Constraints to the Proposed Close-in Perturber to GJ 436 b

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Abstract The planet-hosting star GJ 436 has been extensively observed over the last months, including both spectroscopic and fotometric data. Here we review the last studies and comment the validity of the scenario of a close-in perturber in GJ 436, concluding that it is not only plausible, but in our opinion is also the most likely to explain the observations.

1 Introduction

Finding an Earth-like planet is a very exciting challenge and one of the present main goals in Astrophysics. Over the last months several super-Earths (planets with a mass between 1 and 10 times that of the Earth) have been detected with radial velocity mesurements [1] and microlensing [2], lowering the minimum planet mass detected down to $3M_{Earth}$.

In this study we will focus in the possibility of finding light planets through the perturbation that produce to known transiting planets. The number of transiting planets is likely to increase rapidly with the space missions CoRoT [3] and Kepler

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[4], and so does the possibility of detecting changes in their transit properties that would be indicative of further planets in the system. Transit time variations have been the subject of intense attention [5, 6, 7], but also the duration and depth of transit may be modified [8, 5, 9].

When studying the variations in the transits of exoplanets we should realize that the background is plentiful: the study of eclipsing binaries, deeply developed during the last century, can bring us some insights both observational and theoretical. There are some known eclipsing binaries with variable light curves, and in some cases the eclipses have even stopped for several years: SS Lac [10], SV Gem [11], V906 Sco [12]. The most accepted mechanism to produce these variations is the perturbation of a third star in the system [13, 14], an analogous situation of the perturbing planet in the transiting exoplanet scenario.

Here we discuss the possibility that the transit properties of the transiting planet GJ 436 b are changing due to the perturbation from a second planet in the system, as proposed in [15]. We describe the transiting system in §2, and the proposed second planet in §3. The discussion and the conclusions are presented in §4 and §5.

2 GJ 436

GJ 436 is a M2.5-dwarf that hostes the less massive transiting planet ever discovered: a Neptune-mass planet (22 $M_\oplus$) orbiting with a period of 2.6 days, with a surprising non-zero eccentricity of about 0.15 [16, 17]. The origin of this high eccentricity has been debated, with the conclusion that the planet should have been circularized in a timescale of $\sim 10^8$ yr, while the age of the system is significantly larger $\gtrsim 6 \cdot 10^9$ yr, when assuming reasonable values for the planet's tidal dissipation parameter [17, 18].

When the planet was discovered in 2004, the authors also obtained high-precision photometry and ruled out the possibility of a transit with a depth greater than 0.4% [16]. Some years after the discovery, [19] surprised the exoplanet community when reporting the detection of transits with a depth of 0.7%. The transit of GJ 436 b is remarkable because of its near-grazing nature, with an impact parameter about 0.85, impliying an orbital inclination of 86.3°. This relatively high impact parameter makes GJ 436 an ideal system to detect changes in the transit depth due to very small variations in the orbital inclination.

3 A second planet around GJ 436?

In [15] we presented a possible explanation for the apparently contradicting results concerning the detection of transits: the orbital inclination could have changed during the 3.3-year interval between the different photometric observations due to the perturbation of a second planet in the system, that would also explain the non-zero

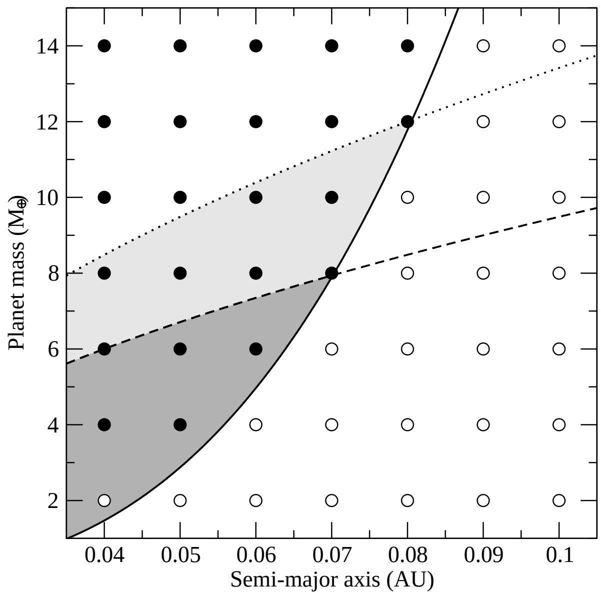

Fig. 1 Allowed region for a perturbing planet to GJ 436b given the observational constraints (dashed and dotted lines correspond to the radial velocity detection limits for inclinations of 90° and 45°, respectively, and the solid line represents the limit from an approximate calculation for a perturber [15]). The shaded regions illustrate the allowed range of masses and semi-major axes for the perturbing object. Figure from [15].

eccentriciy of GJ 436 b. Calculations show that an orbital inclination $\lesssim 86°$ would have made the transit undetectable to the photometric measurements of [16]. From these considerations a small variation of the inclination angle at a rate of roughly $\sim 0.1°$ yr^{-1} could make both the [16] non detection and [19]'s discovery of transits compatible.

