Transiting Planets
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The case for a close-in perturber to GJ 436 b

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Abstract. The increasing number of transiting planets raises the possibility of finding changes in their transit time, duration and depth that could be indicative of further planets in the system. Experience from eclipsing binaries indeed shows that such changes may be expected. A first obvious candidate to look for a perturbing planet is GJ 436, which hosts a hot transiting Neptune-mass planet in an eccentric orbit. Ribas *et al.* (2008) suggested that such eccentricity and a possible change in the orbital inclination might be due to a perturbing small planet in a close-in orbit. A radial velocity signal of a 5 $M_\oplus$ planet close to the 2:1 mean-motion resonance seemed to provide the perfect candidate. Recent new radial velocities have deemed such signal spurious. Here we put all the available information in context and we evaluate the possibility of a small perturber to GJ 436 b to explain its eccentricity and possible inclination change. In particular, we discuss the constraints provided by the transit time variation data. We conclude that, given the current data, the close-in perturber scenario still offers a plausible explanation to the observed orbital and physical properties of GJ 436 b.

1. Introduction

The study of eclipsing binary systems was initiated by the discovery by John Goodricke in 1783 and subsequent proof by Edward C. Pickering in 1881 that the variable star Algol is indeed composed of two stars undergoing eclipses. In the last century, the study of eclipsing binary systems has been a major component to Stellar Astrophysics as a whole, by improving our understanding of a variety of phenomena in binaries, by providing valuable information on the structure and evolution of stars, and by serving as indicators of, e.g., age or distance (see, e.g., Andersen 1991; Guinan 1993; Hilditch 2001; Ribas 2006; Bonanos 2007). Eclipsing binaries still continue to play an important role in this respect. However, in recent years we have witnessed a rebirth of the study of eclipsing binary systems in the particular case of very unequal mass and brightness ratios, i.e., transiting planets. Eclipsing binaries being a field of long tradition (both observational and theoretical) it is convenient to use such outstanding background and adapt it to suit current needs.

A particular aspect of eclipsing binary research has been the study of detached systems that show variable light curves. In some cases, the origin of the variability can be traced to the appearance, migration, and disappearance of inhomogeneities (starspots) on the surface of one or both components, but in some instances the observed changes are of a more fundamental nature. For example, the eclipsing binaries SS Lac and SV Gem stopped eclipsing some 60 years ago (Torres & Stefanik 2000; Guilbault et al. 2001), V906 Sco stopped eclipsing in 1918, then restarted in 1963 and stopped again in 1986 (Lacy *et al.* 1999), and IU Aur shows a fast variation of eclipse depth (Drechsel *et al.*

1994). All these changes are thought to originate from the perturbations of a third star in the system (Söderhjelm 1975; Mazeh & Shaham 1976). Obviously, such large perturbations are not very common among eclipsing binaries, but it is also true that not many systems have been observed intensively enough and with a sufficiently long time baseline to uncover slow light curve variations.

In the case of transiting planets, variations in light curve properties have been predicted to occur from various sources, most notably from the effect of perturbing further bodies in the system. Transit time variations have been the subject of intense attention and indeed been proposed as a way of detecting smaller perturbing planets (Miralda-Escudé 2002; Holman & Murray 2005; Agol *et al.* 2005). But not only the transit central time may suffer variations. The duration and depth of the transit (Schneider 1994; Miralda-Escudé 2002; Laughlin *et al.* 2005) may also be modified because of changes in the orbital inclination, semi-major axis, eccentricity and argument of periastron.

The numerous ongoing surveys from both the ground and space are now producing new transiting planet discoveries at an ever increasing pace. The total tally of exoplanets undergoing transit events has already surpassed 50. With these increasing statistics and the eclipsing binary experience, one may wonder if changes in the light curve are already observable in some cases.

