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III.6

Exploration of the brown dwarf regime around solar-like stars by CoRoT

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1. Introduction

How shall we classify brown dwarfs? Are they gaseous giant planets as Hatzes & Rauer (2015) suggest, or are they stars as we can find in Trentham et al. (2001), or do they form a separate class of celestial objects in their own right?

Beyond the classification problem, their role is not well understood in planet formation, in evolution of planetary systems, in the chemical and dynamical evolution of the Galaxy; their impact on habitability is not well known both as host objects as well as additional objects in a planetary system; they can have moons whose habitability is not clear; and they are not studied well enough as planet hosts, although they can harbour planets up to about 5 Earth-masses (Payne & Lodato 2007).

When the minimum mass-limit to hold nuclear fusion was investigated some decades ago, it was found that a hydrogen gas sphere over 80 $M_{\rm jup}$ has enough mass to hold nuclear fusion – fusion of hydrogen, helium or heavier elements – for millions to billions of years, so they are called stars; below 13 $M_{\rm jup}$ we find the regime of planetary objects who exhibit no natural fusion at all. Between these limits sit brown dwarfs who fuse deuterium (D) or lithium (Li) to helium-3 and helium-4, respectively, but only for typically ~0.1 Myrs which sounds a very episodic event in their life-cycle because after this phase they simply cool down and contract (Baraffe et al. 2003). Their evolution after this event is quite similar to the contraction of Jupiter-like gas planets. This is not surprising because they consist of mostly hydrogen-forming degenarate electron gas core inside and this structure, of course, resembles the structure of gas giant planets. The modern lower and upper limits for brown dwarfs are 11–16 $M_{\rm jup}$ depending in exact internal chemical composition (Spiegel et al. 2011) and 75–80 $M_{\rm jup}$ (Baraffe et al. 2002), respectively.

The number of known brown dwarfs is over 2200 and more than 400 are in binary systems, the rest are single (Johnston 2015). Only 66 brown dwarfs orbit their host stars on closer orbit than 2 au (65 are listed in Ma & Ge 2014 and we extended their list with CoRoT-33b, see Csizmadia et al. 2015). Only 12 or 13 transiting bona fide brown dwarfs are known (Table III.6.1), depending on how we count the status of KOI-189b whose mass is 78 ± 5 Jupiter-masses, so it is at the brown dwarf – star boundary. There are at least two eclipsing binary systems known in which two brown dwarfs orbit each other (see Table III.6.1). At least one eclipsing binary system is known where a brown dwarf orbits an M-dwarf (NLTT 41135Ab, Irwin et al. 2010). The remaining eclipsing brown dwarfs orbit solar-like stars (defined as main sequence or just slightly evolved FGK stars). For the study of their evolution, internal structure and impacts in the aforementioned issues we need very precise and model-independent mass, radius, luminosity and chemical composition values. Transiting systems can provide mass and radius with good precision and therefore they are important cases.

Here we summarize the contribution of CoRoT to the development of our knowledge of brown dwarfs, especially of those which are in binary systems around solar-like stars.

2. Brown dwarfs found by CoRoT

CoRoT has reported three brown dwarf discoveries. This is comparable to the four brown dwarfs detected by Kepler (see Table III.6.1) since both mission observed about the same number of stars (ca. 150,000) but for different time-intervals (30–150 days vs four years). Notice that the detection bias for Jupiter-sized objects are the same at short periods and in this size-range. Therefore it is not surprising that the derived brown dwarf occurence rates were found similar by both space missions (Csizmadia et al. 2015; Santerne et al. 2015). Hereafter we discuss the individual cases one by one and in the next section we concentrate on the occurence rates.

2.1. CoRoT-3b: the first habitant of the brown dwarf desert

Brown dwarfs, as companion objects in binary systems, exhibit a much smaller occurence rate than stars and planets

Table III.6.1. Basic data of known transiting brown dwarfs. ρ is the mean density of the brown dwarf component. Below the line one can find the questionable systems. Periods are truncated after the third decimal place. This table is an extended and updated version of the one published in Csizmadia et al. (2015) © A&A.

