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The mass-radius relationship from solar-type stars to terrestrial planets: a review

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Abstract. In this review, we summarize our present knowledge of the behaviour of the mass-radius relationship from solar-type stars down to terrestrial planets, across the regime of substellar objects, brown dwarfs and giant planets. Particular attention is paid to the identification of the main physical properties or mechanisms responsible for this behaviour. Indeed, understanding the mechanical structure of an object provides valuable information about its internal structure, composition and heat content as well as its formation history. Although the general description of these properties is reasonably well mastered, disagreement between theory and observation in certain cases points to some missing physics in our present modelling of at least some of these objects. The mass-radius relationship in the overlaping domain between giant planets and low-mass brown dwarfs is shown to represent a powerful diagnostic to distinguish between these two different populations and shows once again that the present IAU distinction between these two populations at a given mass has no valid foundation.

Keywords: stars: fundamental parameters, low-mass, brown dwarfs, formation - Binary: general, close, eclipsing, visual - Stars: planetary systems

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INTRODUCTION

The mass-radius relationship (MRR) of a body in hydrostatic equilibrium at a given time of its evolution is entirely determined by (i) the thermodynamic properties of its internal constituents, (ii) its ability to transport and evacuate its internal entropy content, a consequence of the first and second principles of thermodynamics. In this review, we examine our present understanding of such properties, in the stellar, substellar and planetary domains, respectively, by comparing state-of-the-art theoretical calculations with observational determinations of the MRR.

GENERAL BEHAVIOUR OF THE MASS-RADIUS RELATION

Figure 1 portrays the general behaviour of the MRR from the Sun down to gaseous planets, i.e. over 3 orders of magnitude in mass. The essential physics characteristic of such a behaviour can be grasped with the help of the polytropic mass-radius relation, $R \propto M^{\frac{1-n}{3-n}}$ [10, 15]. The low-mass star (LMS) regime, from the Sun to the hydrogen-burning minimum mass (HBMM) is characterized by an evolution of the polytropic index from a value $n \approx 3$, characteristic of stars with a large radiative core, to n = 3/2 below

 $M \sim 0.4 M_{\odot}$, when the star becomes fully convective. In the stellar regime, both the ions and the electrons obey classical statistical physics, so that the combination of a classical nearly perfect gas equation of state (EOS) and of the quasistatic equilibrium condition yields a $R \propto M$ dependence. As the mass decreases, the density increases and the internal temperature decreases, so that the electrons become degenerate (degeneracy can be characterized by a dimensionless number $\theta = T/T_F$, where $T_F \simeq 3.0 \times 10^5 (\rho/\mu_e)^{2/3}$ K is the electron Fermi temperature, with μ_e the electron mean molecular weight). The onset of degeneracy ($\theta < 1$) corresponds to the bottom of the main sequence and to the brown dwarf (BD) domain. Indeed, BDs are defined as objects not hot enough to sustain hydrogen fusion in their core and thus are supported primarily by electron degeneracy. Densities in the interior of BDs, however, are not large enough for the electrons to be fully degenerate, like in the interior of white dwarfs, where $\theta \le 10^{-2}$. Electrons in BD interiors are only partially degenerate, with $\theta \sim 10^{-1}$ - 10^{-2} . As density decreases with mass in the substellar regime, the electrostatic contribution from the (classical) ions becomes comparable to the (quantum) electrons one. This yields the flattening in the MRR illustrated in Fig.1. This growing ion contribution compared with the electronic one leads to a decreasing polytropic index, from a value $n \sim 3/2$ near the HBMM, where density is highest, to $n \approx 1$ for Jupiter-mass objects. It is easily seen from the above polytropic relationship that for n = 1 the radius does not depend on the mass. Eventually, as the body mass decreases, one reaches the regime of terrestrial planets characterized by homogeneous (constant density) interiors, i.e. incompressible matter, n = 0. The polytropic index n is directly related to the EOS, $P \propto \rho^{\gamma}$, with $\gamma = 1 + 1/n$, and thus to the compressibility $\chi = (\rho \frac{\partial P}{\partial \rho})_T^{-1} = (\gamma \rho^{\gamma})^{-1}$. The decreasing polytropic index when going from nearly perfect gas dominated stellar objects to terrestrial bodies thus corresponds in first approximation (neglecting the density variation with mass) to less and less compressible interiors. We will now examine this general MRR behaviour in the various mass ranges and discuss the agreement between theory and observation.

