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ON THE REALITY OF THE SUGGESTED PLANET IN THE ν OCTANTIS SYSTEM

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ABSTRACT

The aim of this study is to explore an enigmatic finding about the ν Octantis binary system that indicates the possible existence of a Jupiter-type planet even though the planet seems to be located outside the zone of orbital stability. We perform a detailed analysis of orbital stability based on previous studies that carefully considers the ν Octantis system parameters including their observationally deduced uncertainties. In our analysis, we confront the probability distribution of the parameter space of the system with the requirements of planetary orbital stability. Our results indicate that the suggested planet, if in a prograde orbit with respect to the motion of the binary components, is virtually impossible. However, the estimated probability of existence for a planet in a retrograde orbit is nearly 60%, an estimate that encapsulates the probability distribution of the mass ratio of the stellar components. This estimate increases if a relatively low stellar mass ratio (within the error bars) is assumed. The principal possibility of a planet in a retrograde orbit is also consistent with long-term orbital stability simulations pursued as part of our study. Thus, the existence of the suggested planet in the ν Octantis system constitutes a realistic possibility.

Key words: astrobiology – binaries: general – celestial mechanics – planetary systems – stars: individual (ν Octantis)

1. INTRODUCTION

A topic of fundamental importance to astrophysics and astrobiology is the study of orbital stability of theoretical and observed planets in star–planet systems; see, e.g., Roy (2005) for textbook information on planetary orbital stability. A significant controversy has emerged concerning the ν Octantis binary system where observational evidence indicates the possible existence of a Jupiter-type planet even though the planet (if existing) seems to be located outside the zone of orbital stability; see Ramm et al. (2009) for details. Previous observations have shown that planets are, in principle, able to exist in relatively close binary systems with separation distances of 20–25 AU, as pointed out by, e.g., Patience et al. (2002), Eggenberger et al. (2004), and Eggenberger & Udry (2010). Additionally, theoretical simulations have been pursued on planet formation in binary systems with different parameters that have led to highly favorable outcomes (e.g., Kley 2001; Quintana et al. 2002; Quintana & Lissauer 2010). The idea that planets in binary systems are now viewed to be possible is furthermore consistent with the detection of debris disks in various main-sequence stellar binary systems obtained by the *Spitzer Space Telescope* (e.g., Trilling et al. 2007).

The ν Octantis binary system consists of a primary of spectral type K1 III (Houk & Cowley 1975) and a secondary of spectral type K7–M1 V, see discussion by Ramm et al. (2009), with a separation distance of 2.55 ± 0.13 AU (see Table 1; note that all parameters have their usual meaning). Its parallax has been estimated as 47.18 ± 1.93 mas (van Leeuwen 2007), corresponding to a distance of 21.10 ± 0.87 pc. Following the analysis by Ramm et al. (2009), the masses of the primary and secondary stars are given as 1.4 ± 0.3 and 0.5 ± 0.1 $M_\odot$, respectively. Ramm et al. (2009) discovered low-amplitude periodic behavior in the residuals of the orbital solution for ν Oct, which they very tentatively attribute to a Jupiter-type planet. If existent, this planet would be located at 1.2 ± 0.1 AU from the primary, i.e., almost midway between the two stellar components, which is very unlikely based on standard orbital stability considerations. Alternative interpretations of the perturbation encompass rotational modulation of surface phenomena or pulsations, which however have been ruled out with high certainty, implying that the observed signals are caused by a planetary mass.

Ramm et al. (2009) also pursued a tentative estimate of the orbital stability of the suspected planet; however, they did not entertain the possibility of a retrograde orbit for the suspected planet. This will be the main focus of the present analysis. Our Letter is structured as follows: in Section 2, we provide a detailed estimate of the orbital stability regime of the planet, if existing. Additionally, we present orbital simulations of the planet by considering both prograde and retrograde orbits about the main component of the binary system. Our conclusions are given in Section 3.