2. GJ 436

The M2.5-dwarf GJ 436 was discovered to host a Neptune-mass planet (22 $M_\oplus$) in a 2.6-d orbit by Butler *et al.* (2004). Two properties made this object especially interesting, namely its relatively small mass and a surprising non-zero eccentricity of about 0.15. Such value of the eccentricity was recently confirmed by the analysis of Maness *et al.* (2007), hereafter M07. Butler *et al.* (2004) also obtained high-precision photometry and ruled out the possibility of a transit with a depth greater than 0.4%. However, a surprise came with the actual detection of transits from GJ 436 b with a depth of 0.7% by Gillon *et al.* (2007b), thus becoming, by far, the smallest transiting planet yet detected. A series of studies, mostly using Spitzer, have greatly contributed to establishing the properties of the planet and also to strengthen the case for an eccentric orbit by observing the occultation event at orbital phase 0.59 (Deming *et al.* 2007; Gillon *et al.* 2007a).

The origin of the high eccentricity of GJ 436 b was investigated in detail by M07 and Demory *et al.* (2007). Both studies conclude that the circularization timescale ($\sim 10^8$ yr) is significantly smaller than the old age of the system ($\gtrsim 6 \cdot 10^9$ yr) when assuming reasonable values for the planet's tidal dissipation parameter. M07 also pointed out the presence of a long-term trend with a value of 1.3 m s^{-1} per year on the systemic radial velocity of GJ 436. Thus, the authors investigated the possibility that the eccentricity and the long-term velocity trend could be explained from the perturbation exerted by an object in a wider orbit without reaching conclusive results.

But GJ 436 b has yet another remarkable trait and this is the near-grazing nature of its transit. The impact parameter of the transit was found to be about 0.85, which implies an orbital inclination of 86.3°. If the inclination happened to be just 85.3° the planet would not cross the disk of the star. GJ 436 b makes an ideal system to find evidence for a perturbing small planet, because of the telltale non-zero eccentricity, and also to put severe constraints on the properties of the perturber owing to the extreme sensitivity of the current configuration to small changes in the orbital inclination. In Ribas *et al.* (2008), hereafter RFB08, we proposed an alternative possibility to explain the eccentricity of GJ 436 b, namely the perturbation from a relatively small planet in a close-in orbit. Our scenario is described in the next section.

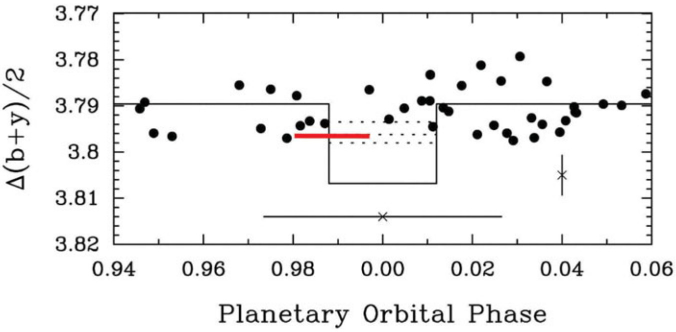

Figure 1. Photometry of GJ 436 from Butler *et al.* (2004) with the true depth of the transit marked by the thick line between phase ∼0.98 and phase ∼0.00. Several measurements fall inside the transit window. Figure adapted from Butler *et al.* (2004).

3. A second planet around GJ 436?

A possible explanation for the apparently contradicting results concerning the detection of transits is that the orbital inclination has indeed changed during the 3.3-year interval between the different photometric observations. Calculations show that an orbital inclination $\lesssim 86°$ would have made the transit undetectable to the photometric measurements of Butler *et al.* (2004). From these considerations a small variation of the inclination angle at a rate of roughly $\sim 0.1°\ \mathrm{yr}^{-1}$ could make both the Butler *et al.* (2004) non-detection and Gillon *et al.* (2007b)'s discovery of transits compatible. Note that this is only a possible scenario since the photometry of Butler *et al.* has relatively sparse phase coverage. As can be seen in Fig. 1, several measurements should have betrayed the presence of the transit, although with low significance.

