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Secular architecture of giant-planet dominated binary star systems

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Abstract

We present a study on S-type planets in binary star systems with separations $a < 100$ AU. For systems with at least one detected giant planet we determine the location of (linear) secular resonances with that planet by means of a semi-analytical method. We demonstrate that under some conditions, e.g. when the secondary star is at about 20 AU, the habitable zone can be perturbed or completely destabilized in these systems.

1. Introduction

Extra-solar planets are present also in binary and multiple star systems. There are currently 106 detected planets in 73 binary star systems, additionally also 20 planets in 15 multiple star systems are known (see Binary Catalogue of Exoplanets[1]). In the majority of binary star systems (56 out of 73) we find so called S-type planets. S-type planets orbit about one of the stars; whereas P-type planets orbit the whole binary in some distance [4].

Duquennoy & Mayor [3] have found for solar-type stars (spectral classes F7 – G9) that about 38% are members of binary star systems, and 5% are in multiple star systems (with three or more stars). Raghavan et al. [8] investigated exoplanet host stars and derived a lower limit of 21% for the fraction of binary star systems. In a more recent study Roell et al. [9] found only a multiplicity rate of 12% for exoplanet host stars.

Currently giant planets dominate the census of exoplanet in binary star systems. Planets with masses comparable to Earth's are missing or rare, a possible candidate is the planet of α Centauri B [2]. We investigate the circumstances when additional terrestrial planets can be expected in binary star systems and whether these would be dynamically stable.

[1] http://www.univie.ac.at/adg/schwarz/multiple.html

2. Systems

We selected 9 binary star systems with (projected) separations of the two stars below 100 AU, i.e. periods between 10^4 and 10^6 days [1].

Table 1: Selection of exoplanet-hosting binary star systems with giant planets. The systems are ordered according to their separation a_B; the given mass ratio is calculated as $M_B/(M_A + M_B)$.

system	a_B [AU]	mass ratio	planets
HD 19994	100	0.40	1
HD 177830	97	0.14	2
HD 1237	68	0.13	1
HD 120136	45	0.24	1
HD 41004	23	0.36	1
HD 128620	23	0.54	1
HD 196885	21	0.25	1
HD 222404	20	0.23	1
HD 13445	19	0.37	1

In these exoplanetary systems the giant planet can be either interior to the habitable zone or exterior to it. The secondary star can be expected to be on an eccentric orbit; after [3] the mean eccentricity is 0.3 for such separations. As a consequence perturbations from both the giant planet and the secondary star will affect the dynamics of potential terrestrial planets.

3. Methods

We investigated the secular dynamics of the terrestrial test planets (assumed to be massless objects) by applying a semi-analytical method [7]. We used the first-order Laplace-Lagrange secular theory [6] to calculate the secular frequencies of objects moving under the gravitational influence of two much more massive bodies. From a single numerical integration we can then determine the apsidal precession frequencies for the massive bodies with a Fourier analysis. Combining these calculated frequencies we determined the location of linear secular resonances and the regions of chaotic motion.

4. Results

Solar-system like combinations of a terrestrial planet interior to the giant planet's orbit may suffer from secular resonances; this is the case for at least three systems from our list, namely HD 41004, HD 196885, and HD 222404. The giant planet's eccentricity plays a crucial role for increasing the test planet's eccentricity. Even initially circular orbits may undergo eccentricity oscillations large enough to remove the planets partly or completely from the habitable zone, in some cases they are even removed from the system. The large eccentricities make it necessary to consider extended or average habitable zones [5].

Close-in giant planets in hot-Jupiter like orbits are generally less affected by the secondary star and have consequently much longer secular periods. However, the general relativistic precession of the pericenter introduces another effect that can increase the precession rate to values large enough to affect planets close to the habitable zone.

5. Conclusions

- Binary star systems with a giant planet can feature linear secular resonances close to or inside the habitable zone of the primary star.
- The giant planet's eccentricity induces a forced eccentricity on initially circular test planets and can lead to their ejection from the system.
- For close-in giant planets the relativistic precession of the pericenter needs to be taken into account when determining their precession frequency.

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