The direct imaging of planet and Brown Dwarf candidates

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Proper characterization of exoplanet and brown dwarf candidates discovered with radial velocities and timing variation methods is nearly impossible due to limited information delivered by the two methods. In this short review we present how they can be supplemented by direct imaging, and what advantages are brought by such a combination of observational data.

1 Introduction

Radial velocities (RV) and timing variations (TV) are two exoplanet detection methods that brought the first discoveries in the field. They offer the longest time span of observations, reaching several decades. They both, however, are fairly limited, as they rely on an indirect approach – recording the orbital motion of the host around the center of mass common with the companion, and only in one (radial) direction. This restriction in information about the companion's orbit causes that we only know the lower limit of its mass $M\sin(i)$ (where i is the orbit's inclination angle) not the true value of M. This means that the planetary or brown dwarf (BD) candidates we observe may not be true planets or BDs at all. Information on the inclination, or the other data that may help constrain the mass, are therefore required.

2 Characteristics of the detection methods

Both RV and TV are similar, in the sense that they are indirect detection methods that give the information in the radial direction (velocity and position, respectively) about the dynamical mass of the planet or BD. They are closely related, as the velocity v is a time derivative of the timing variation τ: $v = c\dot{\tau}$, where c is the speed of light. Both methods are more sensitive to massive companions to lower mass hosts. The RVs are, however, better suited for short-period orbits (larger velocity variation), while TV works better in long-period cases (larger position variation). High-precision RV observations started in the 80's, so the available time span of observations is not always sufficient to detect bodies with periods longer than $\sim$20-30 yr. Sufficient TVs data were available earlier, and, in favorable cases, the time span exceeds 50 yr. There are, however, cases of stellar-mass companions detected in both ways.

Each method also has it's own problems and variety of phenomena that can mimic signals from a companion. Presence of (evolving) spots or pulsations may produce an RV variation of period and amplitude that could be interpreted as caused by a planet. Evolution of spots can also induce a periodicity in TVs of eclipsing binaries. Other possible sources of a non-planetary, periodic TVs include (but are not limited to) the Applegate mechanism or mass transfer.

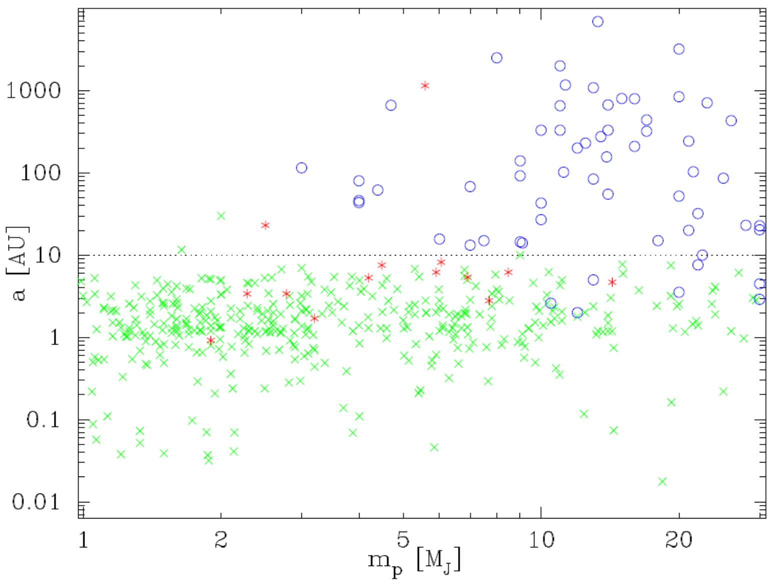

Fig. 1: Planet candidates discovered with the RV (green crosses), TV (red asterisks), and imaging techniques (blue circles) on the mass-separation plane. The dotted line at 10 AU marks an arbitrary border between discovery spaces of each technique. Blue points below annotthis line are components of double-brown-dwarf systems. The point at $\sim 20\,M_J$ and 10 AU is HD 206893 b – a low-mass companion at the smallest separation from a normal star found to date with the imaging method.

The imaging method is substantially different. It works best for relatively bright objects, seen relatively far from the host, so the best targets to look for are young, nearby stars. Multiple detections are required to confirm if the companion is gravitationally bounded to the host, and to put any constraints on the orbit. However, the orbits usually have periods much longer than the time span of observations, and, with very few exceptions, it is impossible to obtain the orbital parameters reliably from this method only. The mass of the companion is inferred from its brightness and age, therefore bases on the models that are used. Nevertheless, when astrometric data are collected, and once the observations cover sufficient part of the orbit, the inclination and size of the orbit can be estimated. Also, in case of no detection, it is possible to put upper limits on the companion's brightness (as a function of the angular distance from the star), and therefore on its mass. Lack of the detection may also indicate that there is another explanation for the observed RV or TV variations.

