Photometric observations of transiting extrasolar planet WASP - 10 b

T. Krejčová[1,2]**, J. Budaj**[2] **and V. Krushevska**[2,3]

[1] *Masaryk University, Department of Theoretical Physics and Astrophysics,*
602 00 Brno, The Czech Republic, (E-mail: terak@physics.muni.cz)
[2] *Astronomical Institute of the Slovak Academy of Sciences*
059 60 Tatranská Lomnica, The Slovak Republic, (E-mail: budaj@ta3.sk)
[3] *Main Astronomical Observatory of National Academy of Sciences of*
Ukraine, 27 Akademika Zabolotnoho St. 03680 Kyiv, Ukraine, (E-mail:
*vkrush@mao.kiev.ua)*

Abstract. Wasp - 10 b is a very interesting transiting extrasolar planet. Although its transit is very deep, about 40 mmag, there are very different estimates of its radius in the literature. We present new photometric observations of four complete transits of this planet. The whole event was detected for each transit and the final light curve consists of more than 1500 individual CCD exposures. We determine the following system parameters: planet to star radius ratio $R_\mathrm{p}/R_\star = 0.168 \pm 0.001$, star radius to semimajor axis ratio $R_\star/a = 0.094 \pm 0.001$ and inclination $i = 87.3 \pm 0.1$ deg. Assuming that the semimajor axis is $0.036\,9 \pm^{0.0012}_{0.0014}$ AU (Christian et al. 2009), we obtain the following radius of the planet $R_\mathrm{p} = 1.22 \pm 0.05\,R_\mathrm{J}$, and radius of the star $R_\star = 0.75 \pm 0.03$. The errors include the uncertainty in the stellar mass and the semimajor axis of the planet. Surprisingly, our estimate of the planet radius is significantly higher (by about 12 percent) than the most recent value of Johnson et al. (2009). We also improve the orbital period $P_\mathrm{orb} = 3.092\,731 \pm 1 \times 10^{-6}$ days and estimate the average transit duration $T_\mathrm{D} = 0.097\,4 \pm 8 \times 10^{-4}$ days.
Key words: extrasolar planets – transit – light curve

1. Introduction

Transiting extrasolar planets are the VIP's (very important planets) of the extrasolar planet community (exoplanets), being the key to the understanding of the physics and various processes in the interior and atmospheres of substellar objects. The orientation of their orbits in space with respect to the observer is so fortunate that they allow us to observe the transit of the planet in front of the parent star as a dip in the light curve. Photometric observations of these transits (in combination with spectroscopy) provide us with important parameters of the system: orbital period, inclination, mass and radius of the planet. The planet radius is a complicated function of the planet mass, age, chemical composition as well as properties of its orbit and the parent star (Guillot &
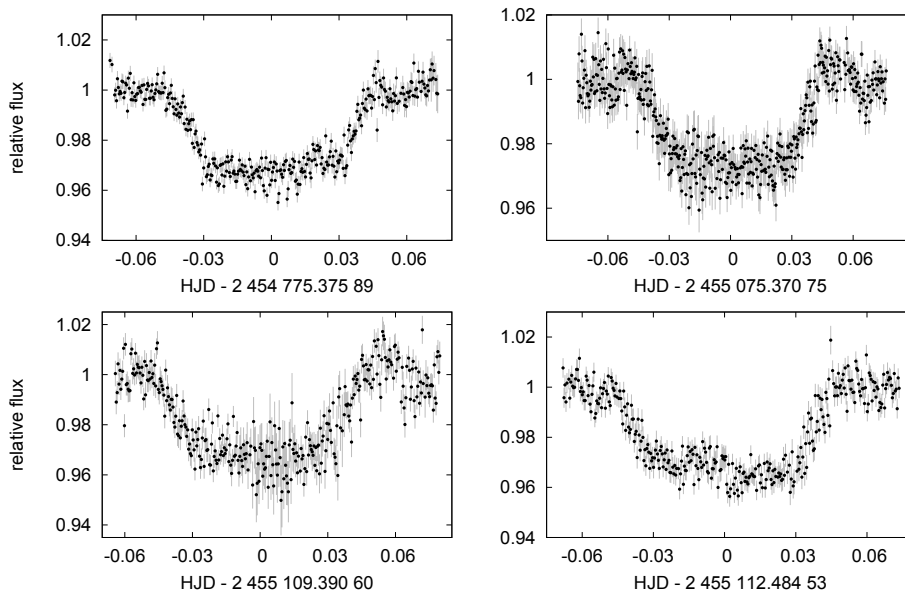
Figure 1. The observations from the following nights from top left: 4/11/08, 31/8/09, 4/10/09 and 7/10/09 (dd/mm/yy).