For more accurate estimates we carried out direct integrations of the equations of motion using the Mercury package [20]. We started with an inner planet in a circular orbit and with the currently observed semi-major axis. Then, we considered different combinations of mass, semi-major axis, eccentricity and inclination for the perturber (see Fig. 1 and [15] for details). We further explored semi-major axis values at mean-motion resonances (MMRs). Location in a MMR can be a stabilizing factor and also perturbations can reach their maximum efficiency [7]. In our calculations, the presence of the planet in a MMR increased the stability and, further, perturbing planets with smaller masses were able to induce the observed eccentricity and orbital inclination change to the inner planet.

For the general case of a perturbing planet with 3–7 $M_{\oplus}$, eccentricity values of 0.15–0.20 and initial inclination differences of only 5–15° were sufficient to explain the observed eccentricity and rate of inclination change of the inner planet.

Further, in [15] we carried out a re-analysis of the available radial velocity data on GJ 436 and identified a second peak (of quite low significance) on the periodogram

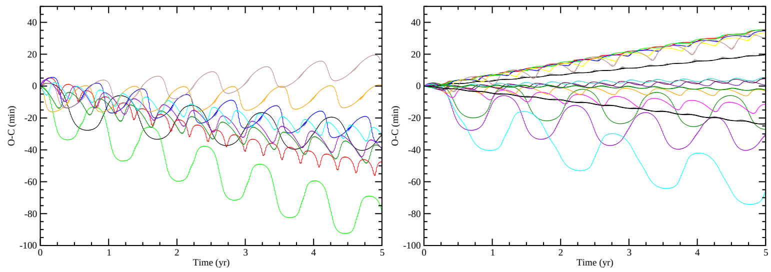

Fig. 2 TTVs arising from a perturber to GJ 436 b. The left panel shows TTVs from a number of configurations inside the 1-σ uncertainties of the perturber planet in [15]. The right panel depicts TTVs from the nominal parameters of the perturber but from different values of the longitude of the line of nodes, which is an orbital element unconstrained from the radial velocity data. Figure from [22]

with a period of 5.18 d. Such peak corresponded to a planet with a minimum mass of 4.7 $M_\oplus$ and close to the 2:1 MMR with the inner planet. Remarkably, a planet of such characteristics would be a perfect match to the perturbing object revealed by the evidence on the orbital eccentricity and inclination change.

4 Discussion

In the last months, further radial velocity data on GJ 436 have been presented (Howard, Bonfils, private communication) and the 5.18 d peak is not present, showing that it came from a spurious signal. Moreover, new photometry has been presented that puts constraints the variations in the transit time (TTV). [21] used this lack of TTVs to rule out the presence of a close perturber in the system, but this argument is not strictly correct because TTV signals may vary quite significantly with small changes of orbital elements. For example, very small TTVs can be found for certain configurations at the center of the strong 2:1 MMR [22], and [23] showed that even with the present TTVs constraints there is still room for a second planet in the system (see Fig. 2).

But independently of the precise identity of the perturbing planet, the scenario where a second planet in the system is responsible for the eccentricity of GJ 436 b and its (hypothetical) inclination change is still plausible. Besides the 2007 season data, new photometry has been presented both from professional [21, 25, 24, 26] and amateur astronomers [1], but while extending the current time baseline, do not have sufficient accuracy for a current estimate of the possible change. However, [26] showed that using also an unpublished transit data from January 2005, the variation in inclination could be as high as $0.119 \pm 0.062°$, supporting the hypothesis of [15].

[1] `http://brucegary.net/AXA/GJ436/gj436.htm`

5 Conclusions

The proposed 5 $M_\oplus$ planet with a period of 5.18 d in GJ 436 [15] has been ruled out with the new radial velocity data presented in the last months. Although the new data set a more stringent limit to possible a further planet, the scenario of a close-in perturber is still plausible, and in our opinion is the most likely to explain the observations of GJ 436. Strong proof should come from changes in the transit duration measured over the coming seasons.

As more transiting planets are discovered, the chances of observing variations in their transit properties with time increase. The case of near-grazing events is especially suitable because of their sensitivity to perturbers. In the coming years, this technique combined by intensive studies of transiting planets (ensured by the interest in the field) should provide us with new insight into the architecture of planetary systems.

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