Name	Mag	$M_{star}/M_{\odot}$	$R_{star}/R_{\odot}$	T_{star} [K]	[Fe/H]	P (days)	e	M_{BD}/M_{Jup}	R_{BD}/R_{Jup}	ρ [g/cm^3]	Ref.
2M0535-05a[a]	19.21R					9.779	0.3225 ± 0.0060	56.7 ± 4.8	6.5 ± 0.33	0.26 ± 0.06	1
2M0535-05b[a]						9.779	0.3225 ± 0.0060	35.6 ± 2.8	5.0 ± 0.25	0.35 ± 0.08	1
CoRoT-3b	13.29V	1.37 ± 0.09	1.56 ± 0.09	6740 ± 140	-0.02 ± 0.06^{b}	4.256	0.0	21.66 ± 1.0	1.01 ± 0.07	26.4 ± 5.6	2
CoRoT-15b	15.4R	1.32 ± 0.12	$1.46^{+0.31}_{-0.14}$	6350 ± 200	$+0.1 \pm 0.2$	3.060	0	63.3 ± 4.1	$1.12^{+0.30}_{-0.15}$	59 ± 29	3
CoRoT-33b	14.25R	0.86 ± 0.04	$0.94^{0.14}_{-0.08}$	5225 ± 80	$+0.44 \pm 0.10$	5.819	0.0700 ± 0.0016	$59.0^{+1.8}_{-1.7}$	1.10 ± 0.53	55 ± 27	4
KELT-1b	10.63V	1.335 ± 0.063	$1.471^{+0.045}_{-0.035}$	6516 ± 49	$+0.052 \pm 0.079$	1.217	$0.01^{+0.01}_{-0.007}$	27.38 ± 0.93	$1.116^{+0.038}_{-0.029}$	$24.5^{1.5}_{-2.1}$	5
Kepler-39b[c]	14.43R	$1.10^{+0.07}_{-0.06}$	$1.39^{+0.11}_{-0.10}$	6260 ± 140	-0.29 ± 0.10	21.087	$0.121^{+0.022}_{-0.023}$	$18.00^{+0.93}_{-0.91}$	$1.22^{+0.12}_{-0.10}$	$12.40^{+3.2}_{-2.6}$	6
Kepler-39b[c]		$1.29^{+0.06}_{-0.07}$	1.40 ± 0.10	6350 ± 100	$+0.10 \pm 0.14$	21.087	0.112 ± 0.057	$20.1^{+1.3}_{-1.2}$	$1.24^{+0.09}_{-0.10}$	$13.0^{+3.0}_{-2.2}$	7
KOI-189b[d]	12.29K	0.764 ± 0.051	0.733 ± 0.017	4952 ± 40	-0.07 ± 0.12	30.360	0.2746 ± 0.0037	78.0 ± 3.4	0.998 ± 0.023	97.3 ± 4.1	8
KOI-205b	14.47i	0.925 ± 0.033	0.841 ± 0.020	5237 ± 60	$+0.14 \pm 0.12$	11.720	<0.031	39.9 ± 1.0	0.807 ± 0.022	75.6 ± 5.2	9
KOI-205b		$0.96^{+0.03}_{-0.04}$	0.87 ± 0.020	5400 ± 75	$+0.18 \pm 0.12$	11.720	<0.015	$40.8^{=1.1}_{1.5}$	0.82 ± 0.02	$90.9^{+7.2}_{6.8}$	7
KOI-415b	12.66K	0.94 ± 0.06	$1.15^{+0.15}_{-0.10}$	5810 ± 80	-0.24 ± 0.11	166.788	0.698 ± 0.002	62.14 ± 2.69	$0.79^{+0.12}_{-0.07}$	$157.4^{+51.4}_{-52.3}$	10
LHS 6343C[e]	13.88V	0.370 ± 0.009	0.378 ± 0.008	3130 ± 20	$+0.04 \pm 0.08$	12.713	0.056 ± 0.032	62.7 ± 2.4	0.833 ± 0.021	109 ± 8	11
LHS 6343C[e]		0.381 ± 0.019	0.380 ± 0.007	3431 ± 21	$+0.03 \pm 0.26$	12.713	0.030 ± 0.002	64.6 ± 2.1	0.798 ± 0.014	170 ± 5	17
WASP-30b	11.91V	1.166 ± 0.026	1.295 ± 0.019	6201 ± 97	-0.08 ± 0.10	4.156	0	60.96 ± 0.89	0.889 ± 0.021	107.6 ± 1.1	12
NLTT 41135b	8.44V	$0.188^{0.026}_{0.022}$	0.21 ± 0.015	3230 ± 130	0.0	2.889	n/a	33.7 ± 2.8	$1.13^{+0.27}_{-0.17}$	29^{+23}_{-15}	14
EPIC 2038a[i]						4.451	0.3227 ± 0.0042	23.22 ± 0.47	2.75 ± 0.05	1.38 ± 0.08	18
EPIC 2038b[i]						4.451	0.3227 ± 0.0042	25.79 ± 0.58	2.485 ± 0.004	2.09 ± 0.07	18
1SWASP J1407b[f]	12.4V	0.9	0.99 ± 0.11	4400^{+100}_{-200}	n/a	3725 ± 900	n/a	20 ± 6	n/a	n/a	13
Kepler-27c[g]	n/a	0.65 ± 0.16	0.59 ± 0.15	5400 ± 60	0.41 ± 0.04	31.330	n/a	$<13.8^{h}$	0.44	n/a	15
Kepler-53b[g]	16.0V	0.89	0.98	5858	n/a	18.648	n/a	$<18.41^{h}$	0.26	n/a	16
Kepler-53c[g]	16.0V	0.89	0.98	5858	n/a	38.558	n/a	$<15.74^{h}$	0.28	n/a	16
Kepler-57b[g]	15.5V	0.83	0.73	5145	n/a	5.729	n/a	$<18.86^{h}$	0.195	n/a	16

