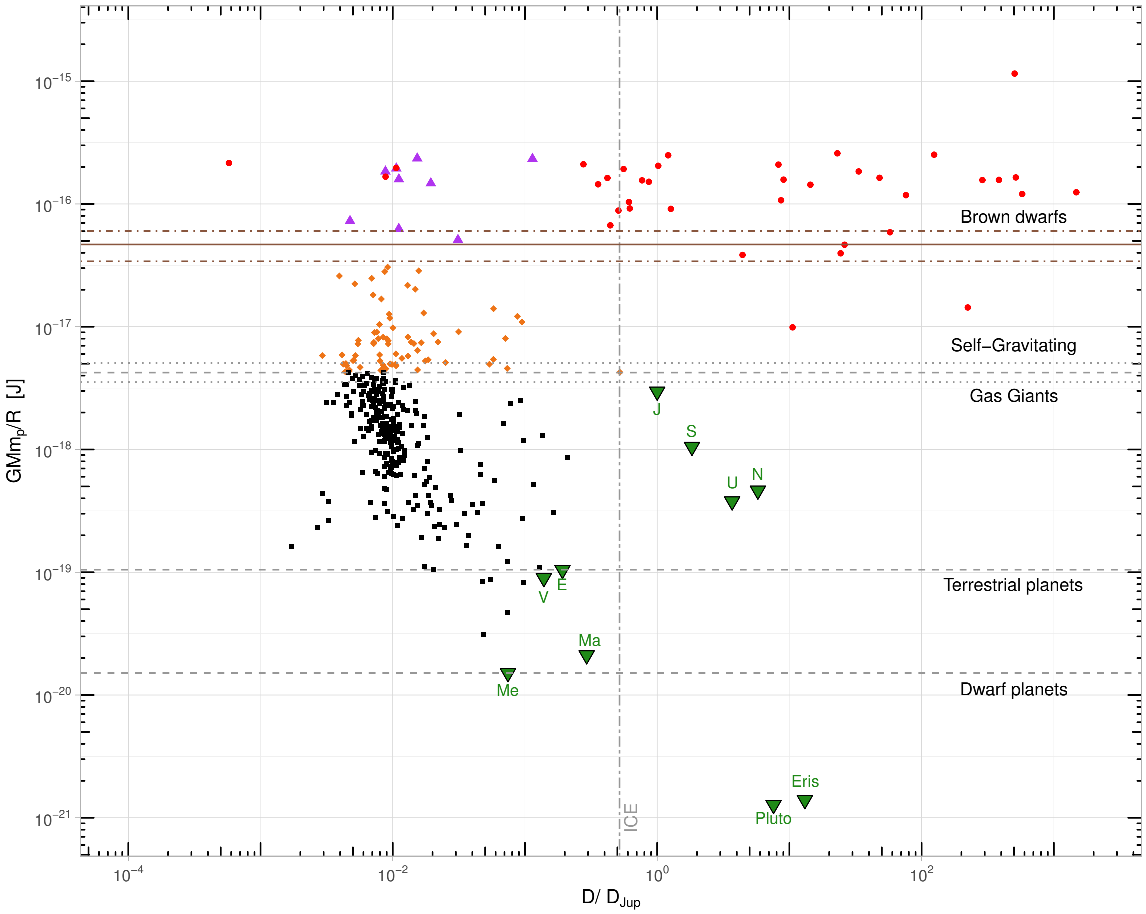

Figure 1: The BGP diagram for exoplanets and BDs: nSGEs (black squares), SGEs (orange diamonds), and BDs (red solid dots); the SGEs falling in BD region are identified by purple triangles. The inverted green triangles correspond to the positions occupied by the different kinds of planets in the solar system. The position of the ice line (or water "snowline") in the solar system (vertical dot-dash line) is also indicated.

