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TROY – The Search for Exotrojan Planets.

Lillo-Box, J.

European Southern Observatory (ESO), Alonso de Cordova 3107, Vitacura, Santiago, Chile

Abstract

As the field of extrasolar planets evolves with numerous discoveries of new and diverse planets, we can start thinking in more challenging (observationally speaking) scientific cases that can bring up new, hidden pieces of the exoplanetary science puzzle. This is the case of the TROY project, a multi-technique effort to look for the first co-orbital planets and to provide estimates of the occurrence rate of these bodies down to the Earth-mass regime. Despite being missed in our Solar System, where only kilometer-size (or smaller) bodies co-rotate with most of the planets, theory allows even equal-mass planets to co-exist in the same orbit. In this invited talk I will present the news on the TROY project including the last ground-based observations, the results from the first radial velocity search involving 46 planetary systems and the first results from our Kepler/K2 search.

1 Introduction

After millennia of wondering, we now know that extrasolar planets abound [30, 27, 2, 25]. We have also proven several instances of exocomets (β Pic, [16]) and since 1984, with IRAS, we are also aware of Kuiper belt structures around other stars (see [29] and references therein). These discoveries imply that the non-planetary components of our Solar System are not an exception but instead the rule, being also present in extrasolar systems as a result of the planet formation process. Thus, it becomes clear that other existing bodies in our planetary system that have not yet been found abroad should (or at least can) also exist. Two examples are natural satellites (or moons) and trojans. Both types of objects abound in our Solar System, with the gas giants hosting tens of moons and Jupiter having thousands of trojans at both Lagrangian points. The hunt for exomoons is being carried out by several groups, including the HEK project (see [17] and the recent result of this project in [32]) and other different works (see, e.g., [33, 12]). In this project, we deal with the challenge of detecting and characterizing trojans co-orbiting to extrasolar planets (hereafter exotrojans).

The gravitational forces exerted by two massive bodies create a gravitational field with a distinct peculiarity: five locations of this field (called Lagrangian points) happen to be of

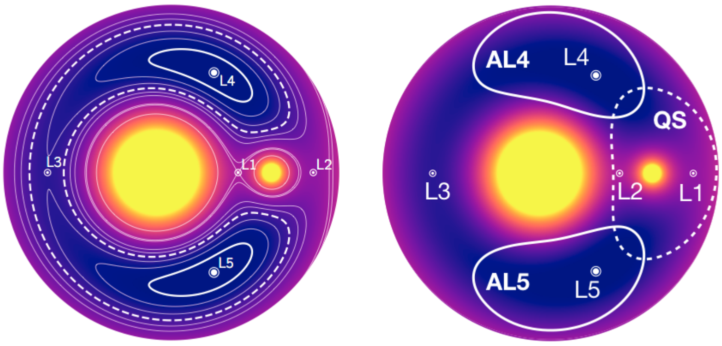

Figure 1: Stable co-orbital configurations. The left panel shows the tadpole (thick solid lines around L4 and L5) and horseshoe (thick dashed line) orbits. The right panel shows the location of the quasi-satellite stability point surrounding the planet (QS) and the two anti-Lagrangian stable points (AL) surrounding the Lagrangian points in the co-rotating frame.

equilibrium. Among them, three (L1, L2, and L3) are unstable to small perturbations (i.e., hills of gravitational potential) and two (L4 and L5) are stable to small perturbations (i.e., valleys of gravitational potential). The stable regions form an equilateral triangle with the planet and the star, being at $\pm 60°$ leading and trailing the planet on the exact same orbit (see Fig. 1, left). This implies that these are stability regions for wandering objects co-orbiting with the planet. Indeed, the analysis of orbital dynamics offers a whole buffet of co-orbital stable configurations: In tadpole orbits, the trojan inhabits one of the Lagrangian points, surrounding it with libration periods that scale with the mass ratio of the three objects. The Jupiter trojans describe this type of orbits. In horseshoe, the co-orbital moves from L4 to L5 describing a horseshoe-shape. The only example of this in the solar system are the Saturnian moons Epimetheus and Janus. In eccentric planets, new configurations become possible: in quasi-satellite orbits (QS, [28]) the co-orbital surrounds the planet in a very wide orbit in the co-rotation frame, like if it were a natural satellite (see Fig. 1, right); in anti-Lagrangian configurations (AL4 and AL5, [11]) the stability point (and hence the co-orbital) surrounds each of the Lagrangian points in the co-rotation frame. In total, in a star-planet system, there are six known islands of stability that allow other objects to co-orbit with the planet: L4, L5, horseshoe, QS, AL4, and AL5.

