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A ~5 $M_\oplus$ SUPER-EARTH ORBITING GJ 436? THE POWER OF NEAR-GRAZING TRANSITS

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ABSTRACT

Most of the presently identified exoplanets have masses similar to that of Jupiter and therefore are assumed to be gaseous objects. With the ever-increasing interest in discovering lower mass planets, several of the so-called super-Earths ($1\ M_\oplus < M < 10\ M_\oplus$), which are predicted to be rocky, have already been found. Here we report the possible discovery of a planet around the M-type star GJ 436 with a minimum mass of $4.7 \pm 0.6\ M_\oplus$ and a true mass of $\sim 5\ M_\oplus$, which would make it the least massive planet around a main-sequence star found to date. The planet is identified from its perturbations on an inner Neptune-mass transiting planet (GJ 436b), by pumping eccentricity and producing variations in the orbital inclination. Analysis of published radial velocity measurements indeed reveals a significant signal corresponding to an orbital period that is very close to the 2 : 1 mean motion resonance with the inner planet. The near-grazing nature of the transit makes it extremely sensitive to small changes in the inclination.

Subject headings: planetary systems — planetary systems: formation — stars: individual (GJ 436)

Online material: color figures

1. INTRODUCTION

Hundreds of exoplanets have been discovered over the past decade using a variety of techniques, notably precision radial velocities, most of them being Jupiter-like. While such planets are extremely useful to understand the morphology and evolution of planetary systems and star-planet connections, there is an obvious interest in eventually identifying an Earth-like object. Model calculations indicate that planets with masses in the interval $1\ M_\oplus < M < 10\ M_\oplus$ are of terrestrial type (e.g., Ida & Lin 2004; Valencia et al. 2007). Such planets have often been dubbed "super-Earths." In this quest for smaller planets there have already been some successful detections of planets that fall in the super-Earth domain (Rivera et al. 2005; Beaulieu et al. 2006; Udry et al. 2007), and even their habitability may be evaluated (Selsis et al. 2007).

Besides the direct detection from radial velocities or transits, methods for the discovery of low-mass planets as perturbers to other planets have been suggested (although without any successful detections yet). These are mostly based on monitoring variations in the timing of the transit over a relatively long timescale so that perturbations by planets as small as a few Earth masses could be detected (Miralda-Escudé 2002; Schneider 2004; Holman & Murray 2005; Agol et al. 2005).

In this Letter we make use of yet another method that has allowed the possible detection of a super-Earth perturbing the transiting planet GJ 436b. In this case, it is not perturbations to the transit midtime but to the overall orbital elements of the inner transiting object that cause variations on the transit shape and depth. We show that, for near-grazing transits, their duration is strongly sensitive to small changes in the orbital inclination.

2. AN UNUSUAL HOT NEPTUNE AROUND GJ 436

The M2.5-dwarf GJ 436 was discovered to host a Neptune-mass planet in a 2.6 day orbit by Butler et al. (2004). Two properties made this object especially interesting, namely its relatively small mass and a surprising nonzero eccentricity of about 0.15. Such value of the eccentricity was recently confirmed by the analysis of Maness et al. (2007). Butler et al. (2004) also obtained high-precision photometry to investigate the presence of transits but 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 436b with a depth of 0.7% by Gillon et al. (2007a), thus becoming by far the smallest transiting planet yet detected. A series of studies, mostly using the *Spitzer Space Telescope*, have greatly contributed to establishing the properties of the planet (Deming et al. 2007; Gillon et al. 2007b; Demory et al. 2007; Torres 2007) and also to strengthening the case for an eccentric orbit by observing the occultation event at orbital phase 0.59.

The origin of the high eccentricity of GJ 436b was investigated in detail by Maness et al. (2007) and Deming et al. (2007). Both studies conclude that the circularization timescale ($\sim 10^8$ yr) is significantly smaller than the old age of the system ($\gtrsim 6 \times 10^9$ yr) when assuming reasonable values for the planet's tidal dissipation parameter. Maness et al. (2007) 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.