THE LOW-MASS STAR RANGE

The radii of many LMS have been accurately determined from various techniques. Eclipsing binaries provide the most natural method but include only a limited number of systems below $1 M_{\odot}$ (see [33] for a summary of present observational determinations). Interferometry allows a precise determination of the radii of nearby binaries [47, 6], while transit observations from the OGLE microlensing survey improve significantly the statistics. Comparison between the theoretical and observed radii from the Sun to the hydrogen-burning limit [40] is illustrated in Fig. 1 of [22]. As shown on this figure, the excellent agreement between theory and observation all along the LMS domain for all the stars except the eclipsing binaries gives confidence in the underlying physics used to determine the mechanical structure of these cool and dense objects. Recent determinations [13] have cast doubt on such a general agreement between theory and observation. Note, however, that these results are based on *indirect* determinations, based on emprical T_{eff} -color scales whose accuracy is questioned by some of the authors themselves (Bessell, private communication), and cannot be considered as robust

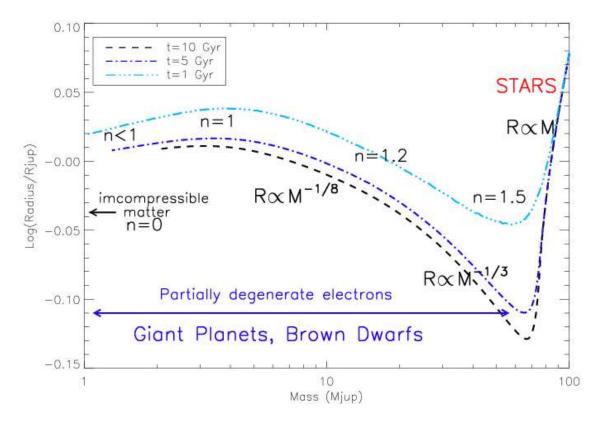


FIGURE 1. Mass-radius relationship from the Sun to Jupiter for three different isochrones. Characteristic values of the polytropic index n are indicated.

as the aforementioned direct radius determinations. The observed radii for the eclipsing binaries, on the other hand, are found to be systematically $\sim 10\%$ larger than all the other observational determinations, and thus disagree with the theoretical values at the same level [52]. Problems with the atmospheric opacity have sometimes been invoked as the source of the discrepancy. As shown in Table 1 of [14], however, opacity has a modest impact on the stellar radius for these compact stars. Changing the metallicity in the atmosphere by a factor 10 (100) affects the radius by a factor $\sim 3\%$ ($\sim 7\%$), so that the opacity of eclipsing binaries should have to be increased to an unrealistic level to yield the observed 10% effect on the radius. Missing opacity thus seems to be unlikely to explain the radius discrepancy. All these eclipsing binaries, however, are fast rotators and are magnetically very active. It is thus natural to imagine that spot area covers a significant fraction of their irradiating surface, possibly with a modest but non-zero temperature constrast. Chabrier et al. (2007) [22] have suggested that inhibition of internal convection, due to rotation and/or magnetic field, and/or spot coverage yields a reduction of the internal heat flux and thus a smaller contraction during evolution, providing an appealing explanation for the larger radius in rapidly rotating, very active stars. The value of the equilibrium field inferred in these (phenomenological) calculations to hamper convection is consistent with the observationally determined value [44] and with the one obtained with 3D resistive MHD simulations [9]. As mentioned above, surface density increases with decreasing mass in the LMS regime, reaching a maximum near the HBMM [15], so that convection becomes more and more efficient with decreasing mass in this regime. The aforementioned decreasing convective efficiency is thus expected to be relatively less and less consequential as one moves along the mass sequence from the Sun to the bottom of the main sequence. Such a behaviour is indeed supported by observations. These very same effects of magnetically driven inhibition of convection and spot coverage are also shown to provide a plausible explanation for the temperature revearsal observed in eclipsing brown dwarfs [51], with the most massive object being more affected by magnetic fields than the smaller one [22]. Interestingly, H_{α} emission has been detected in the primary of this system at a 7 times stronger level than the emission from the secondary [43]. This brings support to the aforementioned scenario.

