

Search for invisible satellites of visual binary stars by studying the stability of their long-term orbital dynamics

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Abstract. We present a brief teaser of an extension of the long-term orbital stability analysis technique for application to the search for a low-mass companion in a wide binary star system. The stability analysis is performed by computing the Lyapunov characteristic exponents over a set of possible orbital parameters for a component that may exist in the system. The method was applied to the optically discovered companion in ADS 15571. The satellite is located within the ranges determined by long-term stability limits. In addition, the ranges for possible companions of 17 wide binaries with highly accurate orbital parameter values were determined.

Introduction

Multiple-star system properties partially reflect stellar formation features and trends driven by long-term dynamical evolution. To date, there is no comprehensive scenario that can provide an answer to all questions in this field of astronomy [1]. Consequently, searching for low-mass companions in wide binaries is an important aspect of building a representative multiple-star dataset.

The observational program of the Pulkovo Observatory 26-inch refractor concentrated on collecting relative positions (ρ, θ) of the wide binaries. These data, spanning several decades, make it possible to identify variations in the ρ, θ time series [3]. These quasi-periodic offsets may be caused by a set of reasons. One possibility is a genuine gravitational perturbation induced by a low-mass companion orbiting, for instance, one of the components. Historically, such low-mass companions were called invisible satellites.

Typically, detecting such low-mass stars via spectral measurements or high-resolution imaging is challenging because of their low brightness and subarcsecond angular separation from the much brighter primary star. Examining the orbital

stability of an unconfirmed satellite offers an alternative approach to assessing the reality of a potential companion. A similar methodology is routinely employed in investigations of exomoon candidates [7]. This paper provides a brief review of the approach and presents several results of its application.

1. A review of the technique of the long-term orbital stability analysis for the wide binary with a low-mass companion

The stability analysis was performed by means of numerical integration and calculation of the Lyapunov characteristic exponents (LCEs; see [8] for details). The LCEs were computed over sets of possible orbital parameters of the low-mass companion. In the representative orbital parameter planes, regions with stable dynamics and significant values of the Lyapunov time (the time of predictable system dynamics) $T_L = 1/L$ were identified, where L is the maximum LCE. It is assumed that the orbital parameters of the yet unidentified companion may reside precisely within these regions. This methodology is described in more detail in [6, 7].

2. The ADS 15571 system companion test

Numerous examples of confirmed invisible satellite detections based on Pulkovo Observatory data are known. For instance, the ADS 15571 companion had been initially detected from the Pulkovo 26-inch refractor astrometric series [2] and confirmed with BTA 6-m telescope speckle imaging [5]. Figure 1 presents an example of stability diagrams constructed for a low-mass companion in the ADS 15571 system. The integration of orbital dynamics and the calculation of LCEs were performed over a time interval of 10^5 years. As can be seen from Figure 1, the orbital parameters of the low-mass companion determined in [5] correspond to its stable dynamics with $T_L \geq 10^4$ years. This fact confirms the reliability of the observational data analysis results presented in [5].

3. Dataset forming

The dataset to examine the technique was formed from a wide binary orbit set published in [4]. This orbit set contains the results of the most accurate Pulkovo technique-based determination of orbital parameters from astrometric and radial velocity measurements.

Currently, the approach to assessing orbital stability requires data coverage over a significant orbital arc. This was possible only for binaries with a period less than 350 years. Hence, our set contains only 17 stars. Some of the dataset properties are demonstrated in Figure 2. The selected binary systems are located between 10 and ~ 60 pc from the Sun, with primary masses ranging from 1.0 to 1.5 solar masses, and component mass ratios between 0.4 and 1.0.

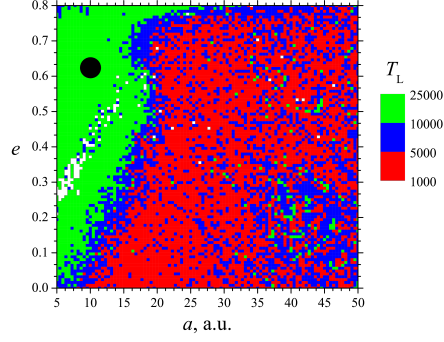


FIGURE 1. Lyapunov times (in years) for a low-mass companion in the ADS 15571 system computed on the semi-major axis–orbital eccentricity plane. White areas represent unstable orbits. The position of the low-mass component is indicated by a black dot according to [5].

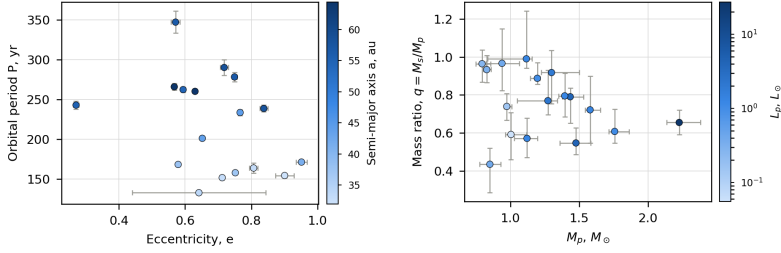


FIGURE 2. Dataset properties. Left: eccentricity – period diagram (the corresponding semi-major axis values are shown by colour). Right: primary mass – mass ratio diagram (the corresponding luminosity of primary components is shown by colour).

Long-term orbital stability analysis requires separate mass estimations for both components. We apply the astroARIADNE¹ [9] code to do this.

The results and conclusion

Our analysis demonstrates that long-term orbital stability investigations of wide binary stars are an effective method for establishing natural constraints on the orbital parameters of potential companions. This conclusion is supported by our

¹<https://github.com/jvines/astroARIADNE>

results for the ADS 15571 system, where satellites detected via speckle imaging were found to lie within the ranges dictated by orbital stability requirements. A subset of 17 short-period wide binaries was analyzed using the described approach. Constraints on the possible orbital parameters of low-mass companions were determined using mass estimates of the primary components, obtained from photometric spectral energy distributions (SEDs) and the astroARIADNE code.

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