2.1 The discovery spaces

The facts that time span of RV or TV observations is limited to few decades (at best), and that our imaging instrumentation does not reach sufficiently low separations with sufficiently good contrast, means that the discovery spaces of RV/TV and imaging started to overlap only very recently. In Fig. 1 we show planet candidates discovered with the techniques in question[1], with masses larger than $1\,\mathrm{M_J}$, on a mass M vs. major semi-axis a plane. One can see that there is a strong cut-off around $a = 10$ AU – very few RV/TV candidates are located above, and timing candidates below that line are all in double-brown-dwarf systems, not companions with normal stars. The lowest-separation companion, located at exactly 10 AU is HD 206893 b, announced only in 2017 (Milli et al., 2017). However, the separation from RV/TV observations is only the lower limit $a\sin(i)$, and the true a can be much larger for small i. This means that the imaging method is capable of disproving the candidates currently, by showing that the companion is a much more massive body, on a much larger separation orbit than given by the lower limits by other methods.

2.2 The combination of RV/TV with imaging

In principle, the combination of *radial* (from RV or TV) and relative astrometric[2] measurements (from direct imaging, astrometry, interferometry) gives complete set of orbital parameters and hence dynamical masses of components. Information about inclinations brakes the degeneracy of i with M and a i.e. $M\sin(i)$ and $a\sin(i)$. The comparison of the angular (measured) size of the orbit with its physical size (from Kepler's 3rd law, for example), directly gives the distance to the system, and allows for calculation of absolute magnitudes of the components. Such an approach has been used for decades for stellar binaries. Because the orbital period may be very long, obtaining i only from relative astrometry may be very difficult, therefore it is preferable to look for the orbital solution on the combined radial and astrometric data simultaneously. Such a way also ensures that various uncertainties are properly taken into account, and some parameters (e.g. distance, host's mass) do not have to be assumed during the fitting process.

3 Examples

3.1 RV trends

A very distant companion will first manifest itself in RV measurements by causing a linear or nearly-linear trend. This already allows to put some weak constraints on the character of the companion. Stars with RV trends were subject of several recent imaging surveys (Crepp et al., 2012b, 2014; Hagelberg et al., 2016; Ryu et al., 2016) including cases when a substantial curvature in RVs has been observed (Crepp et al., 2012a,b), but time coverage was insufficient to securely constrain the orbital period P. Notably, without sufficient time coverage, P is degenerated with eccentricity e, and can easily be underestimated, which leads to underestimation of the companion's minimum mass $M\sin(i)$ (Hełminiak et al., 2016).

[1] From `http://exoplanet.eu`. This repository includes low-mass BDs with large mass uncertainty as planet candidates.

[2] Here, astrometry means position of the companion relatively to the host, not the host on the sky relatively to other (background) objects.

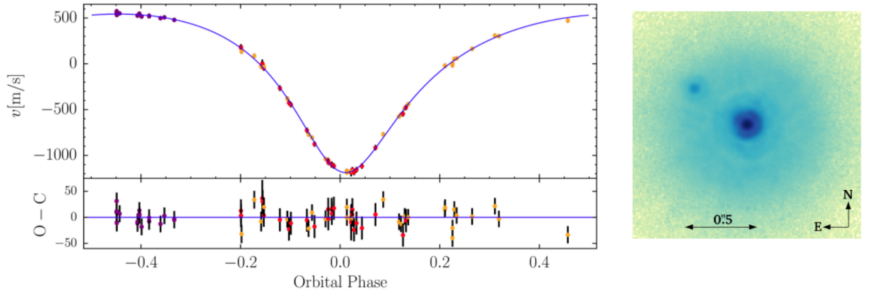

Fig. 2: RV curve (left) and direct imaging observations (right) of V450 And. The companion is clearly seen NE from the host (from Hełminiak et al., 2016).

3.2 Nearly full RV orbits

Discovered with RVs in 2009 independently by two groups (Bouchy et al., 2009; Sato et al., 2009) HD 16760 b was thought to be a 13-14 M_J object. Measurements spanned several full orbits, thanks to a relatively short period (~ 1.28 yr). Almost at the same time, the companion has been directly detected with sparse aperture masking technique, and a full binary solution was published (Evans et al., 2012). The astrometric data were, however, not fitted simultaneously with RVs, but some parameters have been assumed. Nevertheless, the inclination of the orbit was (securely) found to be very low – 2.6° – and the true mass of the companion was estimated to be 0.28 $M_\odot$, making it an M-dwarf, rather than a massive planet.

Crepp et al. (2016) presented a simultaneous RV+astrometric analysis of HD 4747. The companion is most likely a massive brown dwarf on a 38 yr orbit, of which the RV data cover 47% of the orbit, including passage through pericenter. Astrometry suggests inclination of 66.8°, which does not drastically change the true companion's mass from its lower limit: 60.2 vs. 55.3 M_J. This solution seems to be quite secure, but still may be hampered by the RV data coverage, and further confirmation is still required. Notably, even though the RV and astrometric data were fitted simultaneously, the mass of the host has been assumed.

