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Relative photometry of transiting exoplanet COROT-Exo-2b

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Abstract. Relative CCD photometry of the extrasolar planet COROT-Exo-2b transiting in front of its parent star was carried out at the Astronomical and Geophysical Observatory of Comenius University at Modra (AGO). Physical and orbital parameters were determined and compared with the previous published data.

Key words: extrasolar planet – relative photometry

1. Introduction

The idea of planets orbiting another stars appeared through philosophic ideas of ancient Greeks, centuries later in book by Huygens (1698) and finally since the middle of the 20th century. Despite reasonable methods observers were not successful (e.g. Strand, 1943; Reuyl and Holmberg, 1943; van de Kamp, 1963; Harrington *et al.*, 1983; McCarthy *et al.*, 1985). Recent development of observation techniques and instrumentation finally led to the first discovery of a planet orbiting a star - surprisingly a pulsar (Wolszczan and Frail, 1992) by a pulse timing method. Three years later the first planet orbiting a sun-like star 51 Pegasi was discovered (Mayor and Queloz, 1995) by radial velocity method. Yet, first planets were strange in comparison to those in our Solar system - usually with their mass several times greater than the mass of Jupiter and with orbital periods of only several days, heavily irradiated by their parent star ("hot Jupiters"). 333 objects classified as extrasolar planets (exoplanets) were known before December 10, 2008 (*The Extrasolar Planets Encyclopaedia, 2008*), most of them detected thanks to precise spectroscopy (a radial velocity method) and photometry (a transit method), 31 of them in multiple systems. Currently, the object is considered an exoplanet if its $M \sin i$ is less than $13\,M_{jup}$ (Jupiter masses, approx. a boundary between planets and brown dwarfs, lighter objects never go through a Deuterium burning stage, e.g. Burrows *et al.*, 1997), orbiting s star or multiple star systems. Several ground-based (HAT - Bakos *et al.*, 2002; OGLE - Udalski *et al.*, 2002; TrES - Alonso *et al.*, 2004, WASP - Pollaco *et al.*,

2006) and the first space-based exoplanet survey (COROT) are carried out and new discoveries increase rapidly. Less massive planets are discovered. Some data become inaccurate because the errors spread in time from published dates. Photometry of a transiting exoplanet could reveal the transit time, depth of transit, duration of transit, revolution period, radius of planet and the inclination of the orbit quite precisely and the method is applicable also for a small astronomical telescope. We present the first successful attempt to detect an extrasolar planet transit from Slovakia, calculate physical parameters of the system and update the transit time and reduce errors.

2. COROT-Exo-2b

COnvection ROtation and planetary Transits (COROT) is a space mission telescope led by ESA and French Space Agency, launched on December 27, 2006. The 27 cm telescope is aimed for two main goals: discovery of short period transiting exoplanets and asteroseismology. The advantage of the mission lies in ability to scan the same field of view for a long period of time (weeks) without an interruption and perform almost real time photometric analysis of tens of thousands stars. Also its space-based position allows to acquire high precision photometry of the order of 10^{-3} magnitude in one exposure. COROT-EXO-2b was the second exoplanet discovered by this mission (Alonso *et al.*, 2008). The "hot Jupiter" like planet is rotating around K0V type star GSC 00465-01282 at 930 ly distance (Bouchy *et al.*, 2008) in Aquila constellation. Physical properties of the parent star and planet are given in Table 1. It is assumed that the planet originated much farther from the parent star and has overcome substantial orbital evolution. Strong tidal effects from its parent star might have affected the physical and orbital properties of the planet (Jackson *et al.*, 2008, Pont, 2008). The detailed lightcurve analysis of the star confirmed the existence of stellar spots and facular fields, also the stellar rotation rate is relatively high (4.5 days). The star is most likely more active than our Sun. The oscillation of spotted photospheric regions is equal to 10 synodic periods of the planet and suggests the magnetic interaction between the exoplanet and parent star (Lanza *et al.*, 2008). Alonso et al. (2008b) detected a tentative secondary eclipse at the level of $5.5\text{x}10^{-5}$. They also studied the O-C diagram and concluded that there are no periodic variations in the O-C residuals larger than 10 s. Many observations of COROT-Exo-2b transits with the basic parameters derived (such as the transit duration, epoch and depth) can be found in the Exoplanet Transit Database.

