Mem. S.A.It. Vol. 84, 1013

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Brown dwarfs or planets?

Some direct imaging detections that blur the border

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Abstract. We have been conducting an adaptive optic imaging survey to search for planetary-mass companions of young M dwarfs in the solar neigbourhood, in order to probe different initial conditions of planetary formation. We report here the direct-imaging discovery of 2MASS J01033563- 5515561(AB)b, a 12-14 $M_{\rm Jup}$ companion at a projected separation of 84 AU from a pair of young late-M stars, with which it shares proper motion. This young L-type object at the planet/brown dwarf mass boundary is the first ever imaged around a binary system at a separation compatible with formation in a disc.

Key words. Brown Dwarfs – Planets – Adaptive Optics

1. Introduction

The discovery of hundreds of extrasolar planets in the last 20 years has radically modified our understanding of planetary formation. Though radial velocity and transit detection methods have proven by far the most prolific, the few planetary-mass companions which have been discovered by direct imaging have provided very challenging constraints for formations models, especially the core-accretion model (Pollack et al. 1996) that is preferred to explain the formation of Solar System planets. 2M1207B, discovered by Chauvin et al. (2004), with a mass-ratio of 20-25% is too massive with respect to its primary to have formed by core accretion, while most of HR8799 (Marois et al. 2008) would be very difficult to form in situ by core-accretion. Only β-Pictoris b (Lagrange et al. 2010) fits relatively well with the core-accretion scenario. Also, several imaged substellar companions (e.g. Chauvin et al. 2005; Lafrenière et al. 2008; Carson et al. 2013) straddle the arbitrary -and debated- 13 $M_{\rm Jup}$ planet/brown dwarf boundary. For most of these massive planets (or light brown dwarfs) the formation mechanism, stellar or planetar, is still debated (Luhman et al. 2006; Bate 2009; Rafikov 2011; Boss 2011; Stamatellos et al. 2011). The discovery of a possibly vast population of free-floating planets (Lucas & Roche 2000; Zapatero Osorio et al. 2000; Sumi et al. 2011; Kirkpatrick et al. 2012) has furthermore blurred the debate on what is a planet.

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2. An adaptive optic survey for planets and brown dwarfs around M dwarfs

Using NACO at VLT-UT4, we conducted L'-band adaptive optics observations of 56 nearby (d<50 pc) young M dwarfs belonging to known young moving groups aged between 8 and 120 Myrs. Depending on each target, the exposure time ranged from 30 to 90 minutes and observations were carried-out as close as possible from the meridian transit. This maximised the parallactic rotation of each target and therefore improved the impact of Angular Differential Imaging (hereafter ADI, Marois et al. 2006; Lafrenière et al. 2007; Lagrange et al. 2010) PSF subtraction techniques. After reduction of the data and ADI analysis of all targets (see Delorme et al. 2012, for details), our survey is typically sensitive to planets more massive than 1-2 Jupiter mass for separations ranging between 20 and 200 AU.

3. Hints of a distinct population of very massive planets and low mass brown dwarfs ?

While our survey was sensitive to planets below 5 $M_{\rm Jup}$, no such planet was found around any of our 56 targets. However we found 3 bound companions with masses ranging between 5 and ~20 $M_{\rm Jup}$ (2M1207B, 2M0103(AB)b, and another one (Gagné et al., in preparation) in the same sample. Though relying on small number statistics, it is important to note that we found no lighter planets or heavier brown dwarfs, even though we were sensitive to such objects.

Figure 2 shows that while such a trend is not seen for radial velocity and transits surveys, for which lighter planets are much more more numerous than very massive ones, a similar trend of a relatively flat distribution in mass from ~5 to ~20 $M_{\rm Jup}$ is visible for other directly imaged companions. Given the many observational and selection biases of combining the results of various direct imaging surveys it is difficult to draw quantitative conclusions. Some biases would hide any overdensity of imaged companions in the ~5 to ~20 $M_{\rm Jup}$ mass range (e.g, because massive candidate companions are not followed-up nearly as thoroughly as lighter ones, comfortably in the nominal planetary mass range), while other would enhance it (notably because some of the imaging surveys that found objects shown in Fig. 2 have sensitivity limits as high as 5 $M_{\rm Jup}$ which could artificially minimise the number of lighter planets). However the flat distribution in masses of imaged planets (11 objects in the 6-12 $M_{\rm Jup}$ range, 10 objects in the 12-18$M_{\rm Jup}$ range) from ~6 to ~20 $M_{\rm Jup}$, where survey sensitivity is close to 100%, stands in contrast to the sharp increase in the density of short separation planets (69 objects in the 6-12 $M_{\rm Jup}$ range, 16 objects in the 12-18 $M_{\rm Jup}$ range). If we could neglect the numerous biases of this rough comparison, and assume poissonian noise, this would be a more than 5σ difference. We do not claim such a significance, but this certainly hints toward the existence of a bump in the stellar/planetary mass function right where they intersect. Since the intersection of 2 distributions tails cannot create a bump in the numbers of observed objects, but only a flat valley, this also hints that there could be a third formation mechanism (and a third mass function associated, beyond the planetary and the stellar mass function) which would account for an overdensity of very massive giant planets and very low mass brown dwarfs.