2. RESULTS AND DISCUSSION

2.1. *Estimates of the Orbital Stability Regime*

The outer limit of orbital stability with respect to the planetary host star, i.e., the primary star of the ν Octantis system, can be estimated based on a statistical fitting formula given by Holman & Wiegert (1999). Previous work on the deduction of fitting formulas as well as subsequent studies of orbital stability of planets in binary systems were given by Dvorak (1986), Rabl & Dvorak (1988), Pilat-Lohinger & Dvorak (2002), Musielak et al. (2005), and others. Holman & Wiegert (1999) obtained empirical expressions based on a large number of simulations for various stellar mass ratios and binary eccentricities with the length of integration given by 10^4 binary periods. They found that the ratio between the critical semimajor axis (to be interpreted as orbital stability limit) and the semimajor binary axis $a_{\rm bin}$ depends roughly linearly in both the mass ratio $\mu = M_2/(M_1 + M_2)$ and the binary eccentricity $e_{\rm bin}$, although terms of higher order exist. Note that the given formula is only available for prograde planetary orbits.

Using the parameters for ν Octantis (see Table 1), we found that the outer limit of planetary orbital stability is given as 0.240

Table 1
Stellar and Planetary Parameters

Parameter	Value	Reference
Spectral type (1)	K1 III	Houk & Cowley (1975)
Spectral type (2)	K7–M1 V	Ramm et al. (2009)
R.A.	21 41 28.6463	ESA (1997)[a,b]
Decl.	−77 23 24.167	ESA (1997)[a,b]
Distance (pc)	21.20 ± 0.87	van Leeuwen (2007)
M_V (1)	2.10 ± 0.13	[c]
M_V (2)	~ 9.9	Drilling & Landolt (2000)
M_1 ($M_\odot$)	1.4 ± 0.3	Ramm et al. (2009)
M_2 ($M_\odot$)	0.5 ± 0.1	Ramm et al. (2009)
$T_{\rm eff,1}$ (K)	4790 ± 105	Allende Prieto & Lambert (1999)
R_1 ($R_\odot$)	5.9 ± 0.4	Allende Prieto & Lambert (1999)
$P_{\rm bin}$ (d)	1050.11 ± 0.13	Ramm et al. (2009)
$a_{\rm bin}$ (AU)	2.55 ± 0.13	Ramm et al. (2009)
$e_{\rm bin}$	0.2358 ± 0.0003	Ramm et al. (2009)
$M_p \sin i$ (M_J)	$2.5 \pm \ldots$	Ramm et al. (2009)[d]
a_p (AU)	1.2 ± 0.1	Ramm et al. (2009)[d]
e_p	0.123 ± 0.037	Ramm et al. (2009)[d]

Notes.

[a] Data from SIMBAD, see http://simbad.u-strasbg.fr.

[b] Adopted from the *Hipparcos* catalog.

[c] Derived from the stellar parallax, see Ramm et al. (2009).

[d] Controversial.

with a 1σ uncertainty of 0.066. This is consistent with the value deduced by Ramm et al. (2009), given as 0.25 ± 0.01, and also appears to be commensurate with the results from the circular and elliptical restricted three-body problem (e.g., Cuntz et al. 2007; Eberle et al. 2008; Szenkovits & Makó 2008). Note that the uncertainty bar deduced in our study was obtained through a detailed Monte Carlo approach based on the uncertainties in μ, $a_{\rm bin}$, and $e_{\rm bin}$. In order to maximize the uncertainty bar in the stability limit, we also pursued a computation based on an extreme exhaustion of the uncertainties in μ, $a_{\rm bin}$, and $e_{\rm bin}$. In this case, the resulting uncertainty bar in the stability limit is obtained as 0.114; note that although this approach is unrealistic, it has been pursued anyhow for the sake of curiosity. The attained stability limit with the two versions for associated uncertainty bars are given in Figure 1.

This approach allows us to estimate the probability of the suggested planet in the ν Octantis system for the particular case of a prograde orbit relative to the orbital motion of the binary components. Figure 1 depicts the various limits with respect to the distance ratio ρ_0, which in the circular case denotes the ratio of the initial distance of the planet from its host star (i.e., the stellar primary) to the distance between the binary components. In the elliptical case, ρ_0 denotes the ratio of the initial distance of the planet from the primary (a_p) relative to the semimajor axis of the binary components ($a_{\rm bin}$). Our analytic approach shows that for the realistic, i.e., Monte Carlo type estimate the 1σ uncertainty bar barely penetrates the 2σ uncertainty regime of distance ratio ρ_0. The latter has been deduced based on the uncertainties of the stellar masses M_1 and M_2 following the approach by Cuntz et al. (2007) and Eberle et al. (2008). Thus, assuming that the obtained uncertainties are consistent with Gaussian distributions, the implied probability for the existence of the suggested planet in the ν Octantis system is only about 1%. Therefore, if in a prograde orbit, the previously suggested planet in ν Octantis is virtually impossible.