We propose an alternative possibility to explain the eccentricity of GJ 436b, namely the perturbation from a relatively small planet in a close orbit. We show below that the effects of the perturber on the inner planet can excite the eccentricity up to the observed value. But GJ 436b has yet another characteristic that makes it different from other transiting planets 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

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the star. Studies mostly focused on triple-star systems have pointed out that perturbations may not only change the eccentricity but also other orbital properties of the inner orbit. When the perturber resides in a non-coplanar orbit this gives rise to a modulation in the inclination of the inner object (e.g., Söderhjelm 1975). As an example, the triple-system scenario has been advocated to explain the cessation of eclipses in the binary SS Lac (Torres & Stefanik 2000; Torres 2001). In the context of exoplanets, Schneider (1994), Miralda-Escudé (2002), and Laughlin et al. (2005) considered the possibility that precession induced by a perturbing planet could lead to observable changes in the duration (and existence) of the transit of an inner giant planet.

GJ 436b makes an ideal system to find evidence for a perturbing small planet, because of the telltale nonzero eccentricity, but 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 angle.

3. A SECOND PLANET AROUND GJ 436?

3.1. *Dynamical Study*

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 yr interval between the different photometric observations. Calculations show that an orbital inclination $\lesssim 86°$ would have made the transit undetectable to the Butler et al. (2004) photometric measurements. 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) nondetection and the Gillon et al. (2007a) discovery of transits compatible. Note that this is only a possible scenario since the photometry of Butler et al. has relatively sparse phase coverage. In retrospect, from the currently known duration and properties of the transit, three measurements from Butler et al. (2004) should have betrayed the presence of the planet, although with low significance.

Assuming this hypothesis, it is reasonable to explore the possibility of a perturber that could be responsible for both the relatively large eccentricity and the inclination change, while remaining undetected by the radial velocity measurements. From this, one can assume that the semiamplitude of the perturber should be below about 4 m s^{-1}, implying that its mass should satisfy the following inequality: $M_p \lesssim 30a^{1/2}\ M_\oplus$, with a being the orbital semimajor axis in AU. On the other hand, because of the inclination change, the variation of the transit duration with time is of about 10^{-5}. Following Miralda-Escudé (2002) we find that the perturber mass should satisfy $M_p \gtrsim 3 \times 10^4 a^3\ M_\oplus$. From both inequalities, there is an allowed range of perturber masses and semimajor axes.

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 semimajor axis. Then, we considered different combinations of mass (from 1 to 14 $M_\oplus$), semimajor 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. In Figure 1 we provide an illustration of the region in the mass versus semimajor axis plane where perturbers can meet all constraints, i.e., sufficient eccentricity of the inner planet and minimum inclination variation rate.

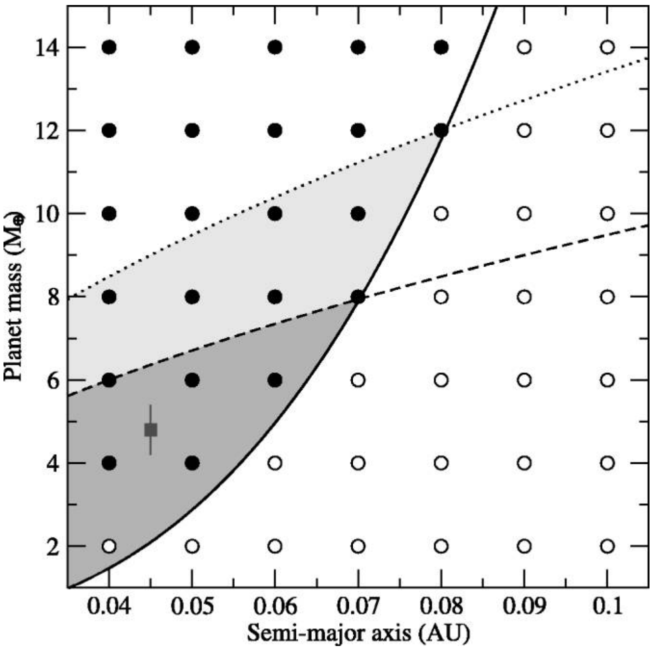

FIG. 1.—Allowed region for a perturbing planet to GJ 436b given the observational constraints. The dashed and dotted lines correspond to the radial velocity detection limits for inclinations of 90° and 45°, respectively, and the solid line represents the limit from an approximate calculation for a perturber (see text). The shaded regions illustrate the allowed range of masses and semimajor axes for the perturbing object. The circles correspond to a grid search to identify cases in which a planetary companion to GJ 436b could be able to induce the observed eccentricity and rate of orbital inclination change. Positive cases are marked with filled circles while empty circles indicate configurations with negative results. The square marks the position of the planet detected from the radial velocity analysis. [*See the electronic edition of the Journal for a color version of this figure.*]

