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Circumstellar habitable zones and the location of resonances in binary star systems

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Abstract

Binary and multiple star systems are harsh environments for the formation and long-term stability of extrasolar planetary systems. Circumstellar planets are subject to periodic perturbations from the distant companion star (the secondary). We combine two analytical models for the investigation of the secular evolution of exoplanets in the habitable zone, and quantify the effect of various system parameters (masses, distances, eccentricities) on the occurrence and position of secular resonances. These results allow to quickly identify exoplanetary systems with perturbed habitable zones and to exclude them from in-depth observational programs and habitability analyses.

1. Introduction

A considerable fraction of stars in our Sun's neighborhood are members of binary or multiple star systems. Observational surveys found that about 45% of all Sun-like stars belong to multiple star systems [2], [5]. Not all of these stars host exoplanets, though. Current estimates yield a percentage of 10–15% of binary stars with planets, whereas approximately 2% of the multiple star systems (3 or more stars) are exoplanet hosts [3].

Planet formation in binary star systems proceeds in an analogous way as for single stars [4], but a close-in secondary could truncate the proto-planetary disk and possibly limit the occurrence rate of planets.

In this work we investigate circumstellar planetary systems that consist of a Jupiter-like giant planet (GP) external to the habitable zone (HZ), and potentially habitable terrestrial planets in the HZ. Our aim is to identify those systems in general for which a certain combination of physical parameters (masses) and orbital parameters (distances and eccentricities) of the secondary star and the GP generate a secular perturbation (secular resonance, SR) in the host star's HZ. We provide results for a Sun-like host star for a wide range of possible binary and GP parameters. Such a quick identification of SR is relevant for both habitability studies and to exclude systems from observational searches for low-eccentricity planets in the HZ.

2. Methods

The applied dynamical model is a restricted four-body problem that consists of two stellar components, a giant planet, and a massless test-planet in the HZ. Both planets are in circumstellar motion about the host star, and the GP is located external to the HZ. There exist about 220 exoplanet systems that meet these criteria according to the exoplanet.eu database.

We are interested in secular perturbations in the HZ. The strongest perturbations arise when the orbital precession frequency g_{TP} of the test planet is comparable to that of the giant planet, g_{GP}:

$$g_{TP} = g_{GP} \qquad (1)$$

This relation forms the basis of the investigations. The quantity on the right-hand side is mainly influenced by the parameters of the secondary star, and we employ the simple but accurate analytical model of [1] to evaluate it. In the left-hand side the GP's effect dominates over the secondary star. For this expression we apply the well-known Laplace-Lagrange secular model to calculate the precession frequency of the TP under the influence of multiple massive perturbers.

The combination of these two analytical models leads to an expression in five parameters (masses, distances, eccentricity) of the GP and secondary star: (m_{GP}, m_B, a_{GP}, a_B, e_B). When fixing the habitable zone borders, we can solve equation (1) iteratively to find the set of parameters that generate an SR in the HZ.

3. Results

We show an example of this procedure in figure 1. Along the grey curve an SR affects some part of the host star's HZ, while in the surrounding white area there is no SR inside the HZ. The two horizontal lines indicate a Jupiter-mass GP placed at different distances (5.2 and 9.6 au, respectively). In both cases there is a certain range of secondary star distances that force the GP's orbital precession frequency to coincide with those in the HZ. This lead to a periodic large amplitude forcing of the test planet eccentricities, such that they can temporarily leave the HZ an become uninhabitable in the long-term.

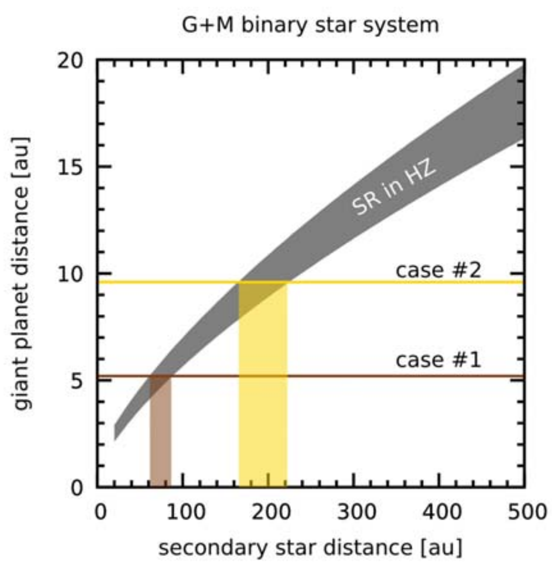

Figure 1: A visualization of system parameters that lead to a secular resonance in the habitable zone of a binary star system. With a Jupiter-like giant planet at 5.2 au (case #1) such a perturbation falls into the HZ for a companion star between 60–80 au. In case #2 the planet is moved to 9.6 au, but even these more distant secondaries (~200 au) lead to the same results.

4. Summary and Conclusions

We show that certain combinations of the system parameters in binary star systems with a giant exoplanet can lead to secular perturbations in the HZ. Such perturbations even appear for very distant secondary stars (up to 500 au), which previously were believed to be an unimportant factor to any circumstellar planetary systems. A comprehensive study with more details is in preparation (Bazsó and Pilat-Lohinger, 2019). These results also imply that a slight modification of the secondary's orbital parameters (e.g. by a stellar fly-by to the system) might turn a non-perturbed HZ into a perturbed (and dynamically truncated) one.

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