For more accurate estimates we carried out direct integrations of the equations of motion using the Mercury package (Chambers 1999). 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 (from 1 to 14 $M_\oplus$), semi-major axis (from 0.04 to 0.1 AU), eccentricity (from 0.05 to 0.3) and inclination (from 85° to 45°) for the perturber. The integrations were performed for a time interval of 10^5 yr to guarantee the stability of the planetary systems. 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 (e.g., Agol *et al.* 2005). Integrations for semi-major axes corresponding to the following MMRs were carried out: 3:2, 5:3, 2:1, 3:1, and 4:1. In all cases, 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 in the inner planet. For the strongest 2:1 resonance we found a lower limit to the perturbing planet mass of only 1 $M_\oplus$ at an extreme eccentricity and relative inclination. 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.

In the analysis we neglected tidal dissipation since we focused on the current snapshot of the orbital configuration of the system, but the planets must be undergoing significant tidal dissipation because of the non-zero eccentricity. Other effects have been neglected at this stage, which include precession caused by the quadrupole moment of the star and by General Relativity (GR).

Further, in RFB08 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 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

Further radial velocity data on GJ 436 have been acquired by at least two groups (Howard *et al.*, Bonfils *et al.*) and the 5.18 d peak is not present. The amount and the accuracy of the new data is also superior and the authors do not find any further significant signals above the noise level. Thus, it is now clear that the planet proposed by RFB08 to be responsible for the observed perturbations comes from a spurious signal. In addition, the new velocities show the long-term velocity trend to be an artifact from insufficient time baseline and sparse coverage. But independently of the precise identity of the perturbing planet, one can constrain its properties by measuring the rate of inclination change and also the presence of transit time variations. Obviously, GJ 436 has been the focus of attention and numerous observations have been acquired during this season, as illustrated from different papers presented in this volume.

Conclusive evidence of the existence of a perturber would come from the measurement of variations in the transit shape. This cannot be done directly by comparing inclination values from different studies because of correlations with other parameters. The best way is to look for changes in the total transit duration, which is a fundamental quantity derived from the photometry. Besides the 2007 season data, new photometry has been presented by Alonso *et al.* (2008). From a ground-based transit of outstanding quality the authors measure a marginally longer transit duration than in 2007, which can be translated into a rate of inclination change of $+0.03 \pm 0.05^\circ$ yr^{-1}. This is both compatible with zero and with the $\sim$0.1° yr^{-1} rate suggested by RFB08. New transit data have been acquired by HST (Bean *et al.* 2008) in Dec'07 and Jan'08 but the transit duration information is not given, and also the data do not enhance the time coverage. Transit duration measurements from amateur astronomers†, while extending the current time baseline, do not have sufficient accuracy for a current estimate of the possible change (some 1–2 min compared with a scatter of 5–10 min). High-precision observations during the coming seasons will permit the measurement of the putative transit duration variation and, if confirmed, willo put stringent constrains on the perturbing planet.

Another way to test the presence of perturbing planets is via transit time variations (TTVs). When two planets are near an MMR, their interaction gives rise to libration motions that translate into relatively large variations in the time of conjunction (i.e., transit) with typical short characteristic timescales (months). The detection of TTVs is a clear and unambiguous signal of further planets in a system. However, there are two very important caveats. One is that the inverse problem may not be well defined. In other words, it is not guaranteed that there exists a unique combination of planet parameters that will reproduce a given TTV signal. Very high timing accuracy may be needed to disentangle subtle differences, and there may be some inherent degeneracies, especially with a time coverage of only a few years.