There are two main mechanisms for the formation of co-orbital planets. [5] presented the in situ scenario where these bodies are allowed to grow through accretion at the Lagrangian regions. [4] went a step further and demonstrated that in both gas-free and gas-rich evolutionary stages of the protoplanetary disk this accretion process is efficient in forming co-orbitals in situ of up to 6 $M_{\rm Mars}$ (0.6 $M_{\rm Earth}$) that will remain stable in tadpole orbits. This process is supported by different hydrodynamical simulations of planet formation showing that gas and dust accumulates already in the Lagrangian points of the forming planets (e.g., [18]; [10]). A second possible mechanism is the capture of the co-orbitals during the early stages of the planetary system through dynamical interactions. Indeed, co-orbital bodies are common outcomes of the planet formation and early evolution studies. [6] demonstrated that more than 30% of the simulated multi-planetary systems end up with long-lived co-orbital configurations of the proto-planets being formed. The conditions for capture strongly depend on the disk surface density profile and the number of planets in the system. Even more, the resonant capture of co-orbitals prevented the ejection or fate of the other planets in the system, thus acting as anchors of the multi-planetary system, with strong impact in the architecture of planetary systems. Regardless of their formation scenario, once trapped, the co-orbital configuration can remain stable during the inward migration of the planet, with the only caveat of an increase in the libration amplitude that eventually can lead to the co-orbital disruption. Very close-in co-orbital configurations are thus disfavored, although they can survive under certain conditions ([7])

The implications of their presence in a planetary system (or even of short-term co-orbital phases) has key implications in many aspects of the formation and evolution of planetary systems. For instance, [7] demonstrated that the capture of planet-size co-orbitals during the first stages strongly depends on the properties of the disk; and in particular on its surface density. Additionally, the dynamical properties of the co-orbital bodies strongly depend on the migration history of the system, with large librations indicating large journeys of the planet inward into the system. The Lagrangian regions are also a reservoir of bullets for the so-called giant-impacts that have been proposed as mechanisms to form moons of rocky planets and that strongly influence the atmospheric composition of planets. Indeed, this is one of the proposed mechanisms for the formation of our own Moon. [3] proposed a trojan origin for *Theia*, the Mars-size body that could have hit the proto-Earth to form the present (unique) Earth-Moon system.

Hence, co-orbital planets can be formed and remain stable in planetary systems under certain (very much relaxed) conditions. And their mere formation can have relevant implications for our understanding of the history of planetary systems. The past, current, and forthcoming instrumentation (Kepler, TESS, CHEOPS, PALTO, etc.) and the detection techniques developed over several decades allow us to start a homogeneous search and study of these bodies that might be one of the few missing pieces of planetary systems [23]. The TROY project is leading this effort through an exhaustive study and search of co-orbital planets.

2 The combined radial velocity - transit technique

In [8] the authors demostrate that if the radial velocity (RV) of a star is induced by a pair of co-orbital planets, the predicted time of transit from the RV data is shifted with respect to the actual time of transit of either of the two co-orbitals. Indeed, even though the Keplerian signal in the RV of the star is induced by the barycenter of the two co-orbitals, the time of transit predicted from the RV is hence the time of transit of that barycenter, while the actual planets transit before and after, if at all. This detection technique was applied by [8] to a handful number of known planets at the time, while assuming circular orbits, to set upper limits to the masses of possible trojan bodies in those systems. Also, [26] applied this technique to 25 known planets and found no evidence for a trojan up to their upper mass limits.