We further explored semimajor axis values at mean-motion resonances (MMRs). Location in an MMR can be a stabilizing factor and also perturbations can reach their maximum efficiency (e.g., Agol et al. 2005). Integrations for semimajor 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 an 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 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 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 focus on the current snapshot of the orbital configuration of the system. The planets must be undergoing significant tidal dissipation because of the nonzero eccentricity. Our calculation of the dynamical evolution of the system is valid to first order because the tidal evolution timescale ($\sim 10^8$ yr) is long compared with the timescale of the orbital perturbations ($\sim 10^2$–10^3 yr). Other effects have been neglected at this stage, which include precession caused by the quadrupole moment of the star and by general relativity. A more detailed dynamical study of the system is left for a future paper.

3.2. *Reanalysis of the Radial Velocity Data*

To place more stringent constraints on the perturbing planet we studied the available radial velocity observations, covering a time lapse of 7 yr. The orbital solutions of Butler et al. (2004)

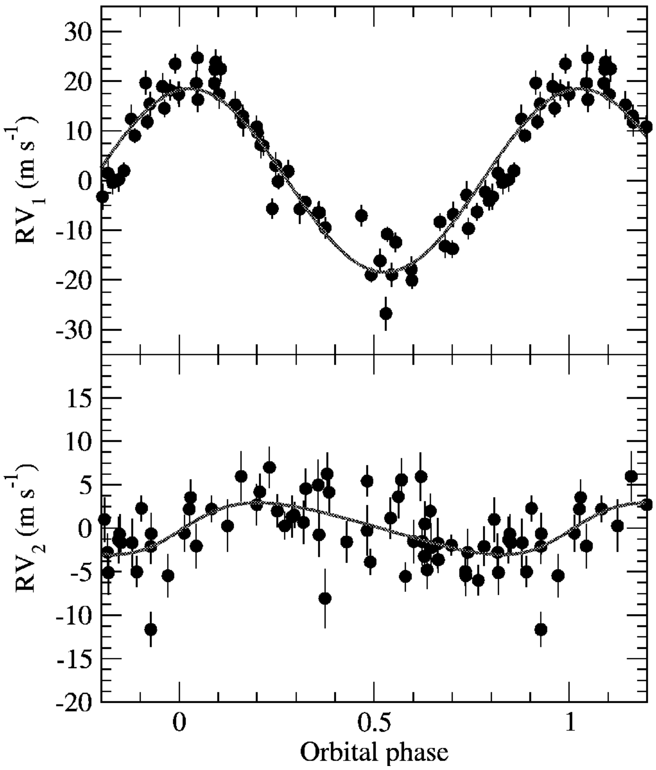

FIG. 2.—Two-planet radial velocity fit to GJ 436. Radial velocity observations of GJ 436 (Maness et al. 2007) were fitted with a model considering the orbital motions of two planets combined plus a long-term radial velocity drift. The panels show the radial velocities (with 1 σ error bars) associated with each respective planet where the contribution from the other planet has been removed, together with the best orbital fit. [*See the electronic edition of the Journal for a color version of this figure.*]

and Maness et al. (2007) yield radial velocity semiamplitudes of about 18 m s^{-1} for GJ 436b, in a solution with a rms residual of 4.8 m s^{-1}. We further analyzed the data by prewhitening of the frequencies from the reported Neptune-mass planet. The periodogram revealed a relatively strong peak corresponding to a period of about 5.2 days. To evaluate the significance of the detection, we calculated the false-alarm probability following the Monte Carlo procedure in Butler et al. (2004). From 1000 realizations we conclude that the false-alarm probability of the observed peak is ~20%, considering that only objects with periods between ~4 and ~8 days could be responsible for the observed perturbations in the orbital eccentricity and inclination of the inner planet. In a recent paper, Demory et al. (2007) report 23 spectroscopic measurements of GJ 436 using the HARPS spectrograph. Combining these with the data from Maness et al. (2007) could provide the needed stronger proof of the signal studied here.