Notes. [(a)] 2M0535-05 is an extreme young eclipsing system in which two brown dwarfs orbit each other. Identical to V2384 Orionis. [(b)] [M/H] value is reported in the reference. Notice that $[M/H] \approxeq [Fe/H]$; we did not convert the inhomogeneous [Fe/H] to the same scale. [(c)] Aka KOI-423b. [(d)] Díaz et al. (2014) concluded that KOI-189b can be either a high-mass brown dwarf or a very low mass star, too, therefore its status is uncertain. [(e)] the brown dwarf orbits companion A of a binary system, and data of the component A is given here. Star B has $M = 0.30 \pm 0.01 M_{\odot}$, $T_{eff} = 3030 \pm 30$ K (Johnson et al. 2011). [(f)] The host star is young (16 Myr) and surrounded by a multiring-structured (protoplanetary?) disc, see Mamajek et al. (2012). [(g)] Masses are TTV masses, not RV. [(h)] Upper limit. [(i)] Full name is EPIC 203 868 608. Similar system to 2M0535-05: two brown dwarfs orbit each other.

References. 1: Stassun, Mathieu & Valenti (2006); 2M0535-05 2: Deleuil et al. (2008), 3: Bouchy et al. (2011a), 4: Csizmadia et al. (2015) 5: Siverd et al. (2012), 6: Bouchy et al. (2011b), 7: Bonomo et al. (2015), 8: Díaz et al. (2014), 9: Díaz et al. (2013), 10: Moutou et al. (2013), 11: Johnson et al. (2011), 12: Anderson et al. (2011) 13: Kenworthy et al. (2014) 14: Irwin et al. (2010) 15: Steffen et al. (2012) 16: Steffen et al. (2013) 17: Montet et al. (2015) 18: David et al. (2015)

and this is called the "brown dwarf desert". It was found and confirmed by the radial velocity method (Marcy & Butler 2000; Lafrenière et al. 2007; Patel et al. 2007; Wittenmyer et al. 2009; Sahlmann et al. 2011), as well as by adaptive optics direct imaging (Metchev & Hillenbrand 2009).

The discovery of CoRoT-3b definitely means a breakthrough and a significant milestone in brown dwarf research (Deleuil et al. 2008). It was the first object in the brown dwarf desert whose mass and radius were measured from its transiting nature. It was also a surprise because nobody expected the existence of a brown dwarf so close – only 7.8 stellar-radii – to a solar-like star (P_{orb} = 4.26 days) because radial velocity surveys did not detect any similar object before the discovery of CoRoT-3b (only two suspected objects between a minimum mass of 10 and 20 Jupiter-masses were known at that time, see Deleuil et al. 2008). Therefore it was not clear then, that CoRoT-3b is a brown dwarf or a "super-planet". A super-planet could be formed via core-accretion whose mass can be up to 25 $M_{\rm jup}$ without deuterium-burning or such a high-mass object can be formed via collision of several smaller planetesimals or planets (Deleuil et al. 2008 and references therein). The origin of CoRoT-3b is still under debate. Notice that model calculations of Mordasini et al. (2009) predict that high mass planets and brown dwarfs can form up to 40 $M_{\rm jup}$ via core-accretion but none of these objects get closer than 1 au to their host star (cf. Fig. 9 of Mordasini et al. 2009). Although Armitage & Bonnell (2002) proposed a very effective migration process for brown dwarfs, it is questionable that it is really so effective that the majority of them are engulfed by their host stars and this is the cause of the rarity of close-in brown dwarfs. Therefore, if CoRoT-3b ($\sim$22 $M_{\rm jup}$) and NLTT 41135b ($\sim$34 $M_{\rm jup}$) formed via core-accretion, then it is an intriguing question how they moved so close to their host stars.