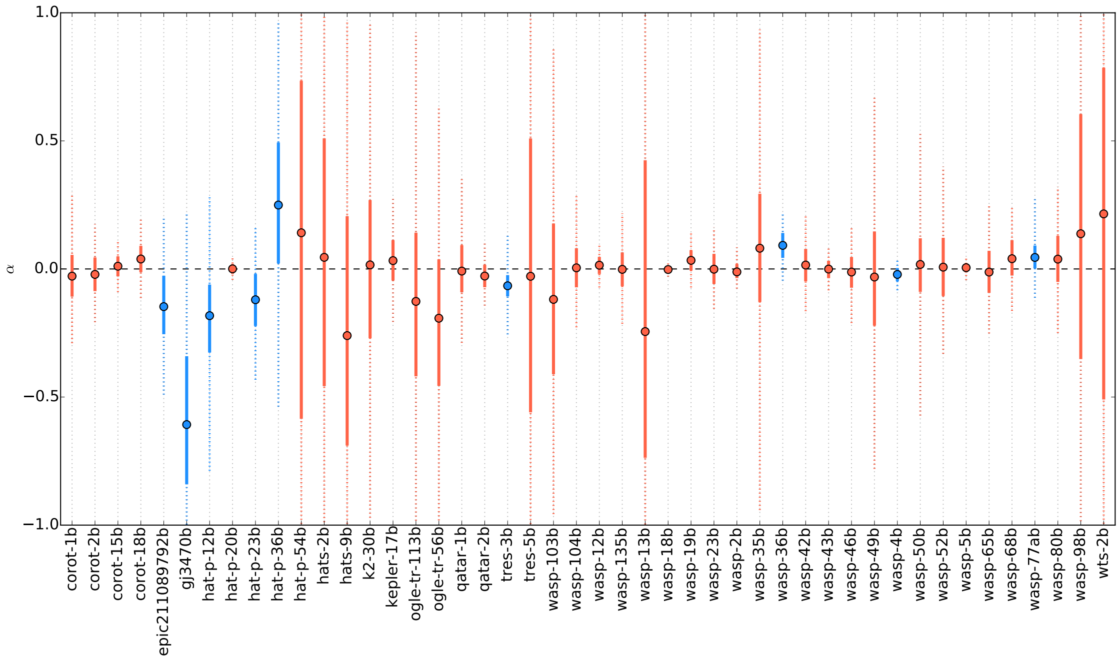

Figure 2: Results for the α parameter from the radial velocity analysis. Color error bars indicate the 68.7 confidence intervals (i.e., 1σ) while the dotted error bars indicate the 99.7% confidence intervals (3σ). We show in blue symbols the 9 systems where the null value for α ($\alpha = 0$) lies outside of the 1σ limits.

A downside of this method is that it is strongly dependent on the eccentricity of the transiting planet. Any error in the determination of the eccentricity would also produce a shift between the predicted transit time from the RV of a single planet and its actual time of transit. We tackled this problem in [19], where we generalized the equations presented in [8] for the case of eccentric orbits in order to extract as much information as possible from the RV signal. This is achieved through the determination of the α parameter, which is proportional to the trojan-to-planet mass ratio ($\alpha \approx m_t/m_p \sin\zeta$, with ζ being the deviation from the Lagrangian point). A value of α that deviates significantly from zero is thus a hint for the presence of a co-orbital planet, with $\alpha < 0$ indicating an L4 co-orbital and $\alpha > 0$ an L5 co-orbital. The constraint on the mass of the co-orbital companion to the transiting planet are in any case greatly improved if the secondary eclipse of the transiting planet can be observed, thanks to the precise determination of the parameter $e\cos\omega$.

In [21], we applied this technique to 46 planetary systems with only one (giant) planet known in the system and having an orbital period shorter than 5 days. We constrained the presence of co-orbital planets in both Lagrangian regions by just using public radial velocity data and determining the α parameter. In Fig. 2, we show the α values for the 46 systems. We found nine cases where α was at least 1σ away from the null value (in blue in this figure), although some of the posteriors are too broad to extract clear conclusions. Furthermore, in two cases (GJ 3470 and WASP-36), the median value for the α parameter is $> 2\sigma$ away from the null hypothesis.

Despite the low number statistics, these results allow us to start estimating occurrence rates of exotrojans in the particular sample studied here (i.e., short-period -$P < 5$ day- single planets). Since we only detect upper mass limits, we can estimate the upper limits for the occurrence rate of trojans up to a certain mass, which is defined as the 95.4% confidence level for the α parameter assuming that the trojan is located exactly at the Lagrangian point. We can say in general terms that at least 12% of planets with periods shorter than five days do not have co-orbital planets more massive than Neptune. Equivalently, at least 50% lack trojans more massive than Saturn. Also, we can discard Jupiter-mass trojans in this particular sample at a $\sim 90\%$ level. The reasons for this absence of massive trojans can be numerous (e.g., difficulties in forming such large bodies in situ at the Lagrangian points or keeping them stable during planetary lifetimes, difficulties in capturing such massive planets in stable orbits around the Lagrangian points, etc.). But in any case, the evidence presented for each individual system already provides empirical feedback to formation and migration theories.