The second caveat concerns the opposite situation, and thus it is more relevant here. We would like to stress that the lack of a TTV signal, in general, does not rule out the presence of a planet inferred from, e.g., radial velocities. This is because some of the orbital elements are not constrained by the radial velocity data and these may be

† `http://brucegary.net/AXA/GJ436/gj436.htm`

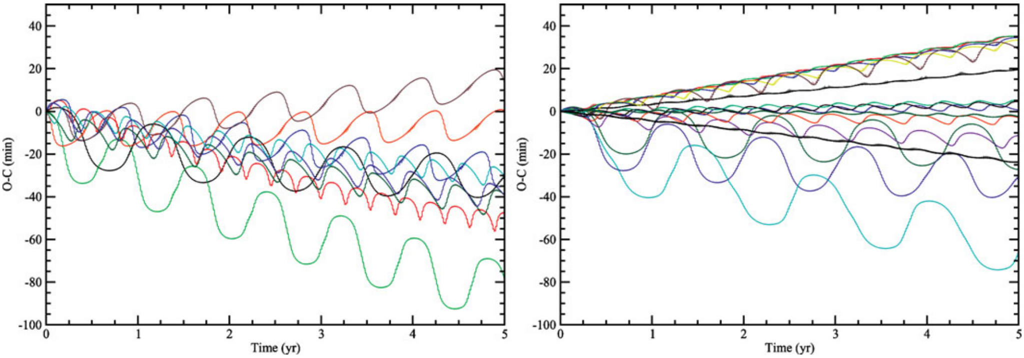

Figure 2. TTVs arising from a perturber to GJ 436 b. The left panel shows TTVs from a number of configurations inside the 1-σ uncertainties of the perturber planet in RFB08. The right panel depicts TTVs from the nominal parameters of the perturber but from different values of the longitude of the line of nodes, which is an orbital element unconstrained from the radial velocity data.

very relevant to TTVs. Common practice is that of averaging over unknown elements but, while statistically sound, this does not apply to a single studied case. In addition, TTV signals may vary quite significantly with small changes of orbital elements. All this is illustrated in Fig. 2 and also by Veras (this volume). For example, very small TTVs can be found for certain configurations at the center of the strong 2:1 MMR. Therefore, the lack of a TTV cannot be generally used as a strong proof against the presence of a perturbing planet. In the case of GJ 436, a statement like "there is no further planet because we do not see the expected TTVs of the order of minutes" is not strictly correct given the limited orbital constraints we have.

Transit timing measurements of GJ 436 b have been published so far by Alonso *et al.* (2008), Shporer *et al.* (2008), and Bean *et al.* (2008), and measurements have also been presented by Winn and Demory (both in this volume), and by amateurs. We have also carried out our own measurements and we have observed three transits from the 60-cm telescope at Esteve Duran Observatory. As can be seen in Fig. 3, the rms of the photometry is of the order of 1.5–2 mmag. The three transit mid-time measurements are: HDJ2454505.51379 ± 0.00050, HJD2454558.39010 ± 0.00063, and HJD2454587.47447 ± 0.00061; with total transit durations (in min) of 60.9 ± 1.1, 63.0 ± 1.5, and 60.6 ± 1.4, respectively. A weighted least squares fit yields the following ephemeris: $T_{\rm mid}$ = HJD2454280.78167(11) + 2.6438975(15); with a χ^2 value of 1.8. The O-C residuals from the linear ephemeris are given in Fig. 3 for all the published timings. From the data available it is still early to draw conclusions, but the timings do not reveal significant variations from a linear trend. At this point, any possible modulation should be below ∼1 minute. This does not favour (although it strictly does not rule out) a perturbing planet in MMR.

Very recently, Bean & Seifahrt (2008) have re-analyzed the radial velocities of M07 and used the available timing measurements by considering a sophisticated model with planet-planet interactions. The authors come up with a possible perturber with a mass of 5 $M_\oplus$ at 0.043 AU. This is close to the planet proposed by RFB08 but located outside the 2:1 MMR because of the additional TTV constraints. Such solution has a significance not much greater than other mass vs. semi-major axis combinations. In light of their simulations, the authors conclude that a close in perturber is possible.