Showman 2002, Burrows et al. 2007, Fortney et al. 2007, Baraffe et al. 2008, Leconte et al. 2010). Precise knowledge of planetary radii is essential for further progress in the field.

Wasp-10 b is one of the 80 so far known transiting extrasolar planets (Schneider, 1995). It was discovered in 2008 by the Wide Angle Search for Planets (WASP) Consortium (Christian et al. 2009). The exoplanet orbits the parent star GSC 2752-00114 (spectral type K5) at the distance of 0.036 9 AU and has the mass of 2.96 M_J (Christian et al. 2009). Wasp-10 b has one of the deepest transit depth, cca 39 mmag (Poddany et al. 2010). This results in the planet radius of about 1.28 R_J (Christian et al. 2009). This radius is quite large and an additional internal heat source is required to understand such large radii. Unfortunately, their most precise observations do not cover the whole transit events.

Soon after the discovery the properties of the exoplanet were revisited by Johnson et al. (2009). They obtained superb observations with the UH 2.2m telescope which covered the whole transit and significantly improved the precision of the radius determination. However, contrary to the discovery paper, they determined a very different radius of the planet: $R_p = 1.08 R_J$, which is 16 percent smaller than that given in the discovery paper. The origin of the difference was not entirely clear. Nevertheless, the new radius is consistent with

previously published theoretical radii for irradiated Jovian planets. Miller et al. (2009) could explain its new radius without any additional heat sources.

2. Observations and data reduction

Our observations were made with the Newton 508/2500 mm telescope with the CCD camera SBIG ST10 XME in R band (UBVRI system). The telescope is located in Stará Lesná in the High Tatra Mountains in Slovakia. The transiting system was observed during four nights — 4/11/08, 31/8/09, 4/10/09 and 7/10/09 (dd/mm/yy). The time base for our observations was provided by the GPS device Motorola-Oncore M12+T. We performed the standard correction procedure (bias, dark and flat field correction) and subsequently aperture photometry with our data using the C-munipack software package[1]. We carefully chose a few comparison stars and created one "artificial" comparison star for each image as an average of individual fluxes of all comparison stars. By means of such procedure we obtain a 1σ accuracy of about 3-5 mmag per 1 CCD exposure depending on observing conditions.

We also removed the linear trend in the out-of-transit data. The resulting light curves from the four nights are depicted in Figure 1.

3. Data analysis

To obtain an analytical transit light curve we used the formulae from Mandel & Agol (2002) assuming the quadratic limb darkening in the form:

$$I(\mu)/I(1) = 1 - c_1(1 - \mu) - c_2(1 - \mu)^2, \tag{1}$$

where μ is the cosine of the angle between the line of sight and the normal to the stellar surface, $I(\mu)$ is the intensity at the place defined by μ, $I(1)$ is the intensity at the center of the disk and c_1 and c_2 are the coefficients of limb darkening. The limb darkening coefficients were linearly interpolated from Claret (2000) for the following star parameters: $T_{\text{eff}} = 4\,675\,\text{K}$, $\log(g) = 4.5$ and $[M/H] = 0.0$ (based on the results of Christian et al. (2009)). The coresponding coefficients for the R band are $c_1 = 0.5846$, $c_2 = 0.1689$. For subsequent analysis we combined observations of all four transits into a single light curve. This final composition is displayed in Figure 2 and consists of more than 1 500 individual CCD exposures.