3. Observation and data reduction

The observation of COROT-Exo-2b was performed from the AGO Modra (Code 118) by the 60cm main Cassegrain type telescope equipped with a CCD camera

Apogee Ap8 in primary focus. We observed during 4 nights, beginning on August 27, September 17, October 1 and 15, whereby the object had to reach the minimal altitude 30 degrees above the horizon. Good photometric conditions were needed since the magnitude drop during the transit was expected to be only 0.032 *mag* in the Johnson R-filter according to data by Alonso et al., 2008. We chose the relative photometry as a method, exposing 30 seconds each image in the R-filter. Data reduction was made with the MaxIm DL and CCD image analysis software by Világi, 2007. The brightness of the parent star COROT-Exo-2 was compared with 8 stars in the field of view of comparable brightness and spectral type with no lightcurve variability (not a variable star according to used catalogues GSC and USNO A2, no variability observed). The overall standard photometric error for comparison stars during the observation reached 0.003 *mag* on August 27, 0.009 *mag* on September 17, 0.015 *mag* on October 1 and 0.02 *mag* on October 15. As seen on quality of photometry, the weather and seeing conditions during the third and fourth night did not provide data with sufficient photometric precision, therefore data from the first two nights were used for lightcurve analysis.

4. Data analysis

Reduction of data from the first night immediately showed the decrease and increase of the parent star brightness among the quasi stable brightness of comparison stars. Only during this night we detected the entire progress of transit and short periods before the first and after the fourth contact between the planet and star disks. To determine the beginning and the end of the transit we used the AVE software (Barbera, 2000) which used the Kwee - van Woerden method (Kwee and van Woerden, 1956). Then the middle of the transit (transit epoch) and transit duration were derived. The second night's observation did not cover the whole transit and the reduced data were therefore used for lightcurve shape improvement only. The transit epoch from the first night with the orbital period of the planet (Alonso *et al.*, 2008) were used for linking the data from the second night of observation. To find selected physical and orbital parameters of COROT-Exo-2b we had to find a model lightcurve which would fit the measured data.

The real shape of the photometric curve depends on the inclination of the orbit i, orbital period P, planet semimajor axis a, diameter of the planet R_P and the star R_* (Cassen *et al.*, 2006). We consider that the stellar disk is not uniformly bright and hat the orbital eccentricity e is zero and P, a are known (Alonso *et al.*, 2008). We used a quadratic expression for limb darkening (Cassen *et al.*, 2006) which depends on dimensionless coefficients c_1, c_2, wavelength λ, projected distance between the center of the planet and the star r and R_*. In this case the intensity is given by

Table 1. Physical properties and orbital parameters of extrasolar planet COROT-Exo-2b and its parent star, left - previously published values, right - our results.

star (GSC 00465-01282)	Alonso *et al.*, 2008	
α(2000)	19 h 27 m 06.494 s	
δ(2000)	+01° 23' 01.17"	
Spectral Type	K0V	
Apparent Magnitude (V)	12.57	
Distance	930 ly	
Mass	$0.97 \pm 0.06\, M_{\odot}$	
Effective Temperature	$5625 \pm 120\, K$	
Radius	$0.902 \pm 0.018\, R_{\odot}$	
planet (COROT-Exo-2b)	**Alonso *et al.*, 2008**	**our results**
Mass	$3.31 \pm 0.16\, M_{jup}$	
Semimajor axis	$0.0281 \pm 0.0009\, AU$	
Orbital period	$1.7429964 \pm 0.0000017\, day$	
Eccentricity	0	
Radius	$1.465 \pm 0.029\, R_{jup}$	$1.318 \pm 0.158\, R_{jup}$
Transit epoch (HJD)	2454706.4016 ± 0.03766	2454706.4041 ± 0.0030
Inclination	87.84 ± 0.10	87.88 ± 0.15
Transit duration	2.28 ± 0.06 *hours*	2.24 ± 0.15 *hours*
Transit depth	0.032 ± 0.002	0.030 ± 0.007

$$I(\lambda, r) = I(\lambda, 0)[1 - c_1(\lambda)(1-\mu) - c_2(\lambda)(1-\mu)^2], \tag{1}$$

where

$$\mu = cos\theta = \sqrt{1 - (r/R_*)^2} \tag{2}$$

θ is the angle from the normal to the surface to the line of sight and $I_\lambda(0)$ is the intensity emerging from the stellar disk center.
The flux from an unocculted star at the observer is

$$F \approx \int I d\omega \tag{3}$$

where ω is the space angle subtended by the star on the sky and $d\omega$ is given by

$$d\omega = 2\pi \frac{R^2}{D^2} \sin\theta \cos\theta d\theta \tag{4}$$

Then

$$F = \frac{2\pi R^2}{D^2}\, I_0 \int_0^{\pi/2} [1 - c_1(1-cos\theta) - c_2(1-cos\theta)^2]\, sin\theta\, cos\theta\, d\theta \tag{5}$$

