NEW OBSERVATIONS AND A POSSIBLE DETECTION OF PARAMETER VARIATIONS IN THE TRANSITS OF GLIESE 436b

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ABSTRACT

We present ground-based observations of the transiting Neptune-mass planet Gl 436b obtained with the 3.5 m telescope at Apache Point Observatory and other supporting telescopes. Included in this is an observed transit in early 2005, over 2 years before the earliest reported transit detection. We have compiled all available transit data to date and perform a uniform modeling using the JKTEBOP code. We do not detect any transit timing variations of amplitudes greater than ≈1 minute over the ≈3.3 year baseline. We do however find possible evidence for a self-consistent trend of increasing orbital inclination, transit width, and transit depth, which supports the supposition that Gl 436b is being perturbed by another planet of ≤12 M⊙ in a nonresonant orbit.

Subject headings: planetary systems — stars: individual (Gliese 436)

Online material: machine-readable table

1. INTRODUCTION

Gliese 436 is an M dwarf (M2.5 V) with a mass of 0.45 M⊙ and hosts the extrasolar planet Gl 436b, which is currently the least massive transiting planet with a mass of 23.17 M⊕ (Torres 2007), and the only planet known to transit an M dwarf. Gl 436b was first discovered via radial velocity (RV) variations by Butler et al. (2004) who also searched for a photometric transit, but failed to detect any signal greater than 0.4%. It was thus a surprise when Gillon et al. (2007b) reported the detection of a transit with a depth of 0.7%, implying a planetary radius of 4.22 R⊕ (Torres 2007) and thus a composition similar to Uranus and Neptune. In addition, both Deming et al. (2007) and Maness et al. (2007) calculated that the significant eccentricity of the orbit, e = 0.15, coupled with its short period of ≈26 days, should result in circularization timescales of ≈106 years, which contrasts with the old age of the system at ≈6 × 109 yr. The existence of one or more additional planets in the system could be responsible for perturbations to Gl 436b’s orbit, and thus result in the observed peculiarities. We considered this possibility right after the initial publication of Gillon et al. (2007b) and began an intensive campaign to observe the photometric transits of Gl 436b in order to search for variations indicative of orbital perturbations (Stringfellow et al. 2008).

Early this year, Ribas et al. (2008a) reported the possible detection of a ∼5 M⊙ companion in the Gl 436 system located near the outer 2 : 1 resonance of Gl 436b via analysis of all the RV data compiled to date. Theoretically this planet would be perturbing Gl 436b so as to increase its orbital inclination at a rate of ≈0.1° yr−1, and thus its transit depth and length, so that the nondetection by Butler et al. (2004) and the observed transit of Gillon et al. (2007b) were compatible. Since the RV detection of this second planet had a significant false-alarm probability of ∼20%, Ribas et al. (2008a) proposed that confirmation could be achieved through 2008 observations of Gl 436b’s transits, which would show a lengthening of transit duration by ∼2 minutes compared to the Gillon et al. (2007b) data. As well, transit-timing variations (TTVs) of several minutes should also be detectable by observing a significant number of transits.

Recently, Alonso et al. (2008) reported a lack of observed inclination changes and TTV evidence for the second planet, based on a comparison of a single H-band light curve obtained in 2008 March to 8 μm data taken with Spitzer 254 days earlier (Gillon et al. 2007a; Deming et al. 2007). This result, combined with additional radial velocity measurements (Howard 2008; Bonfils 2008) that contradicted the proposed period of the second planet, drove Ribas et al. (2008b) to retract their claim of the companion at IAU Symposium 253. However, very recently Shporer et al. (2008) presented multiple light curves obtained in 2007 May, and could not rule out TTVs on the order of a minute. While the planet specifically proposed by Ribas et al. (2008a) most likely does not exist, Ribas et al. (2008b) makes a strong case that a second planet is still needed to explain the peculiarities of Gl 436b, and most likely exists in a nonresonant configuration where no strong TTVs are induced. Amateur astronomers have been diligent in observing Gl 436 since its initial transit discovery, and thus along with this data, published data, and our own data, we are able to present a thorough analysis of the TTVs, inclination, duration, and depth of the transit changes in the Gliese 436 system. We present our observations in § 2, our modeling and derivation of parameters in § 3, and explore the observed TTVs and parameters of the system over time in § 4.