3 The multi-technique approach

The above-described analysis (detailed in [21]) yielded nine potential candidates with values of the α parameters slightly different from zero (although not statistically significant), suggesting the possible presence of co-orbital planets. We used these systems for a more in-depth study using and combining the results from different observing techniques, presented in [22]. In particular, for the nine planetary systems we compiled observations from several observing techniques, including i) new radial velocity data obtained through dedicated observing programs with HARPS, HARPS-N, and CARMENES, ii) archive transit timing variations of the planet (TTVs), which might be explained by the libration of a co-orbital planet (see [9]), and iii) new high-precision photometric observations (with WiFSIP, CAFOS and FORS2) of the transit of the Lagrangian points of the nine systems where the co-orbitals were suspected to lie from the α parameter analysis.

We analyzed each dataset independently to constrain the existence of any co-orbital at the Lagrangian regions in the trojan mass versus libration amplitude parameter space. In particular, the new radial velocity data were used to update the α values; the TTVs were fitted to search for periodic variations and their scatter was used to constrain the trojan parameters (see Eq. 1 in [9] and [1] for a detailed analysis of Kepler data); and the serval photometric observation of the Lagrangian point passages were used to search for the trojan transit and to perform a dynamical analysis to also constrain the libration amplitude based on the non detections. All these allowed us to set important constraints on the presence of these bodies in the system by combining the independent analysis from the different techniques. In Fig. 3 (left panel), we show how the different techniques can constrain the relevant parameter space of trojan mass versus libration amplitude. As shown, each particular technique covers a different region of the parameter space, thus complementing each other. This makes clearer

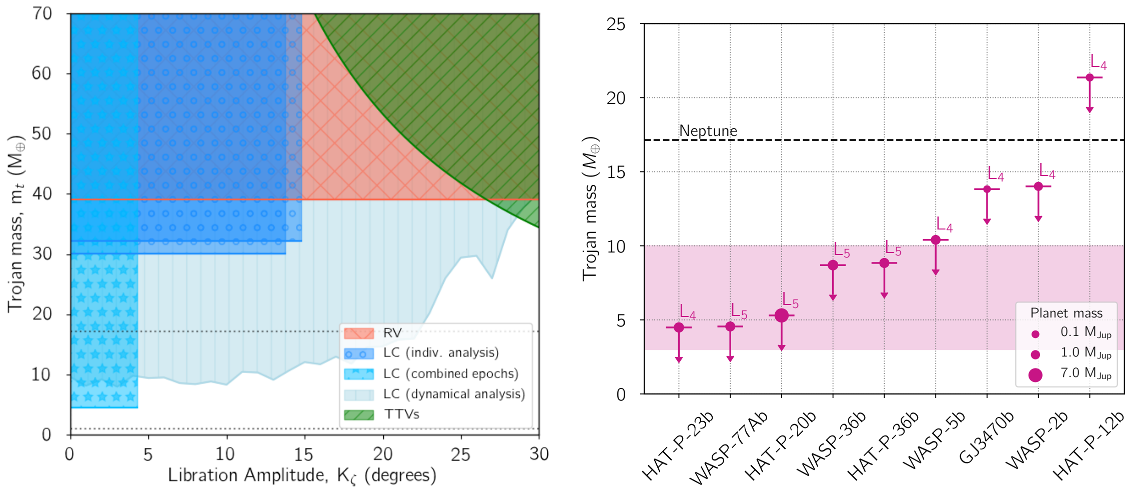

Figure 3: **Left:** Detailed example of the multi-technique constrain of the trojan mass versus libration amplitude parameter space for WASP-77A (see [22]). Only the white region is not explored by our data. **Right:** Upper mass limits for co-orbitals seating exactly at (or with very small librations around) the Lagrangian points for the nine systems studied in [22].

the need for a multi-technique approach to appropriately rule out (and search for) trojans of any kind.