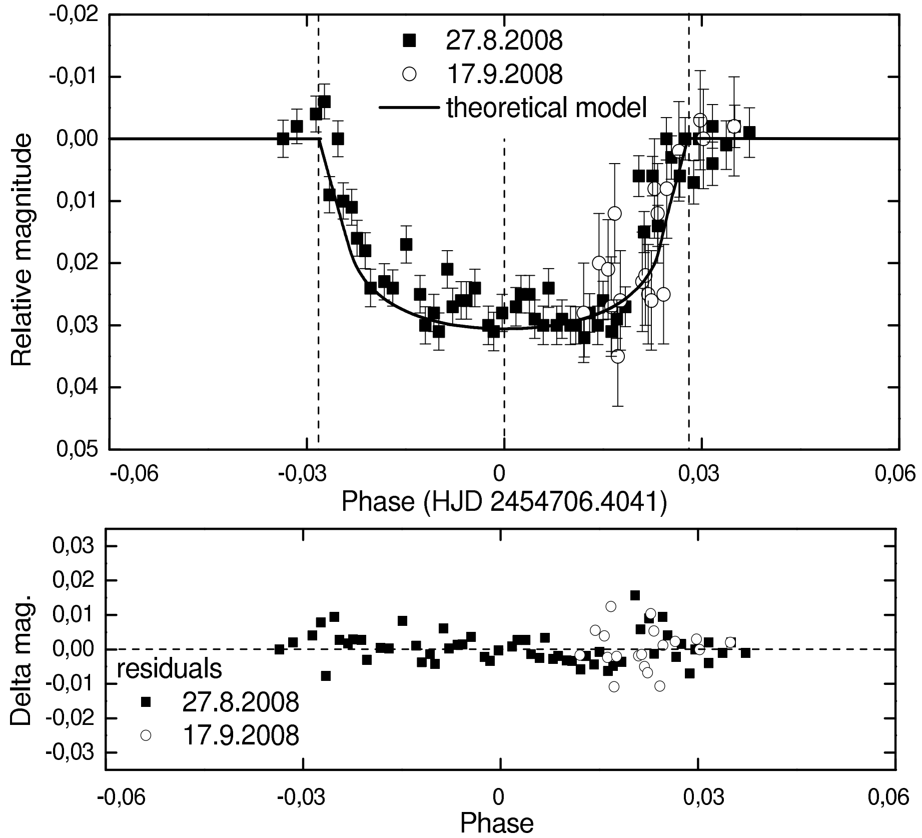

Figure 1. Photometric curve (top) and residuals from our theoretical model (bottom) of transiting extrasolar planet COROT-Exo-2b, data from second night were given to a phase according to first night data, the beginning, center and the end of the transit is marked.

where D is the distance between the observer and the star. The detected flux of unocculted stellar disk leads to

$$F = \pi \frac{R^2}{D^2} I_0 \left[1 - \frac{c_1}{3} - \frac{c_2}{6} \right] \tag{6}$$

Assuming that $R_P \ll R$ the intensity can be considered constant within the eclipsed region. Consequently, within the 2-nd and 3-rd contact we may approximate the eclipsed flux as $\delta F \approx I(\mu) \frac{\pi R_P^2}{D^2}$ and derive the normalized lightcurve as