3 The baryonic gravitational potential (BGP) diagram and the Self-Gravitating (SG) limit

To compare the exoplanets with the BDs, we combine the mass and radius into one physical parameter: the baryonic gravitational potential (BGP), which is defined as the gravitational potential energy of a body, divided by the number of its nucleons, N. Assuming the mass is $M = Nm_p$, where m_p is the mass of a proton, the BGP is thus equal to:

$$\mathrm{BGP} = \frac{V_G}{N} = \frac{GMm_p}{R} \propto \frac{M}{R} \qquad (1)$$

Note that since the BGP $\propto M/R$, this parameter can be taken as a first order approximation for the MRR.

In Figure 1 (hereafter, the BGP diagram) we compare for the exoplanets (black squares and orange diamonds) and BDs (red solid dots) the BGP and distances from their companion stars, as normalized by the distance of Jupiter from the sun ($\mathrm{D/D_{Jup}}$). The BGP diagram is separated in four zones, synonymous with different physical structures. The upper zone is defined by the lower mass limit of 13 M_J for the burning of deuterium in BDs.

Most of the exoplanets in our sample are Hot Jupiters, which is consistent with the well-known observational biases related to the detection methods. A few exoplanets are located above the deuterium-burning limit, while a few BDs are below this limit, suggesting that the deuterium-burning criterion does not allow a clear distinction between these two objects. Also, as observed by Santerne et al. (2016), many BDs in our sample are found at a distance nearer than Jupiter from the Sun, contradicting the BD's desert hypothesis.

Therefore, although the majority of the exoplanets and BDs occupy different regions in the BGP diagram, their separation in terms of physical structures is still somewhat ambiguous.

Based on the SG limit, we separated the gas-giant exoplanets in Self-Gravitating (SGE; orange diamonds) and non Self-Gravitating (nSGE; black squares). The BGP for the SG limit is defined by a critical mass, M_c, and critical radius, R_c (Padmanabhan, 1993). At the SG limit, the maximum number of baryons that an object can contain, N_{max}, is equal to:

$$N_{max} = (\alpha/\alpha_g)^{3/2} \sim 1.38 \times 10^{54} \qquad (2)$$

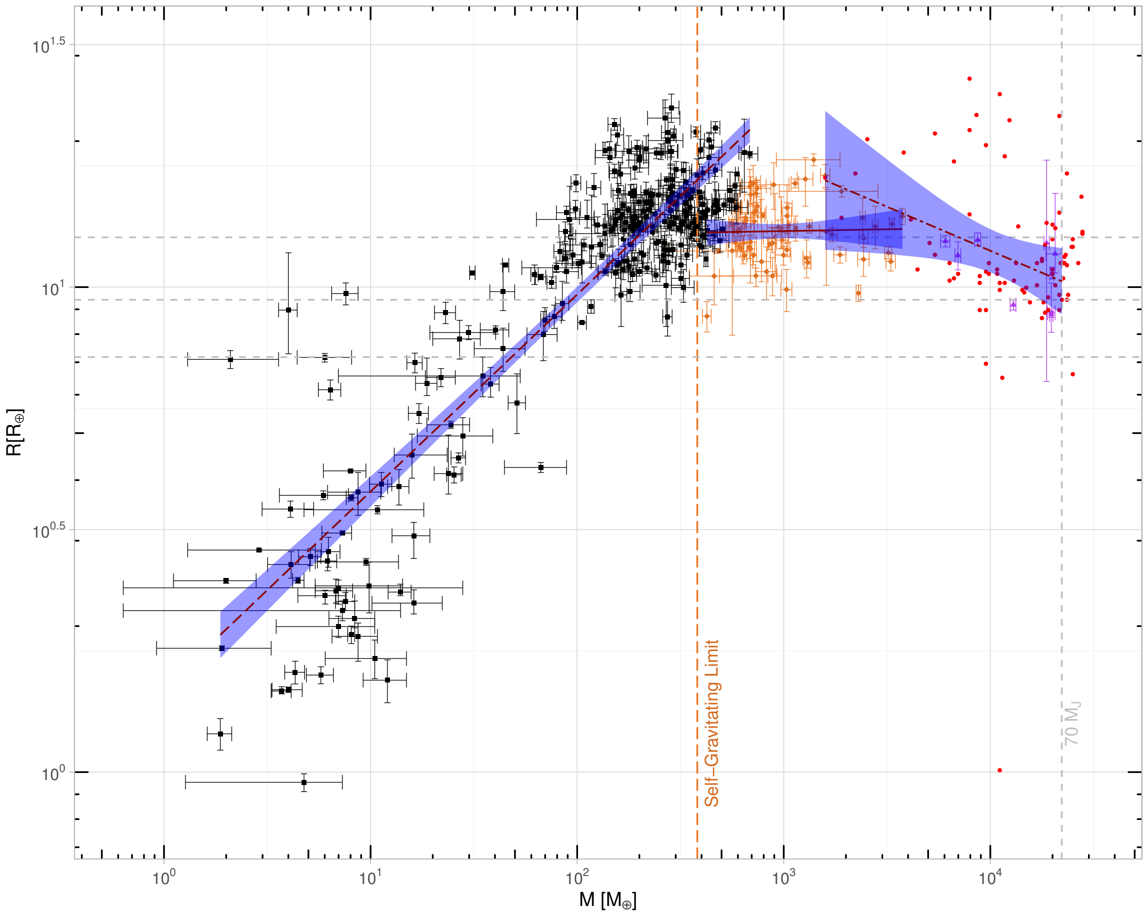

Figure 2: Comparing the MRRs of exoplanets and BDs. The MRRs are traced with their corresponding 95% confidence intervals. The symbols are the same as in Fig. 1. Also shown are the critical mass at the SG limit and the upper mass limit $70M_J$ for BDs.

where α is the fine-structure constant and α_g the equivalent constant for gravity. This corresponds to the critical mass:

$$M_c = N_{max}m_p \sim 2.31 \times 10^{27}\text{kg} \sim 1.2M_J \tag{3}$$

Then, assuming the radius of such object is $R = N_{max}^{1/3}a_0$, where a_0 is the radius of Bohr, we obtain the critical radius:

$$R_c = 6 \times 10^7\text{m} \sim 0.84R_J \tag{4}$$

Note that although both $M_c = 1.2M_J$ and $R_c = 0.84R_J$ are typical values for massive exoplanets, the critical mass is also comparable with the theoretical lowest mass expected for a BD, while the critical radius is consistent with their observed mean radius (Burgasser, 2008; Basri & Brown, 2006; Sorahana, Yamamura & Murakami, 2013).

4 Mass-Radius Relation (MRR)

According to Padmanabhan (1993), the MRRs of bodies with different structures would be expected to change abruptly at the SG limit, from a positive MRR below the SG limit, to a negative one above it, which may help distinguishing between exoplanets and BDs. Indeed, this is what we observe in Figure 2, where we compare the MRRs for the exoplanets and BDs: the nSGEs show a positive MRR while the BDs show a negative one (see Table 1). On the other hand, the SGEs show a relation where the radius does not increase with the mass. Note that this characteristics was also observed by Hatzes & Rauer (2015), although these authors did not offered any physical explanation for this behavior.

Table 1: Linear regression in log, $(R/R_{\oplus}) = 10^b \times (M/M_{\oplus})^a$, and their coefficients of correlation r^2

Sub-samples	**a**	**b**	r^2
nSGE	$+0.41 \pm 0.01$	0.17 ± 0.03	0.785
SGE	$+0.01 \pm 0.03$	1.09 ± 0.10	0.001
BD	-0.18 ± 0.08	1.60 ± 0.33	0.069

For the SGEs, we interpret the radius that shows NO significant change as the mass increases as evidence for the presence of a dominant liquid metallic hydrogen (LMH) envelop (Wigner & Huntington, 1935; Hubbard et al., 1997; Dalladay-Simpson et al., 2016): this is due to the very low compressibility of LMH (Hubbard et al., 1997).