Activity in low-mass stars is presently a thriving domain of research. The remarkable results recently obtained with spectro-polarimetry [25, 38] have brought evidence for an evolution of the topology of the magnetic field with decreasing mass, ie decreasing effective temperature. Whereas objects above about $0.4M_{\odot}$ exhibit a dominantly toroidal field, objects below this mass are dominated by a poloidal, mainly axisymmetric field, although exhibiting only a very modest level of differential rotation. Although several theoretical calculations have recently suggested various mechanisms to generate largescale magnetic fields in fully convective objects like LMS, based on either mean field theories [19] or MHD simulations [24], none of these theories so far can explain the observational results, in particular the presence of a strong dipolar field in an object with very low level of differential rotation. The recent 3D resistive MHD simulations of Browning (2008) [9], although still retaining some limitations, seem to offer a promising avenue to explore this complex problem. In this review, we speculate that the abrupt change of topology of the field with decreasing mass, and the strong decrease of angular momentum loss rate in the same mass range [44, 45], are both connected with the evolution of the Rossby number in LMS interiors [36, 19]. Indeed, the convective time strongly increases with decreasing mass (i.e. temperature), so that the Rossby number eventually reaches a critical value $Ro \lesssim 0.1$, affecting the magnetic field generation process [25, 38]. Work to explore this issue is presently under progress.

THE PLANETARY REGIME

Extrasolar planets are discovered by radial velocity techniques at an amazing pace. The wealth of discoveries now extends from gaseous giants of several Jupiter masses to objects of a few Earth masses. Detailed models of planet structure and evolution have been computed by different groups [27, 5, 11]. These calculations include various internal compositions, based on presently available high-pressure equations of state for materials typical of planetary interiors. While the models of [27, 11] only consider the impact of heavy material on the hydrostatic structure of the planet and neglect the *thermal* contribution of these elements to the planet's cooling rate, the models of [5] fully consistently account for this contribution. A detailed discussion and a comparison

of these models can be found in Baraffe et al. (2008) [5] ¹. This paper also explores the effect of the location of the heavy element material in the planet, either all gathered at depth as a central core or distributed throughout the gaseous H/He envelope, on the MRR. It is shown that these different possible distributions of heavy element can bear important effects on the planet radius and evolution. Unfortunately, although the average internal composition of the planet can be inferred with these models from the observed mass and radius, present uncertainties in the EOS of the aforementioned heavy elements in the T-P range characteristic of planetary interiors prevent a detailed determination of the internal composition in terms of various heavy element mass fractions. This paper also shows that the presence of even a modest gaseous (H/He) atmosphere hampers as well an accurate determination of the internal composition, as the highly compressible gas contains most of the entropy of the planet and thus governs its cooling and contraction rate.

This is no longer true for so-called Super-Earth or Earth-like planets, ie objects below the expected limit for the planet to retain a gaseous atmosphere by gravitational instability, about 10 Earth-masses [35, 50, 42]. The structure of these "terrestrial planets" has been examined by various groups [54, 46, 49]. For these objects, although uncertainties in the EOS still prevent precise determinations of the internal composition, the lack of a substantial gaseous atmosphere allows a more detailed exploration of the internal composition, opening up the route to accurate determinations of the composition of exo-Earths as high-pressure experiments of the relevant materials become available.

For about 40 of these systems, the planet is transiting its host star, allowing a determination of its radius and thus, in combination with the radial velocity observations, of its mean density. This in turn yields a strong constraint on its average internal composition. Although planetary evolution models taking into account the effect of the incoming stellar flux on the internal planetary heat content successfully reproduce the observed radii in many cases [17, 4, 11, 5], a substantial fraction of these transiting planets exhibit radii larger than the theoretical determination by a significant amount. Several explanations have been suggested to explain this puzzling result. Bodenheimer et al.[7] invoked tidal heating due to an undetected companion, a now excluded possibility for HD 209458 b [31], the most illustrative of these abnormalously large planets. Ongoing tidal heating due to these planets being trapped in Cassini states with large obliquity [56] have been shown to be highly improbable for short-period planets [32]. Showman & Guillot [48] suggested the outer kinetic energy due to the strong stellar irradiation being transported downward and transformed at depth into thermal energy, leading to a hotter isentrope. The identification of a robust mechanism for transporting this energy deep enough, however, is still lacking and an accurate (so far missing) description of the (probably smallscale) dissipative processes in such natural heat engines is mandatory to assess the validity and the importance of this mechanism for hot-Jupiters [28]. Burrows et al.[11] arbitrarily invoke a combined effect of tidal heating, in some cases, and/or strongly enhanced (10 times) atmospheric opacity as a possible explanation. These calculations, however, do not provide any explanation for such a persisting strong metal enrichment in the planet's radiatively stable atmosphere and outer envelope, where gravitational sed-