Considering the evidence from the dynamic integrations, the peak in the periodogram is sufficiently significant to merit analysis. Starting from the 5.2 day period, a simultaneous fit to the orbits of two planets yielded the results in Figure 2 and Table 1. In the fit we fixed the period of the transiting planet to 2.643913 days, which provides a good match to the recent ground-based transit timings, and the eccentricity and the argument of periastron to 0.15 and 343°, respectively, for consistency with the observation of the occultation event (Deming et al. 2007; Demory et al. 2007). Certainly, the fit to the radial velocities should be consistent with our dynamical analysis. This is somewhat hampered by two unconstrained parameters, namely the relative inclination of the planets and also the true orbital orientation (radial velocities are only sensitive to the argument of the periastron). We evaluated a range of possible rates of variation in the eccentricities, arguments of periastron, and orbital periods of the two planets and found them to have negligible effects on the fits given the uncertainty of the radial velocity measurements and the time baseline. However, we considered a fit allowing for a linear change in these three elements for the transiting planet and yielded $\dot{e} = 0.03 \pm 0.02$ yr^{-1}, $\dot{w} = -1.8° \pm 1.5°$ yr^{-1}, and $\dot{P} = -5.7 \pm 2.0$ s yr^{-1}, all with low significance. The orbital elements in Table 1 should be regarded as osculating elements at the mean epoch of the radial velocities. Note that the period given is not sidereal but anomalistic (i.e., apparent). From the latter (P), the sidereal period (P_s) can be computed as $P_s = P(1 - \dot{w}P/2\pi)$.

TABLE 1
TWO-PLANET FIT TO THE RADIAL VELOCITIES

Parameter	GJ 436b	GJ 436c
P^1 (days)	2.643913 (fixed)	5.1859 ± 0.0013
$T_{\rm peri}$ (HJD)	2451551.65 ± 0.01	2451553.2 ± 0.7
e	0.15 (fixed)	0.2 (fixed)
ω (deg)	343 (fixed)	265 ± 43
K (m s^{-1})	18.4 ± 0.4	3.0 ± 0.4
a (AU)	0.0287 ± 0.0003	0.0450 ± 0.0004
$M \sin i$ ($M_\oplus$)	23.2 ± 0.5	4.7 ± 0.6
Radial velocity drift	1.1 ± 0.2	
rms (m s^{-1})	3.36	
$\chi^2_{\rm red}$	3.1	

[1] Anomalistic period.

The two-planet fit reduces significantly the rms residuals of the radial velocities to 3.4 m s^{-1}. We fixed the orbital eccentricity of the second planet because of instabilities in the solution. The adopted eccentricity of 0.2 is compatible with our perturbation analysis and provides a good fit to the data. The planet's minimum mass is 4.7 ± 0.6 $M_\oplus$. From the perturbation analysis and planetary system formation arguments, the relative inclination of the two planets is likely to be below 15°, and therefore the real mass of the planet should be about 5 $M_\oplus$ with 12% uncertainty. While this could not be considered an extremely solid detection, its is significant and the planet has the correct properties to explain the orbital effects observed in GJ 436b.

From the final system configuration, our dynamical calculations predict librations of the orbital elements of both planets over different timescales and with different amplitudes. Focusing on the inner planet, the inclination has a libration amplitude of ~5° with a period of ~110 yr. Its argument of periastron precesses with a period of ~500 yr but also has a libration amplitude of ~20° over a period of ~70 yr. For comparison, the general relativistic precession period is ~15,000 yr. Finally, the eccentricity has a libration amplitude of ~0.1 with a period of ~70 yr.

GJ 436c is the least massive planet known to orbit a main-sequence star and only the second bona fide warm super-Earth together with the 7.5 ± 0.7 $M_\oplus$ planet around GJ 876 (Rivera et al. 2005), since only minimum masses are available for the planets around Gl 581 (Udry et al. 2007). Interestingly, GJ 436c is found at an orbital period that is very close to the 2 : 1 MMR with GJ 436b, but not exactly so: $P_c/P_b = 1.9614 \pm 0.0005$. This small but significant departure may be a consequence of the tidal evolution of the system.