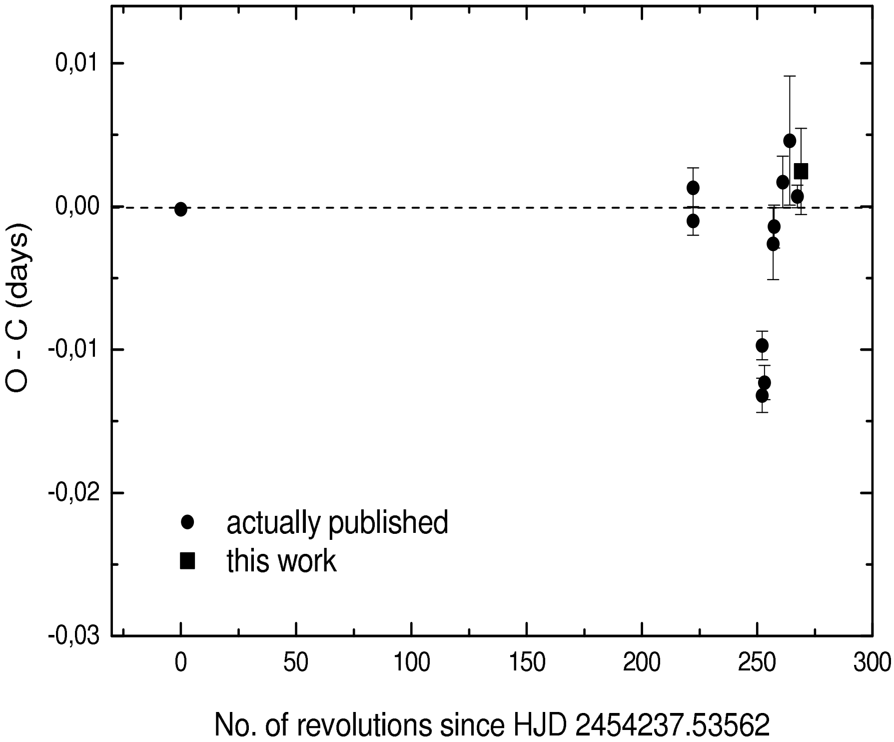

Figure 2. The O - C diagram of all actually published observations. It shows how the observed minus calculated transit epoch differs from the time of observation. X-axis represents the number of planet revolutions around the parent star since the discovery.

$$\frac{F-\delta F}{F} = 1 - \frac{\delta F}{F} = 1 - \frac{1-c_1(1-\mu)-c_2(1-\mu)^2}{1-\frac{c_1}{3}-\frac{c_2}{6}} \frac{R_P^2}{R^2} \tag{7}$$

where $r = a\sqrt{sin^2(2\pi t/P) + cos^2 i cos^2(2\pi t/P)}$. Eq.(7) is time dependent. We derived the stellar limb darkening coefficients $c_1 = 0.38$ and $c_2 = 0.25$ according to the spectral type, mass and temperature of the parent star COROT-Exo-2 (Table 1) from Claret *et al.*, 1995. Now, applying the nonlinear regression method on Eq.(7) we could find its free parameters R_P and i. The method fits the data in order to minimize the sum of χ^2 (standard deviations between the regression function and data points), considering that we know the remaining variables of Eq.(7). Derived parameters are shown in Table 1 and the fitting lightcurve with measured data points in Figure 1. The magnitude drop also yields from a model lightcurve.

Table 2. Table of published transit epochs for COROT-Exo-2b, according to Exoplanet Transit Database, 2008.

transit epoch (HJD)	O - C (min)	reference
2454237.53562 ± 0.00014	0	Alonso *et al.*, 2008
2454624.4799 ± 0.0016	-0.0009	Kleidis (AXA), 2008
2454624.4831 ± 0.0011	0.0023	Ayiomamitis (AXA), 2008
2454676.7577 ± 0.001	-0.013	Roe (AXA), 2008
2454676.7612 ± 0.0008	-0.0095	Roe (AXA), 2008
2454678.5016 ± 0.0012	-0.0121	Mendez (AXA), 2008
2454683.7403 ± 0.0014	-0.0024	Roe (AXA), 2008
2454685.4843 ± 0.0007	-0.0014	Naves (AXA)
2454692.4595 ± 0.0015	0.0018	Mendez (AXA), 2008
2454697.6913 ± 0.0015	0.0046	Roe (AXA), 2008
2454702.9164 ± 0.0015	0.0007	Foote (AXA), 2008
2454706.4041 ± 0.003	0.0025	Vereš *et al.*, 2008

5. Conclusions

We carried out transit observations of the COROT-EXO-2b and a simple analysis of the light curve. The transit depth in the R-filter was $0.030 \pm 0.007\,mag$, which corresponds to the radius of the exoplanet $R_P = 1.318 \pm 0.158\,R_J$ and the inclination of the orbit $i = 87.88 \pm 0.15$. This is in agreement with the parameters from the COROT mission. Our results confirm a relatively large radius of the planet and evolutionary calculations with an alternate source of energy such as a tidal heating might be needed to explain it (see Burrow et al. 2008). The center of the transit was observed at HJD 54706.4041 ± 0.0030 and the duration of the transit was 2.24 ± 0.15 hours. In Figure 2 (see also Table 2) we put it into the context of other ground based observations and study the O - C diagram. At present, we cannot confirm any convincing evidence of the period variability which might have been indicated by the three outlying points and our results are in agreement with those of Alonso et al. (2008, 2008b).

Although the quality of the ground based data cannot be compared with those from the COROT mission they still might help to constrain the properties of the planet. Advantages of the ground observations are a long time baseline and a wavelength limited spectral window. It is hoped that additional ground based observations can improve the orbital period or reveal possible changes in the planet's orbit. Also, additional ground based observations in relatively well defined spectral regions in the red part of the spectrum like those defined by the R, I filters might have a good control over the limb darkening which is wavelength dependent. Consequently, it might help to constrain the planet's radius determined from the wide visual spectral region of COROT.

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URL: The Extrasolar Planets Encyclopaedia, `http://www.exoplanet.eu/`