That gas-giant planets, like Jupiter and Saturn in the solar system, have a LMH envelope was suspected by many au-

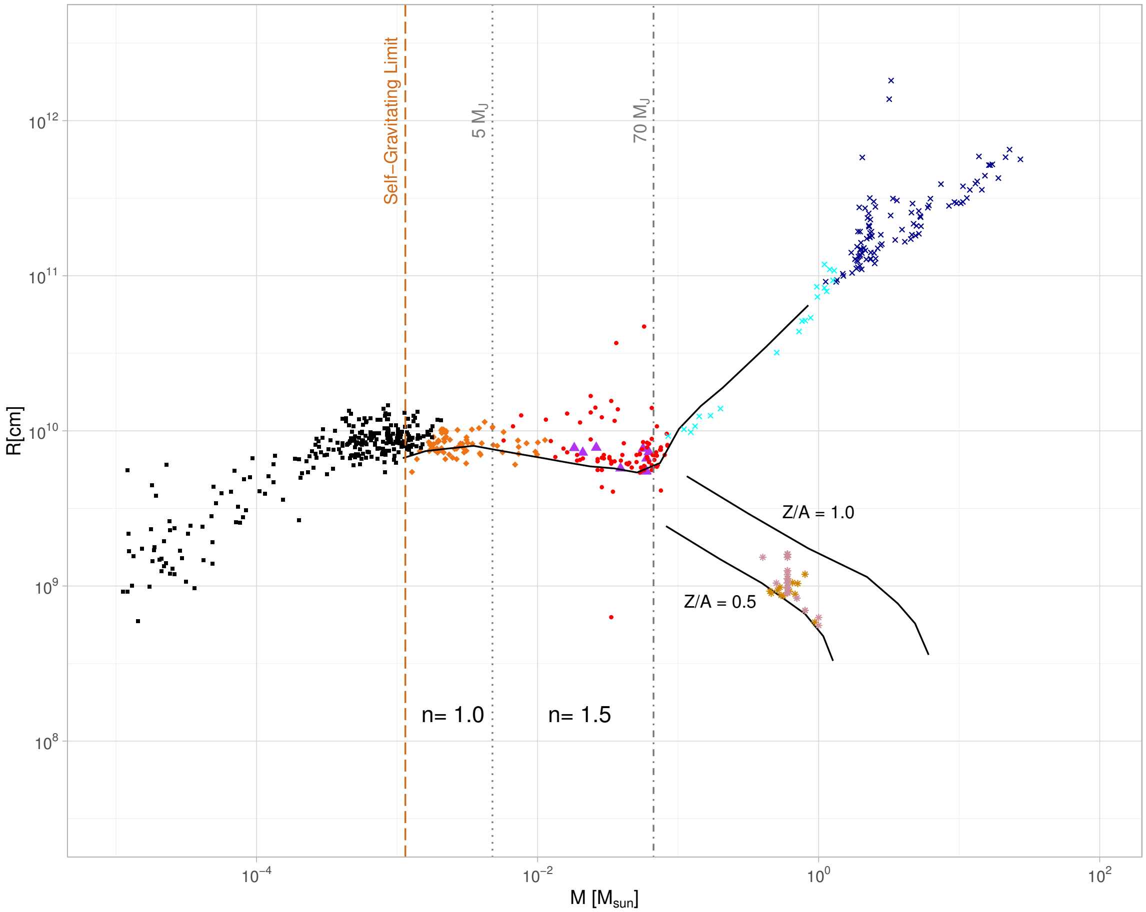

Figure 3: Model of BDs formed of LMH. The unsignificant change of radius of the SGEs is due to a change of the polytropic index, n, below M = 5 M_J from 1.5 to 1.0. Just at the point where the main sequence thermonuclear burning starts, around $70M_J$, there is a bifurcation: the MRR for the very low-mass stars (VLM, in light blue) becoming positive as they evolve towards the main sequence (dark blue x), while the MRR for WDs (white dwarfs, brown squares) is still negative. Two MRR for WDs, with different hydrogen richness (Z/A = 1.0 and Z/A = 1.5), are also represented.

thors since a very long time (see Burrows & Liebert, 1993, and reference therein). But, one would not expect to observe evidence for such envelopes. This is because, although the LMH layer could constitute 50% to 85% of the mass of a gas-giant planet, this layer would generally be hidden below a rich envelope of hydrogen gas. What we think could have happened, therefore, is the following. As the mass of a gas-giant exoplanet increased above the critical mass, M_c, the self-gravity of matter became more important, the pressure increased and most of the hydrogen in the outer gas envelope changed phase, transforming into LMH. Alternatively, since most of these exoplanets are Hot Jupiters with high eccentricities, they might have lost their outer envelop of gas when passing near their stars, revealing their underlying LMH envelopes.