2. OBSERVATIONS

We observed Gl 436 (11h42m11s, +26°42′24″ [J2000.0]) in the V filter on the nights of 2008 April 7, April 28, and May 6 UT with the 3.5 m telescope at Apache Point Observatory (APO). We used a backside-illuminated SITe 2048 × 2048 CCD with 2 × 2 binning, resulting in a plate scale of 0.28′′ pixel−1, and subframed to a field of view of 4.8′ × 0.56′ to decrease readout time. We applied typical overscan, bias, and flat-field calibrations. For photometric reduction we used the standard IRAF task PHOT, with the aperture selected as a constant multiple of the Gaussian-fitted FWHM of each image to account for any variable seeing. We performed differential photometry with respect to the star USNO-...
1167−0208653 (2MASS ID 175252970) located at 11°42′12.08″, +26°46′07.45″ (J2000.0). This star has $V = 10.82$ and color $V−I = 1.48$, compared to Gl 436 which has $V = 10.68$, and color $V−I = 1.70$. In the error bar computation, we account for both standard noise from the photometry, as well as due to scintillation following equation (10) of Dravins et al. (1998). Having obtained at least 30 minutes of data on each side of the transit, we subtracted a linear fit for all data outside of transit versus air mass to account for any differential reddening. Resulting individual data points have errors ranging from 1.5 to 2.8 mmag, which agrees with the rms of the residuals from the model fits, and a typical cadence of about 17 s. We have searched for correlated noise on the timescale of ingress and egress, via the technique of Pont et al. (2006), but only find a statistically significant amount for the night of April 7, measured to be 0.11 mmag. The three transits are shown in Figure 1.

We also carried out accompanying observations with the New Mexico State University (NMSU) 1 m telescope at APO, in the $V$ filter on the night of 2008 April 7 UT, and in the $I$ filter on the night of 2008 April 28 UT. A 2048 $\times$ 2048 E2V CCD was used with $1 \times 1$ binning and subframing, resulting in a field of view of 8.0′ square and a plate scale of 0.47′′ pixel$^{-1}$, and we applied the aforementioned standard calibration and photometric extraction techniques. We performed ensemble photometry with respect to the USNO star that was used as the 3.5 m reference, as well as BD +27 2046 ($V = 10.64$, $V−I = 0.44$), and another star at 11°42′00″, +26°45′56″ (J2000.0) ($V = 12.81$, $V−I = 1.46$). Resulting typical errors on individual points range from 3 to 5 mmag with a typical cadence of about 12 s.

The NMSU 1 m telescope can also function as a robotic telescope, and is used intermittently to photometrically monitor stars with known radial velocity discovered planets to search for transits. A search of the 1 m archives revealed that it observed Gl 436 on the night of 2005 January 11 UT, during which a transit should have occurred, according to the precise ephemeris for Gl 436b that is now available by incorporating the many observed transits in 2007 and 2008. At the time, this 1 m program depended on visual inspection of automatically generated photometry and plots. For this night, the plot had large temporal and brightness ranges, and thus the tiny transit was easily missed. However, now carefully inspecting the region constrained by the ephemeris, as well as reprocessing the photometry to maximize signal-to-noise ratio, we find a transit signature within a minute of that predicted by the ephemeris with reasonable width and depth, as shown in Figure 1. Individual data points have an error of about 4 mmag, a cadence of 30 s, and we do not detect any correlated noise with any level of significance.

We also conducted observations on the nights of 2008 April 28 and May 13 UT using a 24 inch telescope located at the Sommers-Bosh Observatory (SBO) on the University of Colorado at Boulder campus, using an $I$ filter. These observations also used a windowed chip and an exposure time to maximize the signal-to-noise ratio without saturating, and have comparable temporal resolution to the 3.5 m and 1 m telescopes due to a shorter readout time. As well, we used an unfiltered 11 inch telescope at Cloudcroft, NM (CC) with a SBIG ST-7E CCD and $2 \times 2$ binning on 2008 May 6 UT, with a resulting cadence of about 25 s. We have also gathered all the amateur data currently available on the system as compiled by Bruce Gary.\footnote{See http://brucegary.net/AXA/GJ436/gj436.htm.}

3. MODELING AND DERIVATION OF PARAMETERS

We use the Jktebop code (Southworth et al. 2004a, 2004b) to model all the transit light curves in a consistent and uniform manner. Southworth (2008) has recently performed an exhaustive analysis of 14 transiting planets using the Jktebop code, and shows it compares well with results reported elsewhere. Jktebop offers the advantage of incorporating a Levenberg-Marquardt optimization algorithm, improved limb-darkening treatments, and extensive error analysis routines, which are critical for confirming any trends in the system.

