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Follow-up of transiting brown dwarf companions identified with Gaia

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Abstract. Transiting brown dwarfs (BD) have been discovered these last years thanks to radial velocity follow-up of transiting exoplanet candidates identified mainly by the space photometric surveys CoRoT and Kepler. GAIA will discover BD companions orbiting bright stars both by astrometry and by radial velocity. Some of them, especially those at short orbital period and those with low orbital inclination, will have a significant probability to transit their host stars. Complementary ground based observations will permit to identify transiting brown dwarfs and to derive their mass, radius, eccentricity, obliquity, density as well as albedo.

Key words. brown dwarfs - binaries: eclipsing - planetary systems

1. Introduction

Transiting brown dwarf companions have been discovered these last years as a by-product of the radial velocity follow-up of transiting exoplanet candidates detected by ground-based photometric surveys and mainly by the space missions CoRoT and Kepler. With a typical size in the range 0.7 - 1.3 Jupiter radius, they occupy the mass range between the heaviest exoplanet around 13 M_{Jup} and the lightest stars, with an upper limit around 80 M_{Jup}. The properties of known transiting BDs are listed in Table 1 and displayed in the mass-radius diagram in Figure 1 with some massive exoplanets and low-mass stars.

The paucity of this population is illustrated by the fact that only 9 transiting BDs are published so far compared to almost 170 known transiting giant planets with mass determination. Although the occurrence of BD companions is estimated to 0.6% (Sahlmann et al. 2011), most of them are located at large orbital distance to their host star. Short-period BD companions seem to be 20 times less frequent than Hot Jupiters. With an occurrence rate of about 1% for Hot Jupiters orbiting solar-type stars (Mayor et al. 2011, Wright et al. 2012), the occurrence of short-period BD companions of solar-type stars should be close to only 0.05%.

The lack of short-period BDs (P ≤ 10 days) orbiting G-type stars was discussed by Bouchy et al. (2011b) who suggest that such objects may survive when orbiting close to F-dwarfs, but not when close to G-dwarfs. This could be because around G-dwarfs, the star would rapidly spin down and tidal interactions would lead to a migration and eventual engulfment of its companion. In contrast, around F-dwarfs, because of their small or absent convective

Table 1. Properties of known transiting brown dwarfs

Brown Dwarf	Mass [Mjup]	Radius [Rjup]	Period [days]	Host star Teff [K]	Reference
KOI-423b	18.2	1.22	21.09	6260	Bouchy et al. (2011b)
CoRoT-3b	21.8	1.01	4.26	6740	Deleuil et al. (2008)
KELT-1b	27.4	1.12	1.22	6520	Siverd et al. (2012)
KOI-205b	39.9	0.81	11.72	5240	Diaz et al. (2013)
WASP-30b	62.5	0.95	4.16	6200	Anderson et al. (2011)
KOI-415b	62.1	0.79	166.8	5810	Moutou et al. (2013)
LHC-6343C	62.7	0.83	12.7	3030	Johnson et al. (2011)
CoRoT-15b	63.3	1.12	3.06	6350	Bouchy et al. (2011a)
KOI-189b	78.0	0.99	30.36	4850	Diaz et al. submitted

zone, the much weaker braking will avoid the loss of angular momentum and the radii decay of the companion's orbit. However, Diaz et al. (2013) show that the BD KOI-205b orbiting a K-type dwarf is found to be able to evolve towards a stable configuration.

The minimum mass distribution of BD companions found by radial velocity surveys was discussed by Sahlmann et al. (2011). The authors show that the mass distribution function rises below 25 M_{Jup}, which may represent the high-mass tail of the planetary distribution, and presents a peak around 60 M_{Jup}. The mass distribution of transiting BD companions, although based on a limited number of objects, is compatible with this behavior.

The comparison of measured mass and radius of BDs with values predicted by isochrones for models of isolated BDs was discussed by Moutou et al. (2013). A better determination of BDs radius with uncertainties of only few % is clearly requested, which motivates a focus on brighter host stars.

The interests of transiting BDs are multiple. They clearly are the link between massive exoplanets and low-mass stars. Their mass-radius relationship are crucial to constraint their internal structure and evolutionary model. Their metallicity and age could be derived from their host star. Their orbital eccentricity, spin-orbit obliquity and relationship with the rotation velocity of their host stars could be used to investigate their dynamical evolution. From the secondary transit, their albedo and effective temperature could be estimated.

2. Brown dwarf companions from GAIA

We investigate the capability of GAIA to detect transiting brown dwarfs orbiting bright targets with magnitude $G \leq 12$ where a detailed and precise characterization of the system should be expected.

Detection of transiting Jupiter-size companion using the GAIA low-cadence photometry is discussed by Dzigan & Zucker (2012). Such approach will be restricted to very-short orbital period ($P \leq 3$ days). It will required additional ground-based photometric follow-up with directed strategy and it will certainly be affected by the stellar activity. According to the Figure 3 of Dzigan & Zucker (2012) less than 50 giant planet candidates are expected up to G=12 which means that only few transiting BDs will be found through the GAIA photometry.