The case for a 5 $M_\oplus$ at 2:1 MMR has also been studied by Mardling (2008). In this case, the model considered includes the tidal interactions between the planets. The

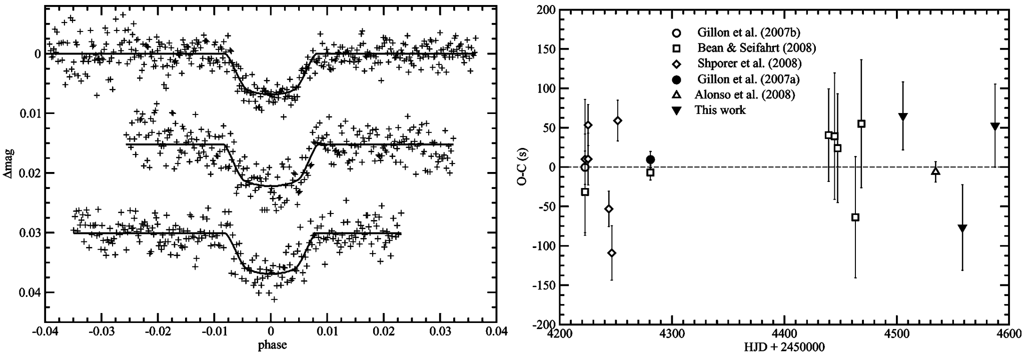

Figure 3. *Left*: Three transit events observed with the 60-cm telescope of Esteve Duran Observatory and the corresponding best fits. *Right*: O-C diagram for the published timing data plus our three new measurements.

analysis indicates that the precise configuration proposed is stable but that it would not stop the inner planet from being circularized at some point. The allowed region in the mass vs. semi-major axis plane for a perturbing planet will have to be defined with all the observational constraints, plus the orbital perturbation model and tidal energy dissipation. We plan to do so in the near future.

5. Conclusions

New radial velocity data have ruled out the presence of a 5 $M_\oplus$ planet with a period of 5.18 d in GJ 436. Although the new data place a more stringent limit on possible further planet in GJ 436, the scenario of a close-in perturber to GJ 436 b is still plausible. Strong proof should come from changes in the transit duration measured over the coming seasons. If such changes are present, this will nail the case for a perturbing object in a slightly non-coplanar orbit, much in the same way as for some eclipsing stellar binaries. This will give rise to the interesting concept of “transient transits”. Still, it is possible that the duration is stable over time and this would rule out a perturber in mild non-coplanarity.

The most certain observational fact is the eccentricity of GJ 436 b’s orbit. Besides the close-in perturber scenario, there are a number of other possible explanations. A distant perturber was proposed by M07 and also by X. Bonfils (priv. comm.). This would explain the radial velocity trend and be responsible for the eccentricity pumping. However, the trend seems not to be confirmed by newer data and, further, the effect of GR precession may prevent the building of significant eccentricity. This is because the GR timescale for GJ 436 b is only 15 000 yr and any eccentricity pumping effect with a longer timescale will not be efficient. The other obvious scenario is that of a large value of the tidal dissipation constant $Q'_{\rm p}$ for GJ 436 b. The value needed is 10^{6-7}, which is one to two orders of magnitudes larger than Neptune’s and larger than that of any object in the Solar System. A large value of $Q'_{\rm p}$, if it can be generalized, should also be made compatible with the distribution of eccentricities of close-in planets. Further, there is weak evidence of tidal heating on GJ 436 b (Deming *et al.* 2007), which advocates for a normal $Q'_{\rm p}$. Finally, one may also think of a recent event (less than 100 Myr ago) that pumped up the eccentricity of the planet (as suggested by Zakamska & Tremaine 2004, in another context), such as the close passing of a star or massive object. However, at this point this is just mere speculation.

We believe that a close-in perturber is still the most likely scenario to explain the observations of GJ 436. Some of the small planets found in around mass stars seem to belong to multiple systems, such as Gl 876, Gl 581, or the recent discovery of HD 40307. Thus, given this remarkable parallelism, it would not be a surprise if GJ 436 hosts more than one planet. This would also be the case in the framework of the hypothesis of packed planetary systems of Barnes & Raymond (2004). 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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