For each transit curve, we solved for the ratio of radii ($k = R_p/R_s$), the orbital inclination ($i$), the time of midtransit ($T_c$), and a scale factor that defines the normalized value of the out-of-transit flux in the light curves. In order to obtain reasonable results for the scale of the system for all data sets, the sum of the radii ($R_s + R_p$) was set to that found by Torres (2007). We also fixed the eccentricity to a value of 0.15 and the longitude of periastron to 343° as given by Deming et al. (2007) and Mardling (2008). We used a quadratic limb-darkening law with coefficients taken from Claret (2000) for $T_{eff} = 3500$ K, $g = 4.5$, $V = 2.0$ km s$^{-1}$, and $[M/H] = 0.0$, for the appropriate filters. In the case of the Spitzer 8 μm data, we used the coefficients as determined by Gillon et al. (2007a). From each fit, still assuming a constant sum of radii, we were thus also able to calculate the individual star and planet radii, as well as the depth and width of transit. In order to rule out any potential correlations in derived planet size and inclination, we then remodeled all data with the same procedure, but also fixing $k$, and thus the star and planet sizes, to that found by Torres (2007).
This generally produced similar results, but for the noisier data sets achieved more consistent results. Parameters from both techniques are shown in Table 1.

In order to obtain robust errors, we ran 1000 Monte Carlo simulations for each data set and performed a residual-permutation analysis (Jenkins et al. 2002) to investigate temporally correlated noise. In both cases, the previously fixed parameters, as well as the limb-darkening coefficients, were allowed to vary so that their individual uncertainties would be taken into account in the derived parameter uncertainties. For each Monte Carlo simulation, random Gaussian noise with amplitude equal to the given error bars, or in the absence thereof the standard deviation of the residual scatter from the best-fit solution, was added to each data point and the curve refitted with random perturbations applied to the initial parameter values. This ensured a detailed exploration of the parameter space and parameter correlations. However, this Monte Carlo technique will underestimate errors for certain parameters in the presence of temporally correlated noise, which can result from trends in seeing, extinction, focus, or other atmospheric or telescope related phenomena (Southworth 2008). The residual-permutation method takes the residuals of the best-fit model, shifts them to the next data point, and finds a new solution. The residuals are shifted again, a new fit is found, and the process repeats as many times as there are data points. Thus, there is a distribution of fitted values similar to the Monte Carlo technique, but any temporal trends will have been propagated around the light curve, and thus taken into account. For our final errors we adopt the larger value found between the two methods, although for the majority of parameters and data sets the two methods agree quite well.

In total we modeled 28 light curves (16 professional and 12 amateur), covering 19 separate transit events over a baseline of nearly 3.3 years.

### 4. TRANSIT TIMING AND ECLIPSE VARIATIONS

Using the derived time of minima in Table 1 for all the data when allowing $k$ to vary, we derive a new linear, error-weighted ephemeris of $T_{\text{trans}} = 2,452,222.6164(1) + 2.643897(2)E$, where the parentheses indicate the amount of uncertainty in the last digit, and $E$ is the epoch with $E = 0$ the initial transit discovery of Gillon et al. (2007b). Using this ephemeris, we then compute an observed minus calculated ($O - C$) diagram for the time of transit center, as shown in Figure 2. We have currently excluded the amateur data from the plot due to much larger error bars, so that the high-precision data points can be seen clearly. We have examined the TTVs and various subsets thereof using a phase dispersion minimization technique (Stellingwerf 1978), but do not find any periods with statistical significance. Examining the best data, specifically the previously published data and our 3.5 m observations, there is a standard deviation of 52 s. Assuming a sinusoidal TTV trend, we can then rule out any TTVs with amplitude greater than $\sim 1$ minute.

We have searched for any trends in derived inclination, width, and depth of transit over time via error-weighted least-squares linear regression. In addition, we have also performed 10,000 Monte Carlo simulations for each fit, where Gaussian noise with amplitude equal to each point’s error bars was added in each iteration and the data refitted, with resulting 1 $\sigma$ parameter distributions giving robust errors. The two methods agree to within 1% for all values. As mentioned in § 3, we modeled all the light curves by both allowing the ratio of radii to vary as well as fixing it, and thus we list the values for each set. Performing fits to all the data, we have a tentative detection of increasing inclination, transit width, and transit depth with time, as shown in Table 2. We present these fits with the actual data derived when fixing the radii in Figure 3. As a precaution against any bias being introduced by the much larger number of data points at later epochs, we decided to separately bin the 2005,

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**Table 1**

| Epoch | Source | Filter | $T_{\text{trans}}$ (HJD − 2,450,000) | Inclination (deg) | $R_p/R_*$ | Depth (mmag) | Width (minutes) |
|-------|--------|--------|-------------------------------------|------------------|------------|-------------|----------------|
| −318  | NMSU 1 m | V      | 3381.85584 ± 0.00179               | 86.02 ± 0.23     | 0.446 ± 0.046 | 6.19 ± 4.81 | 7.05 ± 1.35   | 47.0 ± 7.1   |
| ...   | ...    | ...    | ...                                 | ...              | ...        | ...         | ...           |
| −318  | NMSU 1 m | V      | 3381.85596 ± 0.00212               | 86.15 ± 0.17     | 0.464 ± 0.016 | 4.23 ± 0.28 | 5.61 ± 0.63   | 52.5 ± 3.2   |