Finally, V450 And b was first postulated to be a $M\sin(i) = 52\,M_J$ brown dwarf on a 8.2 yr orbit (Perrier et al., 2003), but the coverage of the orbital period was poor. Further observations revealed the true period close to 21 yr (85% coverage), and $M\sin(i) = 89\,M_J$. Successful imaging detection allowed to obtain a complete orbital solution, and all data were fited simultaneously (Hełminiak et al., 2016), probably for the first time. Masses of both components were derived simultaneously, without prior assumptions. The image of the companion, and the RV orbit are shown in Fig. 2. As for HD 16760, the orbit turned out to be rather face-on (160.4°), and the true companion's mass, 0.28 $M_\odot$, is much higher than the limit from RVs.

The three presented cases prove how important it is to have a proper estimate of the period, and supplement RV data with astrometry or other observations that constrain i. The true mass can be drastically different from the lower limit.

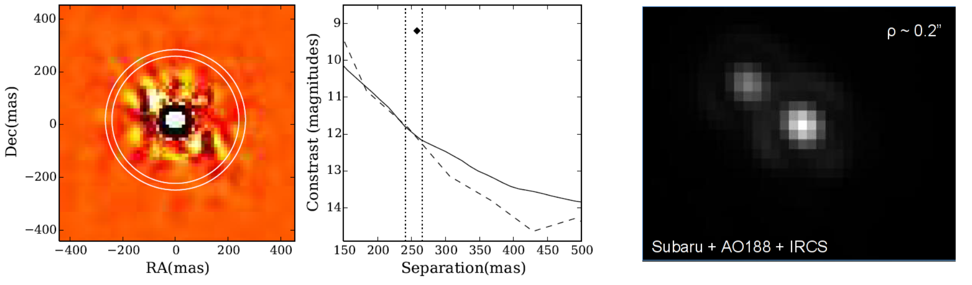

Fig. 3: Left: Imaging observations of V471 Tau with VLT/SPHERE. The BD predicted from TVs should be located inside the annulus marked with white lines. Center: Contrast curve for the same observations, with the predicted separation (vertical lines) and contrast (black diamond). The proposed BD would have been detected at the given separation (Hardy et al., 2015). Right: Positive detection of a stellar companion to XY Leo.

3.3 TV cases

Several candidates discovered with TVs are considered controversial to date (e.g. Goździewski et al., 2015; Silvotti et al., 2018). Their independent confirmation is therefore of the high interest. One of the most significant results were direct imaging observations of a post-common-envelope (PCE) of the eclipsing binary V471 Tau, suspected to harbor a 40 M_J brown dwarf on a 30 yr orbit (İbanoğlu et al., 2005). Recently, negative detection has been announced by Hardy et al. (2015), clearly disproving the existence of the BD in this system (Fig. 3). Several other PCE binaries are claimed to have planets, but this case makes us re-think such scenarios, and look for alternative explanations of the periodic TVs.

Positive detections are however possible. One such recent example is XY Leo, a contact eclipsing binary though to be orbited by another (lower mass) stellar pair (Yakut et al., 2003). The whole system would thus be a quadruple, making it very interesting from the dynamical point of view. An unconfirmed detection has been announced by Rucinski et al. (2007), and recent observations with the Subaru telescope (Fig. 3) show that the companion is real and gravitationally bound to the eclipsing pair (Goździewski et al., in prep.).

4 Summary

Only recently we have reached the technical possibility to use direct imaging to confirm planetary and BD candidates found with other methods. Currently, a positive detection of such a candidate usually indicates that it is a low-mass star or a massive BD, rather than the body of the character suggested by the lower mass limit. Nevertheless, imaging observations are important for adequate characterization of the companion – even without detection we can put upper limits on its mass. In some cases, the imaging technique is also efficient in disproving the existence of such a candidate. However, a lot of work is put to merge the discovery spaces from both sides: long-period RV/TV candidates are subject to new imaging observations, and RV monitoring of directly detected planets with small-angular-separation has started.

The RVs and TVs do not carry information about orbital inclination, therefore the real mass distribution of jovian and super-jovian planets, and BDs is probably different from what we assume from RV surveys. This has been supported by cases like HD 16760 or V450 And. Thanks to the technological advance in imaging (larger telescopes, extreme adaptive optics systems, more sophisticated image processing algorithms), we will be able soon to observe directly planets of $\sim 1\,\mathrm{M_J}$ at few AU – i.e. *true* Jupiter analogues. We should also be able to revise our knowledge of long-period BD and massive planet candidates, their distribution, initial mass function, and mechanisms of their formation, for example by pointing out objects in the *brown dwarf desert*.

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