At the time of the detection of CoRoT-3b, the authors thought that this object confirms the suspicion that "transiting giant planets ($M > 4\ M_{\rm jup}$) can be found preferentially around more massive stars than the Sun" (Deleuil et al. 2008). The discovery of NLTT 41135b, a $\sim 34 M_{\rm jup}$ gaseous giant planet (or a brown dwarf) around an M-dwarf is a remarkable counter-example (Irwin et al. 2010).

2.2. CoRoT-15b, an oversized brown dwarf

CoRoT-15b was the second detected transiting brown dwarf (Bouchy et al. 2011a). Its most exciting feature is its high radius relative to its mass ($1.12^{+0.30}_{-0.15}$ $R_{\rm jup}$, a mass of 63.3 ± 4.1 $M_{\rm jup}$). Notice that brown dwarfs contract slowly until the equilibrium size in most of their lifetime: but at the beginning they can have as large radius as 4–5 Jupiter radii, but at the age of the Universe and at the mass of CoRoT-15b the radius should be around 0.8 Jupiter-radii. The radius-variation is very fast in the first 5 Gyrs (Baraffe et al. 2003). The estimated age of the host star is between 1.14–3.35 Gyr using STAREVOL and 1.9±1.7 Gyr obtained by CESAM. These do not contradict each other but the age is not well constrained – this is a point where PLATO with its well-measured (better than 10%) ages will play a role in the study of brown dwarfs and of planets (Rauer et al. 2014). Therefore Bouchy et al. (2011a) left the question open as to why this brown dwarf has large radius: either the system is young, or cold spots on the brown dwarf surface help to inflate the radius or atmospheric processes blow up it with disequilibrium chemistry. The irradiation effects were found to be negligible in the inflation-process of brown dwarfs.

Interestingly, CoRoT-15b may be a double-synchronous system: the orbital period of the brown dwarf and the rotational period of the star can be equal to each other, but the precision of the rotational period measurement is not enough to make this statement conclusive (Bouchy et al. 2011a). If subsequent investigation can confirm this suspicion, then it seems that tidal interaction between stars and close-in brown dwarfs are strong enough to synchronize their stars or trap it in some resonance. We further discuss this in the light of CoRoT-33b.

2.3. CoRoT-33b, a key object for tidal evolution

This system was reported in Csizmadia et al. (2015). CoRoT-33A could be the presently-known most metal-rich brown dwarf host star because its metallicity is a $[Fe/H] = +0.44 \pm 0.1$ (the other candidate for this title is HAT-P-13A with $[Fe/H] = +0.43 \pm 0.1$, see Bakos et al. 2009).

The host stars of the brown dwarfs in binary systems seem to be metal-poor (Ma & Ge 2014), therefore this system helps to extend the sample to the tails of the distribution.

The host star seems to be older than 4.6 Gyrs and likely it is even older (maybe as old as 11–12 Gyr). The rotation period is too small for a G9V star when we compare it to the braking-mechanisms of the single-star scenarios of Bouvier et al. (1997). The measured $v \sin i$, stellar radius, as well as the observable spot modulation on the light curve show that P_{rot} = 8.95 days. Another interesting feature of CoRoT-33b, whose mass is 59 $M_{\rm jup}$, is its eccentric orbit (e = 0.07). Since the orbital period is just 5.82 d, the circularization time-scale for such a system is much shorter than the age of the system. Even more interestingly, the orbital period of the brown dwarf is within 3% of a 3:2 commensurability with the rotational period of the star.

Béky et al. (2014) listed six hot Jupiters where strange commensurabilities can be observed between the stellar rotational rate and orbital periods of the planetary companions. They also suspected that these are just random coincidences between the stellar rotational period and the planetary companions' orbital periods (maybe a stellar spot at a certain latitude may mimic such a coincidence due to the differential rotation of the star). However, several host stars of brown dwarfs rotate faster – even if we take into account the normal rate for stellar differential rotation – than we expect from their ages, so such random coincidences cannot explain the observed phenomena in star-brown dwarf systems in general. More likely, we see a long-term interaction between the star and the close-in, high mass brown dwarf system. This interaction consists of tidal interaction as well as magnetic braking effects. Such a combination of star – planet/brown dwarf interaction can explain the observed properties – even the eccentric orbit – of CoRoT-33 and other systems. Details of this physical mechanism and the results can be found in Ferraz-Mello et al. (2015).