However, based on the LMH interpretation there is still another alternative, which is that above the SG limit, objects are really BDs. In Figure 3 we compare our data with the predictions made by such a model, as developed by Burrows & Liebert (1993). In this model BDs are formed at 99.9% of LMH, this percentage decreasing as the mass of the star decreases, down to the SG limit. Below 5 M_J, the Coulomb correction competes with the degeneracy component, and the polytropic index, n, changes from 1.5 to 1.0, making the radius independent from the mass. Note that, according to this model, even above 5 M_J, when $n = 1.5$ and $R \propto M^{-1/3}$, the dependence of the radius on the mass would be weak, consistent with the low coefficients of correlation we observed.

5 Conclusions

- We conclude that the unsignificant change of radius of exoplanets above the SG limit is the characteristic signature of objects formed by LMH.
- As for the nature of these objects we propose that they could be either giant gas planets with a dominant layer of LMH, more massive than what is assumed to exist in Jupiter and Saturn, or genuine very low-mass BDs.

Acknowledgments

L.M.F.T. acknowledges the “Direción del Campus Guanajuato” (Folio 10040) of the University of Guanajuato, for special support and travel grants. L.M.F.T. and K.-P.S. both acknowledge travel support by the bilateral Conacyt-DAAD PROALMEX programme (No. 207772). C.A.C. thanks finantial support from DAIP's "Convocatoria Institucional" project #627/15. Our study made use of the Johnston's Archive, which is copyrighted by Wm. Robert Johnston. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

References

Batalha, N. M. 2014, Proceedings of the National Academy of Science, 111, 12647
Basri, G., & Brown, M. E. 2006, Annual Review of Earth and Planetary Sciences, 34, 193
Bate, M. R. 2006, in Planet Formation, Cap. 15, pp. 236, Cambridge University Press
Boss, A. P. 1988, ApJ, 331, 370
Burgasser, A. J. 2008, PhT, 61, 70
Burrows, A., & Liebert, J. 1993, Reviews of Modern Physics, 65, 301
Burrows, A., Hubbard, W. B., Lunine, J. I., & Liebert, J. 2001, Reviews of Modern Physics, 73, 719
Cushing, M. C. 2014, ASSL, 401, 113
, Dalladay-Simpson, P., Howie R. T. & Gregoryanz, E. 2016, Nature, 529, 63
Grether, D. & Lineweaver, C. H. 2006, ApJ, 640, 1051
Hatzes, A. P. & Rauer, H. 2015, ApJ, 810, L25
Hubbard, W. B., Guillot, T., Lunine, J. I., Burrows, A., Saumon, D., Marley, M. S. & Freedman, R. S. 1997, PhPl, 4, 2011
Johnson, J. A. 2009, PASP, 21, 309
Johnston, Wm. R. 2015, Johnston's Archive of BDs: http://www.johnstonsarchive.net/astro/browndwarflist.html
Koch, D. G., Borucki, W. J., Basri, G., et al. 2010, ApJL, 713, LL79
Larson, R. B. 1969, MNRAS, 145, 271
Lissauer, J. J. 1993, Planet formation. 1993, ARA&A, 31, 129
Padmanabhan, T. 1993, in Structure Formation in the Universe, Cambridge, UK: Cambridge University Press, pp. 499
Rees, M. J. 1976, MNRAS, 176, 483
Santerne, A., Moutou, C., Tsantaki, M., et al. 2016, A&A, 587, A64
Silk, J. 1977a, ApJ, 214, 718
Silk, J. 1977b, ApJ, 214, 152
Sorahana, S., Yamamura, I., & Murakami, H. 2013, ApJ, 767, 77
Wigner, E. & Huntington, H. B. 1935, J. Chem. Phys. 3, 764
Winn, J. N. 2010, Exoplanets, ed. S. Seager, University of Arizona Press, p55