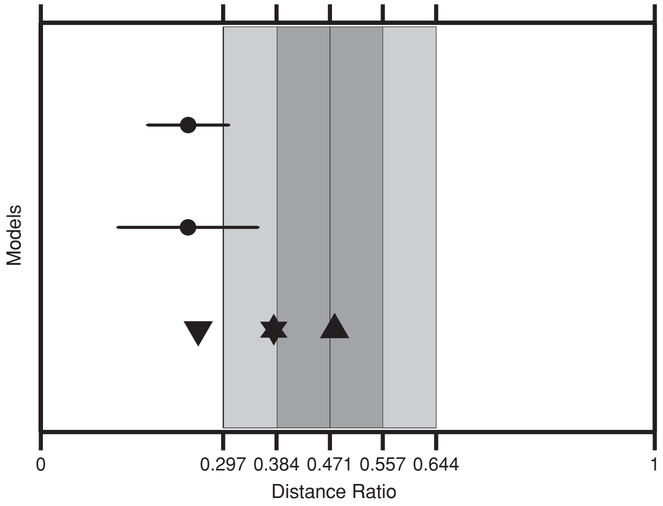

Figure 1. Two dots indicate detailed estimates of the outer orbital stability limit for the suspected planet in the ν Octantis system in prograde orbit based on the statistical fitting formula by Holman & Wiegert (1999); here, we adopted two different approaches for estimating the uncertainty. Note that the stellar primary is placed at the origin, whereas the stellar secondary is positioned at 1. The two triangular symbols highlight the deduced stability limits of the suspected planet in prograde (downward triangle) and retrograde (upward triangle) orbits based on short-term simulations, whereas the stellated hexagon indicates the ρ_0 parameter used in our long-term simulation (10^7 yr). The five symbols are superimposed on domains depicting the estimated region of orbital stability for the planet based on the stellar masses. With $M_1 = 1.4\,M_\odot$ and $M_2 = 0.5\,M_\odot$, the limit of orbital stability is given as $\rho_0 = 0.471$. The dark and light gray domains depict the 1σ and 2σ uncertainty regimes of ρ_0, respectively, given by the uncertainty in the stellar mass ratio (see Table 1). The latter uncertainty regimes are thus inherently separate from the facilitation of the planetary orbital stability simulations.

2.2. *Orbital Stability Simulations*

In addition to the usage of statistical fitting formulas for obtaining estimates of orbital stability, we also pursued detailed short-term and long-term simulations. The method of integration was based on a sixth-order symplectic integration scheme as found in, e.g., Yoshida (1990). Previous versions of our code have been extensively tested against known analytical solutions, including the two-body and restricted three-body problems (see Noble et al. 2002; Cuntz et al. 2007; Eberle et al. 2008, for detailed results). In the framework of our simulations that extended up to 1×10^7 yr, we applied a time-step of 10^{-3} yr per step. Even for the longest term simulations, this seems to be adequate as there were no close encounters of any of the bodies. Furthermore, the total system energy was found to be conserved within less than 5×10^{-7} accuracy.

We selected three different primary masses (1.1, 1.4, and 1.7 $M_\odot$) and, furthermore, for each primary mass three different mass ratios (0.2593, 0.2754, and 0.2908) that are consistent within the uncertainty limits conveyed by Ramm et al. (2009) for a total of nine mass parameter combinations. In regard to prograde planetary orbital stability, we ran 10^3 year simulations (slightly less than 350 binary orbits), whereas for retrograde planetary orbits, we ran 10^4 year simulations (slightly less than 3.5×10^3 binary orbits). The aim of this effort was to contest and improve any analytically deduced stability limits (only available for prograde orbits; see Section 2.1) and to motivate long-term orbital stability simulations (if appropriate), which will also be targeted in future studies.