¹ Models are availble at http://perso.ens-lyon.fr/isabelle.baraffe/PLANET08/

imentation should occur. Moreover, these calculations do not consider any increase of molecular weight due to such a heavy element enrichment in the envelope. Similar calculations by Guillot [29] including consistently the increase of mean molecular weight in the envelope show that, in most cases, such an increase of heavy element abundance in the planet's atmosphere leads to a *smaller* radius. More recently, Chabrier & Baraffe (2007) [21] suggested that the onset of layered or oscillatory convection, due to the presence of an internal compositional gradient, may hamper the internal heat flux transport, slowing down the planet's contraction. Although such layered convection is observed in many situations in Earth lakes or oceans, due to the presence of salt concentrations (the so-called thermohaline convection), it remains unclear whether this process can occur under giant planet interior conditions. Interestingly, although the Showman & Guillot scenario necessarily needs the planet to be strongly irradiated, the Chabrier & Baraffe one does not, even though irradiation does favor the onset of layered convection. The observation of an inflated transiting planet far enough from its parent star for the incident flux to have a negligible effect on the planet's internal heat content would provide a clear demonstration of the validity of the Chabrier & Baraffe scenario. Kepler or Corot will hopefully provide such observational diagnostics.

THE OVERLAPING DOMAIN: FROM PLANETS TO BROWN DWARFS

The distinction between BDs and giant planets has become these days a topic of intense debate. In 2003, the IAU has adopted the deuterium-burning minimum mass, $\sim 10 M_{Jup}$, as the official distinction between the two types of objects. We have discussed this limit in previous reviews [16, 18, 20] and shown that it does not rely on any robust physical ground and is a pure semantic definition. The observation of free floating objects with masses of the order of a few jupiter masses in (low extinction) young clusters [12] shows that star and BD formation extends down to Jupiter-like masses, with a limit set up most likely by the opacity-limited fragmentation, around a few Jupiter-masses [8]. Observations show that young brown dwarfs and stars share the same properties and are consistent with BDs and stars sharing the same formation mechanism [2, 30] (for a recent review see [34]). On the other hand, the fundamentally different mass distribution of exoplanets detected by radial velocity surveys [53] clearly suggests a different formation mechanism, consistent with the so-called core accretion scenario [39, 1]. Consequently, planets are believed to have a substantial enrichment in heavy elements compared with their parent star, as observed for our own solar giant planets, whereas BDs of the same mass should have the same composition as their parent cloud, ie a $Z \sim 2\%$ heavy element mass fraction for a solar environment.

As shown in the previous section, an internal heavy material enrichment yields a smaller radius, for a given mass, and thus the MRR provides in principle a powerful diagnostic to distinguish planets from BDs in their overlaping mass domain. Figure 2 portrays the MRR in the substellar regime, with the observationally determined radii of Hat-P-2b [57] and Corot-3b [23]. These objects provide the first observational constraint in the mass-range between Jupiter-mass planets and the HBMM, where the MRR is predicted to follow the behaviour illustrated in Fig. 1. The first important result is that

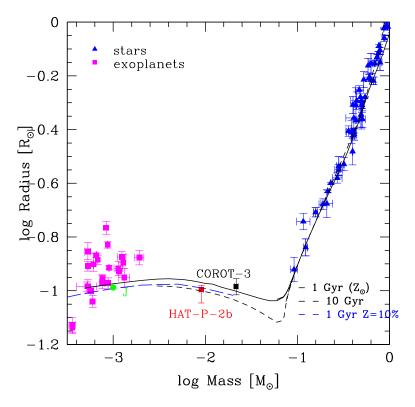


FIGURE 2. Mass-radius relationship from from the stellar to the planetary regime. The (black) solid and short-dash lines correspond to models with solar composition, for two isochrones. The (blue) long-dahs line corresponds to an object with a Z=10% mass fraction of heavy elements (from [5]). The observationally-determined values of Hat-P-2b and Corot-3b are indicated.