4. How to form a very massive planet around a late-type binary star system ?

2MASS0103(AB)b has a companion mass to host system mass ratio of ~0.036, which is too low to match known low mass multiple systems (Allen et al. 2007), but still higher than most star-planet systems confirmed so far. This mass ratio is very close to those of DH Tau B (8-22 $M_{\rm Jup}$, separation of 330 AU) and CHXR 73b (7-20 $M_{\rm Jup}$, separation of 210 AU) (Itoh et al. 2005; Luhman et al. 2006), but its projected separation is much smaller. Luhman et al. (2006) state that

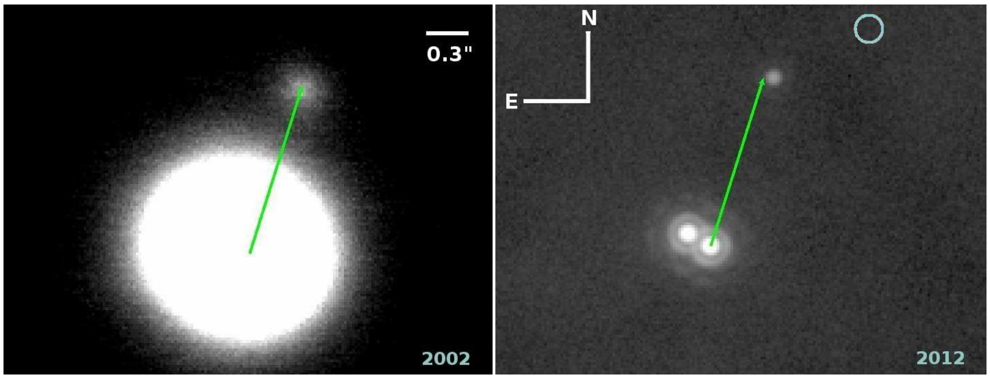

Fig. 1. Left: 2MASS0103(AB)b in October 2002, with NACO in H-band. Right: 2MASS0103(AB)b in November 2012, with NACO in L' band. The arrow shows the position of the companion in 2002. The circle identifies the expected position of the companion if it had been a background source. Note the host binary was also resolved in 2002, in H-band, but this is not visible because of the intensity scale used.

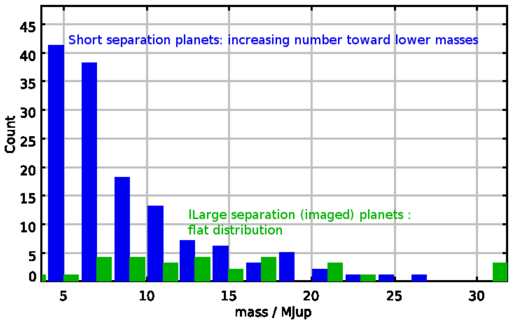

Fig. 2. Mass histogram of known exoplanets from exoplanet.eu catalog(Schneider et al. 2011). In [green] gray are the directly imaged planets (large separation) and in [blue] black are the transit and radial velocity planets (short separation).

neither DH Tau B nor CHXR 73b could be formed in situ by core-accretion or disc instability because of the very large separation from their host stars, and the same holds for the 1100 AU candidate companion to SR12AB (Kuzuhara et al. 2011). The case is different for 2MASS0103(AB)b, at a separation of only 84 AU. At such separations, a formation in a gravitationally instable primordial circumbinary disk would be fully compatible with planetary formation by gravitational instabilities, as described by Boss (2011). However, this scenario is discussed in the literature: Dodson-Robinson et al. (2009) claim that objects formed by disc instabilities around M-dwarfs should have ~10% of the mass of the host system meaning that 2MASS0103(AB)b would not be massive enough for such a scenario, while other studies (Rafikov 2009; Stamatellos et al. 2011) find that such low-mass discs cannot fragment at all. Vorobyov (2013) finds that low-mass stars discs do fragment but that all fragments are ejected or accreted, therefore forming no bound companion. Simultaneous formation and ejection of the 3 components in the massive disc of a more massive original host star is plausible, in a scenario akin to what is described in Stamatellos & Whitworth (2009), but the central binary components, with masses of 0.17 and 0.19 $M_\odot$ are more massive than most objects formed in their simulations.

A planetary formation scenario by core-accretion (e.g. Kennedy & Kenyon 2008; Mordasini et al. 2009; Rafikov 2011) can very probably be excluded for several reasons. First, the separation is too large for a formation in situ. Second, the companion has ~3.6% of the mass of its host system, which is of the order of magnitude of the maximum total mass of the protoplanetary disc from which core-accretion planets are formed. Finally, such a 12-14 $M_{\rm Jup}$ companion would be a very rare occurrence, according to the core-accretion planetary mass function derived by Mordasini et al. (2012).

A purely stellar formation mode by turbulent core fragmentation (see e.g. Padoan & Nordlund 2002; Bate 2009; Hennebelle & Chabrier 2011) is plausible, and in this case 2MASS0103(AB)b would be an extreme case of hierarchical triple stellar with a third component in the 12-14 $M_{\rm Jup}$ mass range. However, a stellar formation scenario would necessitate that cores can naturally fragment into such low mass objects, without requiring any ejection from the the accretion reservoir (such as described in Reipurth & Clarke 2001; Bate & Bonnell 2005), because it would be difficult to starve the accretion of the third component without also stopping accretion on the central binary. From hydrodynamical simulations of stellar formation by cloud fragmentation, Bate (2012) claims that "brown dwarfs with masses $<15\,M_{\rm Jup}$ should be very rare", implying that formation by direct core fragmentation of a 12-14 $M_{\rm Jup}$ object such as 2MASS0103(AB)b would be possible but uncommon. In any case, the discovery of 2MASS0103(AB)b brings most current stellar and planetary formation theories to their limits while others, such as core-accretion, can probably be excluded. The very existence of such a peculiar system therefore provides a very valuable test case against which current and future stellar and planetary formation theoretical models can be tested.

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