To obtain the best fit parameters we found the minimal value of the χ^2 function given by:

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{m_i - d_i}{\sigma_i} \right)^2, \tag{2}$$

---

[1]See http://c-munipack.sourceforge.net
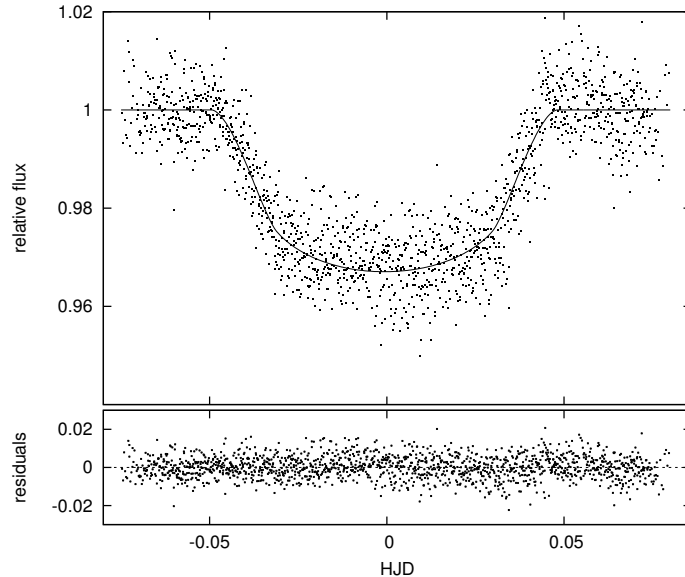
Figure 2. Top: Composition of 1 533 data points from the four nights: 4/11/08, 31/8/09, 4/10/09 and 7/10/09 (dd/mm/yy) of the exoplanetary system Wasp‑10 b. The observation were made in filter R (UBVRI system). The solid line is the best fit transit curve. Bottom: Residuals from the best fit model.

where m_i is the model value and d_i is the measured value of the flux, both for the ith measured value; σ_i is the uncertainty of the ith measurement. For the minimization procedure we used the downhill simplex method (Press et al. 1992). We search for the optimal values of the following parameters: planet to star radius ratio $R_{\mathrm{p}}/R_{\star}$, inclination i, the center of the transit T_{c} and the star radius to semimajor axis ratio $R_{\star}/a$. The orbital period and limb darkening coefficients were fixed.

To estimate the uncertainties of the calculated transit parameters we employed the Monte Carlo simulation method (Press et al. 1992). We produced about 1 000 synthetic data sets with the same probability distribution as the residuals of the fit in Figure 2. From each synthetic data set obtained this way we estimated the synthetic transit parameters. Subsequently, we were able to determine the uncertainties of the real parameters from the distribution of synthetic parameters. Finally, we took into account the uncertainty of the stellar mass and semimajor axis according to the simple error accumulation rule. The uncertainties of the planet and stellar radius are dominated by the uncertainties in the semimajor axis. In case the value of the host star mass and/or the

Table 1. Parameters of extrasolar system Wasp-10 from this work compared with the results from Christian et al. (2009) and Johnson et al. (2009). $R_{\mathrm{p}}/R_{\star}$ is the planet to star radius ratio, $R_{\star}/a$ is the star radius to semimajor axis ratio, i is the inclination of the orbit, P_{orb} is the orbital period, R_{p} is the planet radius, $R_{\star}$ is the host star radius, and T_{D} is the transit duration assuming the semimajor axis $a = 0.0369\pm^{0.0012}_{0.0014}\,\mathrm{AU}$ (Christian et al. 2009).

Parameter	This work	(Christian et al. 2009)	(Johnson et al. 2009)
$R_{\mathrm{p}}/R_{\star}$	0.168 ± 0.001	0.1703 ± 0.0029	$0.15918^{+0.0005}_{-0.00115}$
$R_{\star}/a$	0.094 ± 0.001	—	0.086 ± 0.009
$i\,[\deg]$	87.3 ± 0.1	$86.9^{+0.6}_{-0.5}$	$88.49^{+0.22}_{-0.17}$
$P_{\mathrm{orb}}\,[\mathrm{days}]$	$3.092731 \pm 1 \times 10^{-6}$	$3.0927636^{+0.0000094}_{-0.000021}$	—
$R_{\mathrm{p}}\,[R_{\mathrm{J}}]$	1.22 ± 0.05	$1.28^{+0.077}_{-0.091}$	1.08 ± 0.02
$R_{\star}\,[R_{\odot}]$	0.75 ± 0.03	$0.775^{+0.043}_{-0.040}$	0.698 ± 0.012
$T_{\mathrm{D}}\,[\mathrm{days}]$	$0.0974 \pm 8 \times 10^{-4}$	$0.098181^{+0.0019}_{-0.0015}$	$0.092796^{+0.00033}_{-0.00028}$

semimajor axis are revisited, our results and their errors can be simply rescaled.

