HABITABLE EXTRASOLAR PLANETS IN BINARY STAR SYSTEMS; THE CASE OF GAMMA CEPHEI.

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This paper discusses the orbital dynamics of the binary-planetary system γ Cephei and the orbital stability of a hypothetical Earth-size planet in the habitable zone of its primary star. It has been suggested that the long-lived residual radial velocity variations observed in the precision radial velocity measurements of the primary of γ Cephei are likely due to a Jupiter-size planet around this star [6]. Simulations, which have been carried out for different values of the eccentricity and semimajor axis of the binary, as well as the orbital inclination of its Jupiter-size planet, indicate that, for the values of the binary eccentricity less than 0.5, and for all values of the orbital inclination of the Jupiter-size planet ranging from 0 to 40 degrees, the orbit of this planet is stable for several million years. For larger values of the binary eccentricity, the system becomes gradually unstable. Integrations also indicate that, within the range of orbital parameters for which the binary-planet system is stable, a hypothetical Earth-size planet can have long-term stable orbits only at a distance of 0.3-0.8 AU from the primary star. The habitable zone of the primary, at a distance of approximately 3 AU, is, however, unstable.

Motivation

Among the currently known extrasolar planet-hosting stars, approximately 25% are members of binaries or multistar systems. These systems are mostly wide with separations between 250 to 6500 AU. With the exception of the pulsar-planetary system PSR B1620-26 [1-3], and possibly the newly discovered system HD202026 [4], the planets in these binaries revolve around only one of the stars. At such large distances, the gravitational influence of the farther companion on the dynamics of planets around the other star is un-substantial. Simulations of the orbital stability of a Jupiter-like planet around a star of a binary system have shown that the existence of the farther companion will have considerable effect if the separation of the binary is less than 100 AU [5]. At the present, there are three planet-hosting binary systems with such a separation: γ Cephei [6], GJ 86 [7], and HD188753 [8]. This paper focuses on the dynamics, long-term stability, and the habitability of γ Cephei.

Initial Set Up

The dual-star system of γ Cephei is a spectroscopic binary with a 1.59 solar-mass K1 IV subgiant as its primary [9] and a probable red M dwarf, with a mass-range of 0.34 to 0.78 solar-mass [10], as its secondary. The semimajor axis and eccentricity of this system are, respectively, 18.5 ± 1.1 AU and 0.361 ± 0.023, as reported by Hatzes et al. [6], and 20.3 ± 0.7 AU and 0.389 ± 0.017, as reported by Griffin et al. [11]. The primary star of this system has been suggested to be the host to a planet with a minimum mass of 1.7 Jupiter-mass, on an orbit with semimajor axis of 2.13 ± 0.05 AU, and eccentricity of 0.12 ± 0.05.

The existence of two sets of reported values for the orbital semimajor axis and eccentricity of this binary and also a mass-range for its secondary component, along with the report of only a minimum mass for the Jupiter-like planet of this system create a large parameter-space. This parameter-space that consists of the binary’s semimajor axis ($a_b$) and eccentricity ($e_b$), the planet’s orbital inclination with respect to the plane of the binary ($i_p$), and the binary’s mass-ratio $\mu = m_2/(m_1 + m_2)$ with $m_1$ and $m_2$ being the masses of the primary and secondary stars, respectively, is the space of the initial conditions for numerical integrations of the system. The first goal of this study is to identify regions of this parameter-space where the Jupiter-like planet of the system can have long-term stable orbits.

Stability of the Jupiter-like Planet

The three-body system of γ Cephei binary-planetary system was integrated numerically using a conventional Bulirsch-Stoer integrator. In order to portray a detailed picture of the dynamical state of the Jupiter-like planet in γ Cephei system, and also for the purpose of extending the analysis to more general cases which include inclined orbits, and more importantly, to better understand the dynamical effects of this planet on the long-term stability of a habitable planet in this system, numerical simulations were carried out for different values of the semimajor axis, eccentricity and mass-ratio of the binary, as well as the orbital inclination of the planet. The initial value of $e_b$ was chosen from the range of 0.2 to 0.65 in increments of 0.05, and the initial orbital inclination of the planet was chosen from the values of $i_p =0, 2, 5, 10, 20, 40, 60, 80$ degrees. Numerical simulations were also carried out for different values of $\mu$, and for $a_b$ ranging from 18 to 22 AU. The results indicate that the system is stable for $0.2 \leq e_b \leq 0.45$. The stability of the system for $e_b \leq 0.45$ was observed for all reported values of the binary semimajor axis.
Integrations also indicate that regardless of the initial value of the semimajor axis of the binary, the system becomes unstable in less than a few thousand years when the initial value of the binary eccentricity exceeds 0.5.

To investigate the effect of planet’s orbital inclination ($i_p$) on its stability, the system was also integrated for different values of $i_p$. The results indicate that for $0.20 \leq e_b \leq 0.45$, the system is stable for all values of planet’s orbital inclination less than 40 degrees. Figure 1 shows the semimajor axes and orbital eccentricities of the system for $i=5$, 10, and 20 degrees. For orbital inclinations larger than 40 degrees, the system becomes unstable in a few thousand years.

**Habitability**

A habitable zone is commonly referred to a region around a star where an Earth-like planet can maintain liquid water on its surface. Since this definition is based on the notion of habitability and life on Earth, a habitable zone can be defined as a region where an Earth-like planet can receive the same amount of radiation as Earth receives from the Sun, and develop and maintain similar habitable conditions as those on Earth. This statement implies

$$F(r) = \left( \frac{T}{T_{\text{Sun}}} \right)^4 \left( \frac{R}{R_{\text{Sun}}} \right)^2 r^{-2} F_{\text{Sun}}(1 \text{ AU})$$

where $F(r)$ represents the apparent brightness of a star with a luminosity of $L(R, T)$ as observed from an Earth-like planet at a distance $r$. In this equation, $R$ is the radius of the star and $T$ is its surface temperature. The primary star of $\gamma$ Cephei has a temperature of 4900 K and a radius of 4.66 solar-radii. Considering 5900 K as the surface temperature of the Sun, in order for Earth to receive the same amount of radiation as it receives from the Sun, it has to be at a distance of $r \sim 3.1$ AU from $\gamma$ Cephei’s primary star. Numerical integrations were carried out to study the stability of an Earth-like planet in this region. Although the habitable zone of the system extends from 3 to 3.3 AU, Earth-like planets were placed between 0.3 AU to 3.5 AU from the primary star. Numerical simulations were also carried out for different values of the orbital inclinations of planets. Figure 2 shows the survival times of Earth-like planets in terms of their initial positions for co-planar systems. As shown here, an Earth-like planet will not be able to sustain a stable orbit in the habitable zone of the primary star. Results of numerical simulations indicate that the orbit of an Earth-like planet is stable when $0.3 \leq a_E \leq 0.8$ AU, $0^\circ \leq i_E = i_p \leq 10^\circ$, and $e_b \leq 0.4$, where $a_E$ and $i_E$ represent the semimajor axis and orbital inclination of an Earth-like planet, respectively.

**References**