The initial conditions of the system were chosen such that the secondary star and the planet were both at apoapsis relative to the

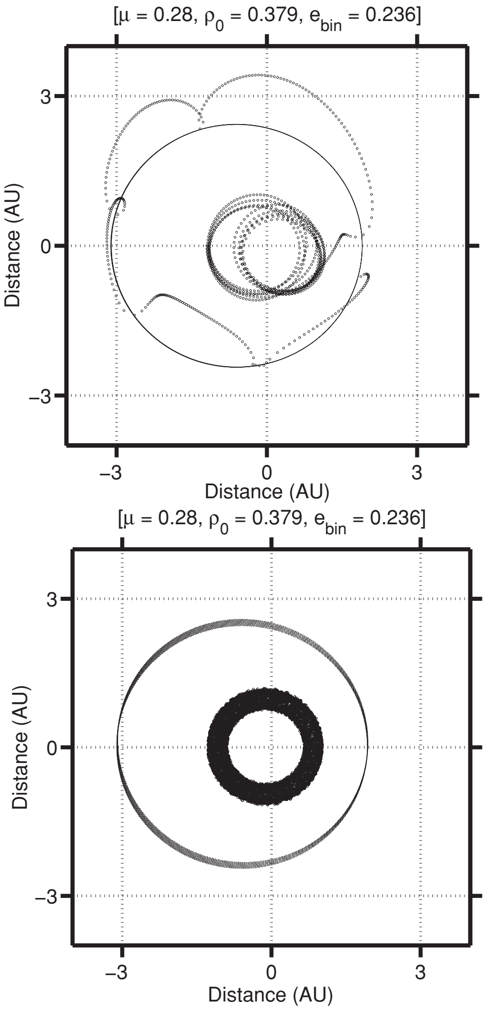

Figure 2. Detailed simulations of orbital stability for a Jupiter-type planet in the ν Octantis system. Top: example of a prograde planetary orbit (small dots) together with the resulting secondary's motion about the primary (solid line) where the primary is at the origin. Evidently, the planet's orbit is highly unstable, a result obtained after a very short amount of time (9.88 yr). Bottom: example of a retrograde planetary orbit based on the same system parameters as before. The simulation spans 1×10^7 yr, corresponding to 3.4×10^6 binary periods. Note that the planet about the primary remains within a ring centered slightly to the left of the origin.

primary star and at the 9 o'clock position. The semimajor axis of the secondary star was chosen so as to keep the period of the binary system fixed at 2.875 years. The distance ratio was varied from 0.22 to 0.54 in 30 equal increments for both prograde and retrograde initial conditions. We then estimated the upper limits of stability based on the cut-off point where simulations survived the 10^3 year duration. The next greater distance ratio resulted in an earlier simulation termination due to close approaches of the planet to one of the stars or ejection from the system altogether. In conclusion, for the prograde setting, the average last stable orbit occurred for an initial distance ratio of 0.251 with a standard deviation of 0.005. The attained distance ratio is very similar to our analytic estimate of 0.240 (see Section 2.1).

In order to probe the cut-off point between stability and instability for the retrograde case, we pursued a set of simulations where the initial distance ratio was varied from 0.42 to 0.50 in ten equal increments with the nine mass parameters previously used; the appropriateness of this interval was obtained by previous trial calculations. For this set, the maximum simulation time was set as 10^4 years. In this case, the outermost stable orbit distance ratio was identified as 0.479 with a standard deviation of 0.008, implying an estimated probability of existence for a planet in a retrograde orbit of about 60%, an estimate that also encapsulates the probability distribution of the mass ratio of the stellar components. Evidently, the upper limit of orbital stability for retrograde orbits is about double that for prograde orbits, which is also in line with earlier work by Jefferys (1974). Most importantly, this value is highly consistent with the possibility of a planet in the ν Octantis system in concert with the stellar mass ratio indicated by observations, including its error bar (see Figure 1).

Figure 2 depicts examples of detailed time-dependent orbital stability simulations for the ν Octantis system. The masses of the stellar components were assumed as $M_1 = 1.4\, M_\odot$ and $M_2 = 0.532\, M_\odot$, corresponding to a mass ratio of $\mu = 0.28$. Figure 2(a) shows the prograde planetary orbit as well as the secondary's motion about the primary where the primary is at the origin. After only a few orbits around the primary, it is evident that the planet's orbit is unstable, as expected. A close approach of the secondary star pulls the planet into a more elliptical orbit for a few more passes until another close approach of the secondary pulls the planet away from the primary and to the eventual collision of the planet with the secondary. The total time of this simulation is only 9.88 years, corresponding to approximately three binary periods.