4. PROSPECTS FOR CONFIRMATION

Because of the inclination change, the effects of the perturbing planet will become evident in high-precision transit photometry collected during 2008. We carried out tests to assess the capability to detect small changes in the inclination using real *Spitzer* IRAC primary transit observations. We adopted a nonlinear limb-darkening law model with four coefficients and followed the procedure described in Mandel & Agol (2002) to fit the transit light curve. Then, we fitted the same data set with models for an inclination larger by 0.1°. Such expected inclination change will increase the transit duration in ∼2 minutes making it detectable from *Spitzer* at a reasonably high confidence level. Figure 3 shows the best fit to the 8 μm *Spitzer* data and the residuals.

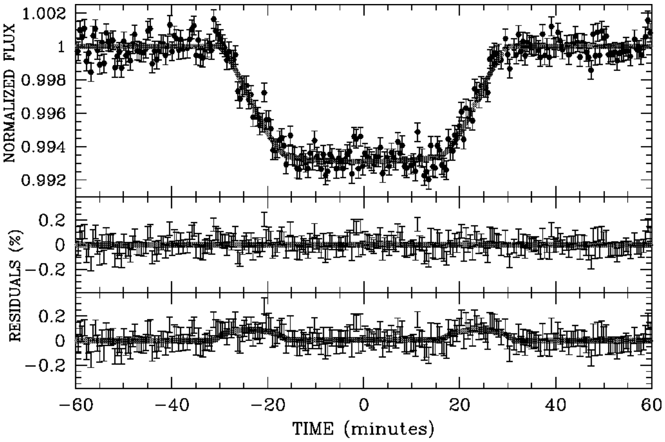

FIG. 3.—Effect of a +0.1° change in the orbital inclination of GJ 436b. The top panel shows the best fit to the 8 μm transit data from *Spitzer* (Gillon et al. 2007b). The middle panel shows the residuals from the fit, which result in a χ^2 value of 486 with 355 degrees of freedom. The bottom panel illustrates the residuals of the fit when assuming an orbital inclination higher by +0.1°, with a χ^2 increasing to 578. [*See the electronic edition of the Journal for a color version of this figure.*]

5. CONCLUSIONS

The proposed existence of GJ 436c is based on three independent pieces of evidence: (1) an orbital inclination change supported by the lack of transit detection in 2004 and the grazing transit observed in 2007; (2) an inner planet with significant orbital eccentricity and a tidal dissipation timescale much smaller than the age of the system; and (3) a low-amplitude radial velocity signal that is fully consistent with a planet in the 2 : 1 mean motion resonance with the inner planet. A key element of our study is a dynamical investigation that explains the observed effects 1 and 2, and predicts the existence of a perturbing planet with constraints on its mass and semimajor axis. Reanalysis of the radial velocity data indeed reveals such a planet closely matching the predicted properties. In other words, the eccentricity of the orbit clearly reveals the existence of a perturbing planet, and a grazing transit will be most sensitive to even mild non-coplanarity between the two objects. We find such possible inclination change and we identify a radial velocity signal matching the predictions of our dynamical integrations.

The resulting planet system around GJ 436 strengthens the trend of a relatively large number of hot Neptunes and super-Earths around stars of low mass (Bonfils et al. 2007). The presence of a long-term radial velocity trend of ∼1 m s^{-1} per year could still be indicative of further planets in the system with wider orbits. Indeed, the system around GJ 436 shows striking resemblances to that around the M-type star Gl 581 (Udry et al. 2007), and thus its planets may experience changes in the orbital elements, perhaps eventually undergoing transits in spite of a previously null result (López-Morales et al. 2006). Our study provides yet another illustration of the variety of exoplanet systems and highlights the potential for complex dynamical histories that imply sizeable variations of the planets' orbital elements over timescales of decades.

The method of using near-grazing transits should be of special interest for discovering small planets. Even for mild non-coplanarity, objects as small as a few $M_\oplus$ can lead to moderately high values of the induced eccentricity and to orbital inclination changes on the order of tenths of degrees per year. This will be especially effective for transit search missions from space, which could overcome the lower detection probability of near-grazing transits, and push the detection limits to even lower mass objects than those responsible for the transit events.

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