GAIA Radial Velocity Spectrometer, with an expected precision of 1 $\mathrm{km\,s^{-1}}$, and GAIA astrometry, with an expected precision better than 30 μas for bright targets, will find plenty of BD companions with orbital distances up to 3 AU. According to Robin et al. (2012), 3.4 million main-sequence and subgiant stars will be monitored by GAIA up to G=12. Considering the occurrence rate of BDs

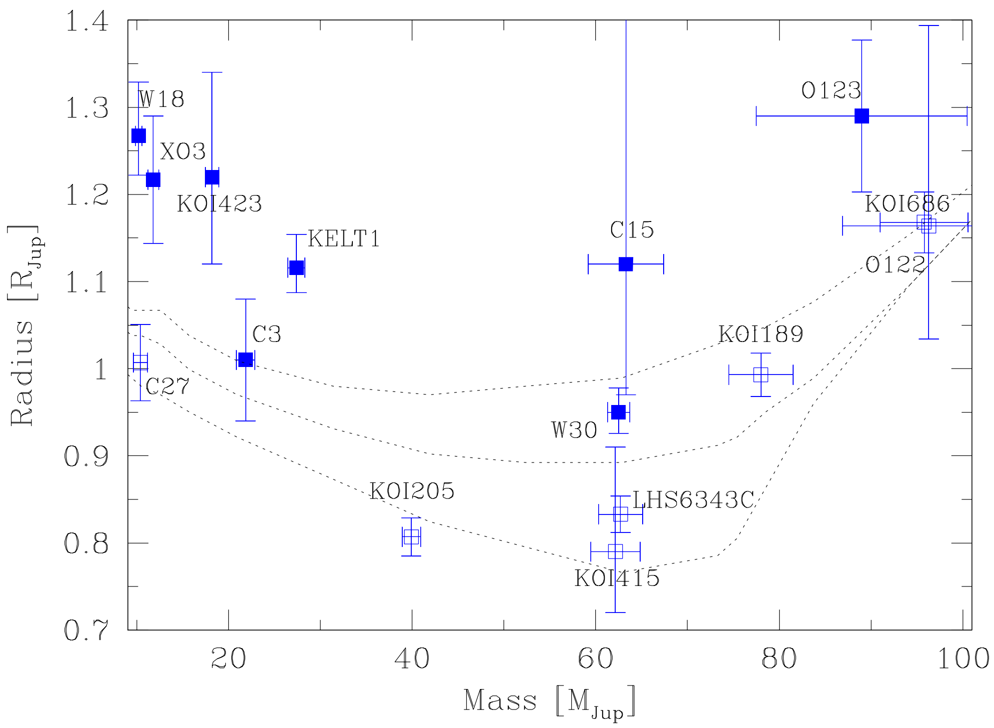

Fig. 1. Mass-radius diagram of known transiting brow-dwarfs including massive transiting planets (M ≥ 10 M_{Jup}) and eclipsing low-mass stars. Open symbols correspond to host stars with T_{eff} ≤ 6000 K. Dotted lines correspond to theoretical isochrones with ages 0.5, 1, and 5 Gyr (from top to bottom) from Baraffe et al. (2003). Letters C, O, W correspond to CoRoT, OGLE and SWASP respectively.

(0.6%), one should expect the identification of 20'000 BD companions with the combination of astrometry and radial velocity GAIA measurements.

3. Follow-up observations of brown dwarf companions identified with GAIA

A rough estimation of transit probability assuming a flat period distribution of these 20'000 expected BD companions orbiting bright (G ≤ 12) solar-type stars gives a total of about 60 transiting BDs. Additional ground-based radial velocities with precision of few $m\,s^{-1}$ will permit to revise and to significantly improve the orbital parameters and ephemeris. Existing facilities like CORALIE, SOPHIE or FIES on 2-m class telescopes will be fully adapted for such measurements. As a by-product of radial velocity measurements, high-S/N high-resolution spectra will permit to derive the parameters of host stars.

The goal will then to select BD companions with the highest inclination (i close to 90°) providing a high probability to transit their host star. Figure 2 illustrates the transit probability of a companion located at an stellar-radius normalized orbital distance a/R for no knowledge of the inclination and for estimated inclination of 90±1, 90±2, 90±5 and 85±5 degrees assuming a normal distribution of errors.

High precision (mmag) photometry will permit to detect the potential transit at the expected transit epoch and to determine the BD radius. Existing facilities like

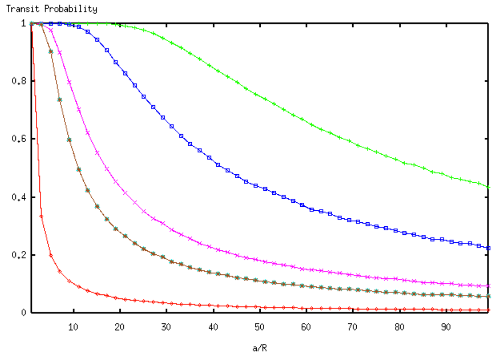

Fig. 2. Transit probability of a companion as function of its stellar-radius normalized distance (a/R). The curves from top to bottom correspond to orbital inclination of 90±1, 90±2, 90±5, 85±5 degrees and unknown inclination.

Trappist, IRIS, Euler, or APACHE will be fully adapted for such follow-up observations. Complementary space-based observations with CHEOPS (ESA) may also be considered for high precision photometry to derive radius with accuracy down to only few % and/or to detect the secondary transit to probe the albedo.

Transit spectroscopic observations of confirmed transiting BDs should also be considered to derive the spin-orbit obliquity through the Rossiter-McLaughlin effect.

4. Conclusions

On-going transit surveys from ground or from space only probe the short-period population of brown-dwarfs. The combination of GAIA and complementary ground-based radial velocities and mmag photometry will be the only way to catch long-period non-irradiated transiting BDs. Several tens of transiting BDs are expected on bright solar-type stars (G $\leq$ 12) and several hundreds if we extend up to G=15. The combined observations will permit to derive mass, radius, metallicity (from the host star), eccentricity, orbital period, spin-orbit inclination, age (from the host star), and albedo (from the secondary transit) of brown dwarfs. All these parameters, derived for a significant sample of brown dwarfs, will allow to probe BDs formation and evolution mechanisms and to compare them with the population of giant planets and low mass stars. Follow-up activities should be coordinated and should be started as soon as GAIA will release the first orbital solutions of non-single stars.

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