Note:—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

**Table 2**

| Data Set | deg yr$^{-1}$ | minutes yr$^{-1}$ | mmag yr$^{-1}$ |
|----------|---------------|------------------|----------------|
| Variable radii: All | 0.120 ± 0.062 | 3.43 ± 1.01 | 0.28 ± 0.16 |
| Binned | 0.126 ± 0.061 | 3.53 ± 0.97 | 0.26 ± 0.14 |
| No 2005 | 0.092 ± 0.099 | 3.10 ± 1.10 | 0.29 ± 0.17 |
| Fixed radii: All | 0.069 ± 0.051 | 2.36 ± 0.84 | 0.32 ± 0.20 |
| Binned | 0.071 ± 0.050 | 2.37 ± 0.81 | 0.32 ± 0.19 |
| No 2005 | 0.020 ± 0.099 | 1.68 ± 1.29 | −0.01 ± 0.42 |

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Fig. 2.—$O - C$ diagram for all professional times of minima.
We have collected and uniformly modeled all available professional and amateur light curves, and searched for any trends in transit timing, width of transit, and depth of transit variations. We find statistically significant, self-consistent trends that are compatible with the perturbation of Gl 436b by a planet with mass $\leq 12 M_{\oplus}$ in a nonresonant orbit with semimajor axis $\leq 0.08$ AU. This conclusion is based on the numerical simulations of Ribas et al. (2008a, see Fig. 1) who constrain the mass and semimajor axis of the theoretical second planet by examining which configurations could produce the observed orbital perturbations while still remaining undetected by the existing radial velocity data. From our analysis, we infer a nonresonant orbit based on a lack of detected TTVs with amplitude $\geq 1$ minute.

We stress that our measured trends are moderately dependent on our 2005 data, and thus subsequent high-precision observations over the next few years need to be carried out to confirm or refute this trend. If confirmed, it would be strong evidence for the first extrasolar planet discovered via orbital perturbations to a transiting planet. Also, we would like to note that although Alonso et al. (2008) had previously limited the rate of inclination change to $0.03^{\circ}$ $\pm 0.05^{\circ}$ yr$^{-1}$, they did so only by measuring the change in width between the 2007 *Spitzer* observations and their own 2008 *H*-band data, which they found to be $0.5^{\circ}$ $\pm 1.2$ minutes. Via Table 1, we find the difference in transit width between the two observations to be $1.5^{\circ}$ $\pm 1.4$ minutes, which is in agreement with our derived inclination and width values, and is a more reliable result due to using full model fits with proper limb-darkening coefficients. With respect to the amateur observations, although they are numerous, the very small depth of the transit makes it a challenge for most small aperture systems, resulting in very large uncertainties in $i$ and $T_p$. Also, while amateur observers are aware of the importance of precision timing, we of course cannot examine each of their observing setups, and thus one must be aware of the possibility, although small, of systemic time offsets on a given night when interpreting their data.

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### REFERENCES

Alonso, R., et al. 2008, A&A, 487, L5

Bonfils, X. 2008, in IAU Symp. 253, Transiting Planets, in press

Butler, R. P., et al. 2004, ApJ, 617, 580

Claret, A. 2000, A&A, 363, 1081

Deming, D., et al. 2007, ApJ, 667, L199

Dravins, D., Lindgren, L., & Mezey, E. 1998, PASP, 110, 610

Gillon, M., et al. 2007a, A&A, 471, L51

———. 2007b, A&A, 472, L13

Howard, A. 2008, in IAU Symp. 253, Transiting Planets, in press

Jenkins, J. M., Caldwell, D. A., & Borucki, W. J. 2002, ApJ, 564, 495

Maness, H. L., et al. 2007, PASP, 119, 90

Mardling, R. A. 2008, MNRAS, submitted (arXiv:0805.1928)

Pont, F., Zucker, S., & Queloz, D. 2006, MNRAS, 373, 231

Ribas, I., Font-Ribera, A., & Beaulieu, J.-P. 2008a, ApJ, 677, L59

Ribas, I., et al. 2008b, in IAU Symp. 253, Transiting Planets, in press (arXiv: 0807.0235)

Shporer, A., et al. 2008, ApJ, submitted (arXiv:0805.3915)

Southworth, J. 2008, MNRAS, 386, 1644

Southworth, J., Maxted, P. F. L., & Smalley, B. 2004a, MNRAS, 351, 1277

Southworth, J., et al. 2004b, MNRAS, 355, 986

Stellingwerf, R. F. 1978, ApJ, 224, 953

Stringfellow, G. S., et al. 2008, in AIP Conf. Proc., Cool Stars XV, in press

Torres, G. 2007, ApJ, 671, L65