4 Space-based long term photometric monitoring

The obvious question when discussing about the possible presence of planet-size co-orbital companions is: why have they not been detected by long-term high-precision photometric space-based missions like Kepler? The question is indeed very pertinent. The fact that no clear evidence of these bodies was found in the data from these missions (although note that some candidates have already been proposed, see [20, 31, 24]) already provides relevant information.

First of all, it is worth to mention that some works have already dug into these data looking for these bodies. In [15], the authors performed a dedicated search for small librating trojans around 2244 Kepler candidates with no success down to 1 R_{Earth}. The reasons for this unsuccessful search can be multiple but one main conclusion can be drawn: trojans larger than Earth seem to not exist lying exactly at the Lagrangian points of their planets. However, the search by [15] suffered from several limitations. First of all, they used KOIs instead of confirmed planets so a large part of their sample was contaminated by false positive planets (note that less than one third of Kepler KOIs have been confirmed/validated). Also, they used the first 12 quarters of the mission (among the 17 available at the end of the mission). Regarding the equations used to search for these bodies, they assumed very small librations around the Lagrangian points. We now know that inward migration excite the libration in

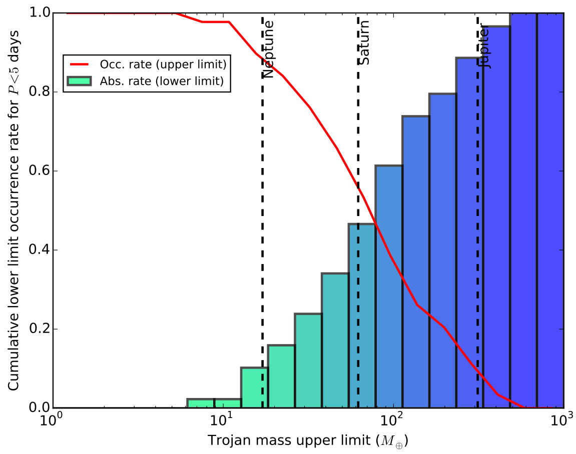

Figure 4: Occurrence rate of co-orbital planets to short-period ($P < 5$ days) giant planets ([21]). These occurrence rates were computed from a sample of 46 planetary systems with only one planet known.

the co-orbital regions and so we expect trojans to librate with relatively large amlpitudes for the kind of planets found by Kepler (i.e., in orbits inner to 1 au).

By contrast, [14] combined all light curves from Kepler candidates to get an average phase-folded light curve of all systems. The results showed dimmings at both L4 and L5 locations, suggesting the presence of an average population of trojans of 970 km in size (Pluto-like) in one third of the systems. This result demonstrates that co-orbital bodies exist with a high probability. Detecting individual co-orbitals is, hence, the challenge.

Consequently, a more dedicated and general search is needed. We have started this search by deriving new equations of motion for the trojan on its co-orbital configuration including several aspects missed by previous works. The preliminary results are promising and a paper is in preparation to describe the methodology and show the outcomes of this search.

5 Conclusions

During the last two years, the TROY project have started to pave the road towards a more comprehensive and homogeneous search and study of co-orbital planets in extrasolar systems. These bodies contain crucial information about the history of a planetary system, including clues on the planet formation and migration mechanisms, the shaping of the different components and architectures, and their potential habitability (see, e.g., [13]). The determination of the occurrence rate of co-orbital planets is thus a missing piece in the jigsaw puzzle of planetary systems that the community has been building up during the past few decades. Although theories of planet formation show that these configurations are common outcomes of the planet formation process, either in situ or captured, no planet-size trojan has yet been found. However, so far all efforts to detect these bodies, although very relevant and inspiring, have either focused on small samples and/or relied on simple assumptions that could have hidden the presence of these bodies. The new computational capabilities and the large amount of data from either space-based observatories or GTO programs from state-of-the-art ground-based instrumentation (like ESPRESSO or HARPS) offer a unique opportunity to push this field forward and provide and empirical feedback to theoretical works developed along decades.

TROY is a dedicated effort in this direction. We have started a search for co-orbital planets in known extrasolar systems by using different techniques and focusing on a main goal of constraining these co-orbitals at any possible configuration and down to the Earth-like domain. The first results presented in [21] and [22] proof that we digging into the correct direction. The use of multiple techniques was proven essential to really constrain the whole parameter space of possible co-orbital bodies. The future is bright for this flourishing field with the many planet-detection-driven facilities that are already working or that will be ready in the forthcoming years.

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