3. Distance-occurance rate relationship?

The CoRoT data allowed us to determine the relative frequency ratio of brown dwarfs to hot Jupiters in the $P < 10$ days orbital period range. Using the true frequency of hot Jupiters as given in Wright et al. (2012), an $0.20 \pm 0.15\%$ true occurence rate of brown dwarfs was found around solar-like stars for $P < 10$ days (Csizmadia et al. 2015). It is also suspected that this occurence rate follows a power-law up to at least 1000 au orbital separations:

$$f = \alpha \left(\frac{a}{1\mathrm{au}}\right)^{\beta} \tag{1}$$

where f is the occurence rate of brown dwarfs around solar like stars below 1000 au orbital separation and first estimates give, $\alpha = 0.55^{+0.8}_{-0.55}\%$, $\beta = 0.23 \pm 0.06$ (Csizmadia et al. 2015). The occurence rate-separation relationship considers radial velocity, microlensing and direct imaging results, too (see the discussion and references in Csizmadia et al. 2015). Although ground-based transit surveys like HAT, WASP etc. did not report this frequency rate so far, the analysis of Kepler data is fully compatible with the CoRoT-results and also supports the aformentioned relationship (Santerne et al. 2015). The meaning of this possible relationship and its connection to formation theories of planetary systems is not studied yet. However, it is worth mentioning that models by Mordasini et al. (2009) predicted the formation of brown dwarfs via core accretion up to 40 M_{jup} but none of these objects get closer than 1 au according to their Fig. 9. Observational results of CoRoT, Kepler and ground based surveys (Table III.6.1) shows that somehow these brown dwarfs moved inward significantly.

4. Summary and future prospects for transiting brown dwarf hunting

CoRoT detected three transiting brown dwarfs, including the first known such object. All three are very close to their host stars ($P_{\mathrm{orb}} < 10$ days). Two of them (CoRoT-15b and -33b) show interesting commensurabilities between the orbital period of the transiting object and the rotational period of the host star (maybe 1:1 in the case of 15b and a strict 3:2 in the case of 33b). Well-measured masses and first estimates of the radii were reported. CoRoT-33b also has an eccentric orbit and all three objects can be subject of future tidal evolution studies. The occurence rate of brown dwarfs was estimated for the ten days orbital period range and it was found to be $0.2\% \pm 0.15\%$ and this was confirmed by an analysis of the Kepler-data later (Santerne et al. 2015). The presence of such close-in brown dwarfs is a challange for presently known formation theories.

Transiting brown dwarfs are gold-mines for their studies. The mass and radius (hence their mean density) can be measured in a model-independent way for them, and the random and systematic uncertainties of their parameters in such binary systems are dominated mostly by the stellar parameters (in double-lined systems this kind of uncertainty does not appear). This will be improved by the next generation of instruments which will be more sensitive for secondary eclipses and phase curves, like PLATO. Since the age can be measured by isochrone fitting or by asteroseismology in the future (Rauer et al. 2014), the predicted contraction rate of brown dwarfs and thus the theoretical models of them (Baraffe et al. 2003) can be checked.

Although almost a dozen transiting brown dwarfs are known, this is still too small a sample for such studies. Since the size of brown dwarfs is in the Jupiter-sized range or it can be bigger (up to several Jupiter-radii) for young ones, they can easily be detected from ground, too. However, interestingly, several brown dwarfs are grazing transiters (like NLTT 41135b or CoRoT-33b) and that decreases the observed transit depth making the discovery hard from ground. For some yet unkown reason, space observatories detected higher brown dwarf/hot Jupiter ratio than what we can suspect from ground based surveys if we simply divide the number of the observed brown dwarfs by the number of hot Jupiters. It is quite unlikely that space observatories missed hot Jupiters, more probably this may be a selection effect of the ground based surveys.

We foresee several ongoing or planned space missions which are able to detect transiting brown dwarfs, like Gaia (launched 2013), CHEOPS and TESS (to be launched 2017), PLATO (to be launched in 2024). Also, EUCLID (to be launched in 2022) may detect a limited number of microlensing brown dwarfs as a by-product. Gaia is also able to detect brown dwarfs via its primary technique, namely via astrometry.

CHEOPS targets known planets and candidates detected by radial velocity technique (RV). CHEOPS may search for the possible transits of these RV-detected objects which would allow to determine the inclination and hence their true masses instead of a lower mass limit; also, their radius becomes known. One can propose that CHEOPS may extend its program by checking the possible transits of RV-detected brown dwarf candidates.

There also are several ongoing ground-based surveys which are able to find transiting (NGTS, WASP, HAT, for instance) or microlensing brown dwarfs. However, the low efficiency or observational biases of ground based survey are hard to understand and requires further study and a careful check of the existing data for undetected brown dwarfs. The same is to apply to space-based observatories' data.

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