The orbital period P_{orb} was determined by the linear fit according to the following equation for the known time of central transits $T_{\mathrm{c}}(E)$ and the epoch E:

$$T_{\mathrm{c}}(E) = T_{\mathrm{c}}(0) + E P_{\mathrm{orb}}, \tag{3}$$

where $T_{\mathrm{c}}(E)$ is the central time for epoch E and $T_{\mathrm{c}}(0)$ is the central time for $E = 0$. We present (Table 1) a preliminary result of the orbital period P_{orb}. A more detailed analysis of the transit timing variations will be presented elsewhere.

4. Conclusions

We have presented the observation and analysis of four light curves of exoplanetary system Wasp-10b. This enabled us to improve the orbital period and revisit the properties of the system. The resulting values of the parameters together with their uncertainties are given in Table 1. For comparison, the parameters from previous works are added there, too. Figure 2 shows the resulting best fit light curve together with measured data from all four nights.

Our results indicate that the radius of the planet is significantly larger than the latest estimate of Johnson et al. (2009). Our observations are in agreement with the original observations of Christian et al. (2009), but are more precise. This is quite surprising since Johnson et al. (2009) had seemingly superior observations[2]. Nevertheless, our value of the planet radius indicates that an additional alternative mechanism is required to inflate the planet size. Enhanced opacities in the atmosphere (Burrows et al. 2007) or a tidal heating mechanism studied

---

[2]Recently, after the submission of our paper, new independent observations and analysis of Wasp-10b with similar conclusions were carried out by Dittmann et al. (2010).

recently by Miller et al. (2009), Ibgui et al. (2010) and Leconte et al. (2010) might be invoked to explain the inflated radius of Wasp‑10 b.

References

Baraffe, I., Chabrier, G., Barman, T.: 2008, *Astron. Astrophys.* **482**, 315

Burrows, A., Hubeny, I., Budaj, J., Hubbard, W. B.: 2007, *Astrophys. J.* **661**, 502

Christian, D. J., Gibson, N. P., Simpson, E. K., Street, R. A., Skillen, I., Pollacco, D., Collier Cameron, A., Joshi, Y. C., Keenan, F. P., Stempels, H. C., Haswell, C. A., Horne, K., Anderson, D. R., Bentley, S., Bouchy, F., Clarkson, W. I., Enoch, B., Hebb, L., Hébrard, G., Hellier, C., Irwin, J., Kane, S. R., Lister, T. A., Loeillet, B., Maxted, P., Mayor, M., McDonald, I., Moutou, C., Norton, A. J., Parley, N., Pont, F., Queloz, D., Ryans, R., Smalley, B., Smith, A. M. S., Todd, I., Udry, S., West, R. G., Wheatley, P. J., Wilson, D. M.: 2009, *Mon. Not. R. Astron. Soc.* **392**, 1585

Claret, A.: 2000, *Astron. Astrophys.* **363**, 1081

Dittmann, J.A., Close, L.M., Scuderi, L.J., Morris, M.D.: 2010, *Astrophys. J.* **717**, 235

Fortney, J.J., Marley, M.S., Barnes, J.W.: 2007, *Astrophys. J.* **659**, 1661

Guillot, T., Showman, A. P.: 2002, *Astron. Astrophys.* **385**, 156

Ibgui, L., Burrows, A., Spiegel, D.S.: 2010, *Astrophys. J.* **713**, 751

Johnson, J.A., Winn, J.N., Cabrera, N.E., Carter, J.A.: 2009, *Astrophys. J., Lett.* **692**, L100

Leconte, J., Chabrier, G., Baraffe, I., Levrard, B.: 2010, *arXiv:1004.0463*

Mandel, K., Agol, E.: 2002, *Astrophys. J.* **580**, L171

Miller, N., Fortney, J.J., Jackson, B.: 2009, *Astrophys. J.* **702**, 1413

Poddaný, S., Brát, L., Pejcha, O.: 2010, *New Astronomy* **15**, 297

Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P.: 1992, *Numerical recipes in FORTRAN*, Cambridge: University Press, London

Schneider, J.: 1995, The Extrasolar Planet Encyclopaedia, *http://exoplanet.eu*