Figure 2(b) shows the retrograde planetary orbit for the same system parameters motivated by the prospect of orbital stability based on our previous short-term investigation. This simulation was continued for a time span of 1×10^7 yr, corresponding to about 3.4×10^6 binary periods. The orbit of the planet about the primary obviously remains within a ring that has a center that is slightly to the left of the origin. This is an unequivocal indication of long-term orbital stability of the planet, if existent, for system parameters compatible with the observational constraints. To further strengthen this interpretation, we also assessed the time line data for the distances between the primary star and the secondary star as well as the primary star and the planet for the retrograde planetary orbit for a 1×10^7 yr time period. The motion of the secondary relative to the primary is essentially a two-body Keplerian motion along an ellipse with an eccentricity equal to 0.236. These data were sampled in 100 year time increments, resulting in very well-defined upper and lower limits corresponding to the planetary apoapsis and periapsis, respectively. The distances between the stars vary between 1.9288 and 3.1125 AU, whereas the distances between the planet and the primary star vary between 0.6452 and 1.2879 AU, an effect due to the ellipticity of the stellar and planetary orbits and by no means indicative of any long-term changes in the system.

3. CONCLUSIONS

Our study has been aimed at exploring an enigmatic finding about the ν Octantis binary system that indicates the possible existence of a Jupiter-type planet, even though the planet seems to be located outside the zone of orbital stability. Ramm et al. (2009) discovered low-amplitude periodic behavior in the residuals of the orbital solution for this star, which they very tentatively attribute to a Jupiter-type planet. Alternative interpretations of the perturbation consist in rotational modulation of surface phenomena or pulsations, which however have been ruled out with high certainty.

In our study, we performed a detailed analysis of orbital stability based on previous studies that carefully considers the ν Octantis system parameters including their observationally deduced uncertainties. We confronted the probability distribution of the parameter space of the system with the requirements of planetary orbital stability. Our results indicate that the suggested planet if in a prograde orbit with respect to the motion of the binary components is virtually impossible; however, the estimated probability of existence for a planet in a retrograde orbit is nearly 60%. This estimate further increases if a relatively low stellar mass ratio (within the error bars) is assumed. The possibility of a planet in a retrograde orbit is also consistent with long-term orbital stability simulations spanning 1×10^7 yr. Based on time-dependent studies, the stability limit of prograde orbits was identified as 0.251, whereas stability limit of retrograde orbits was identified as 0.479; note that the latter value is fully consistent with observationally deduced masses of the stellar companions including the conveyed uncertainty bars. Furthermore, the possibility of a planet in a retrograde planetary orbit in a binary system like ν Octantis is also consistent with earlier studies by Jefferys (1974) indicating significantly enlarged regions of stability for planets in retrograde orbits. This study had been based on a Henon stability analysis while considering the circular restricted three-body problem.

The distance ratio that would correspond to the 5:2 resonance obviously falls within the error bars for the case of an unstable prograde orbit; note that it is related to how Ramm et al. (2009) determined the semimajor axis of the proposed planet in the first place. While we did not specifically deduce the exact parameters for this resonance for the various considered models, we made a strong case for the retrograde orbit as potentially the most likely candidate explanation. The fact that the planet, if existing, appears to be in a resonance orbit with the binary system could be due to the unknown mechanism of how this proposed planet came to be in this orbit. Thus, it is still possible, albeit highly unlikely, that the planet, if existing, could be in a prograde orbit and the particular orbital elements conspire to produce a stable orbit with the observed resonance.

There is another interesting observation with some relevance to our study. Queloz et al. (2010) reported the discovery of WASP-8b, a retrograde transiting planet located in a multiple stellar system, although in this system the planetary retrograde motion occurs with respect to the stellar rotation of the planetary host star rather than the orbital motion of any of the two stellar companions. Akin to the suspected planet in the ν Octantis system, WASP-8b is a Jupiter-type planet of $2.25 \pm 0.08\ M_{\mathrm{J}}$ in a significantly eccentric orbit. Evidently, additional observational and theoretical studies are required concerning ν Octantis to elucidate the possible existence of a planet in that system.

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