the observations do confirm the theroretical predictions, providing confidence in the description of the internal physics characteristic of the cool, dense, partially degenerate objects known as "substellar objects". A detailed composition of Hat-P-2b has been derived in Baraffe et al.(2008) [5]. Models are shown in Fig. 2 for two different internal compositions: one, with a solar abundance of heavy elements, corresponds to solarmetallicity BDs, for two isochrones, whereas the other one, with a 5-times solar metal enrichment, corresponds to massive gaseous planets. Assuming that (i) the theoretical MRR is accurate, (ii) the observational error bars on the radius are reliable, the second important result illustrated in Fig. 2 is that, given the age inferred for the system, $\sim 2-3$ Gyr [3], Hat-P-2b is too dense to be a BD. This in turns shows that planets can form up to at least 9 Jupiter masses, a result of prime importance for constraining models of planet formation. Although such a mass is still compatible with planet formation models based on the core-accretion scenario [37], an alternative possibility for the formation of such high-mass, short-period planets is collisions between less massive planets (see §6 of [5]). Interestingly, although Corot-3b is compatible with this object being a BD with solar composition, for the correct age of the system, ~ 2 Gyr [23], one cannot exclude this object to be a strongly inflated irradiated planet with a massive core. Work is under

CONCLUSION AND PERSPECTIVES

As shown in this review, the non-monotonic behaviour of the mass-radius relationship from the stellar to the planetary regime, through the brown dwarf domain, can be understood qualitatively and quantatively in terms of the physical properties of the ionic and electronic fluids under the appropriate conditions. It is interesting to see that these theoretical predictions have been confirmed by the subsequent observational determinations from the Sun down to the domain of giant planets. The evolution of active objects, both in the stellar and substellar regime, is suggested to differ from the one of non-active objects, as both magnetic field and fast rotation are predicted to affect the internal heat transport and/or escaping flux. A quantitative assessment of this point, however, is still lacking and requires 3D resistive MHD numerical simulations over pressure scale heights characteristic of fully or dominantly convective objects, a formidable challenge. In the same vein, observations have shown that the topology of the magnetic field in LMS interiors varies abruptedly around about $0.4 M_{\odot}$, near the expected transition from centrally radiative to fully convective stars. It is not clear yet what is the main reason for such a strong variation but the Rossby number seems to play a key role in this process.

In the planetary domain, evolution models incorporating EOS for various materials appropriate for planetary interiors, and taking consistently into account the thermodynamic contribution of such materials both on the structure and on the cooling of the planet have become available and provide a reliable diagnostic to infer the internal composition of these planets. Although the presence of a gaseous atmosphere only allows the determination of the planet's gross internal composition, a more detailed balance between the various components can be obtained for terrestrial planets, although solutions remain degenerate. At any rate, all these internal composition determinations provide strong constraints on the formation mechanism for gaseous, icy and terrestrial planets. All these determinations are consistent with the core-accretion model for planet formation. Conversely, the large heavy material enrichment inferred for many of these planets clearly excludes the gravitational instability scenario. The only remaining, although uncertain possibility for this latter is the formation of planets at very large distances (≥ 100 AU), for the disk, assuming it is massive enough, to be cold enough to violate the Toomre stability condition [41, 55] (see [26] for a recent review). The puzzling inflated radius observed for many transiting planets still remains unexplained, and very likely points to some missing physical mechanism in the description of these objects. The expected wealth of transiting planets at large ($\gtrsim\!0.1$ AU) orbital distances from COROT and KE-PLER will hopefully enable us to solve this intriging problem.

The recent observation, by radial velocity and by the COROT mission, of transiting objects around $10\,M_{Jup}$, in the overlaping mass range between planets and brown dwarfs, confirms the theoretical m-R relationship and opens the door to an observational diagnostic to distinguish brown dwarfs and planets and thus to determine, in a foreseable future, the minimum mass for star formation and the maximum mass for planet formation. The theoretical exploration of these observations already suggests that planets

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