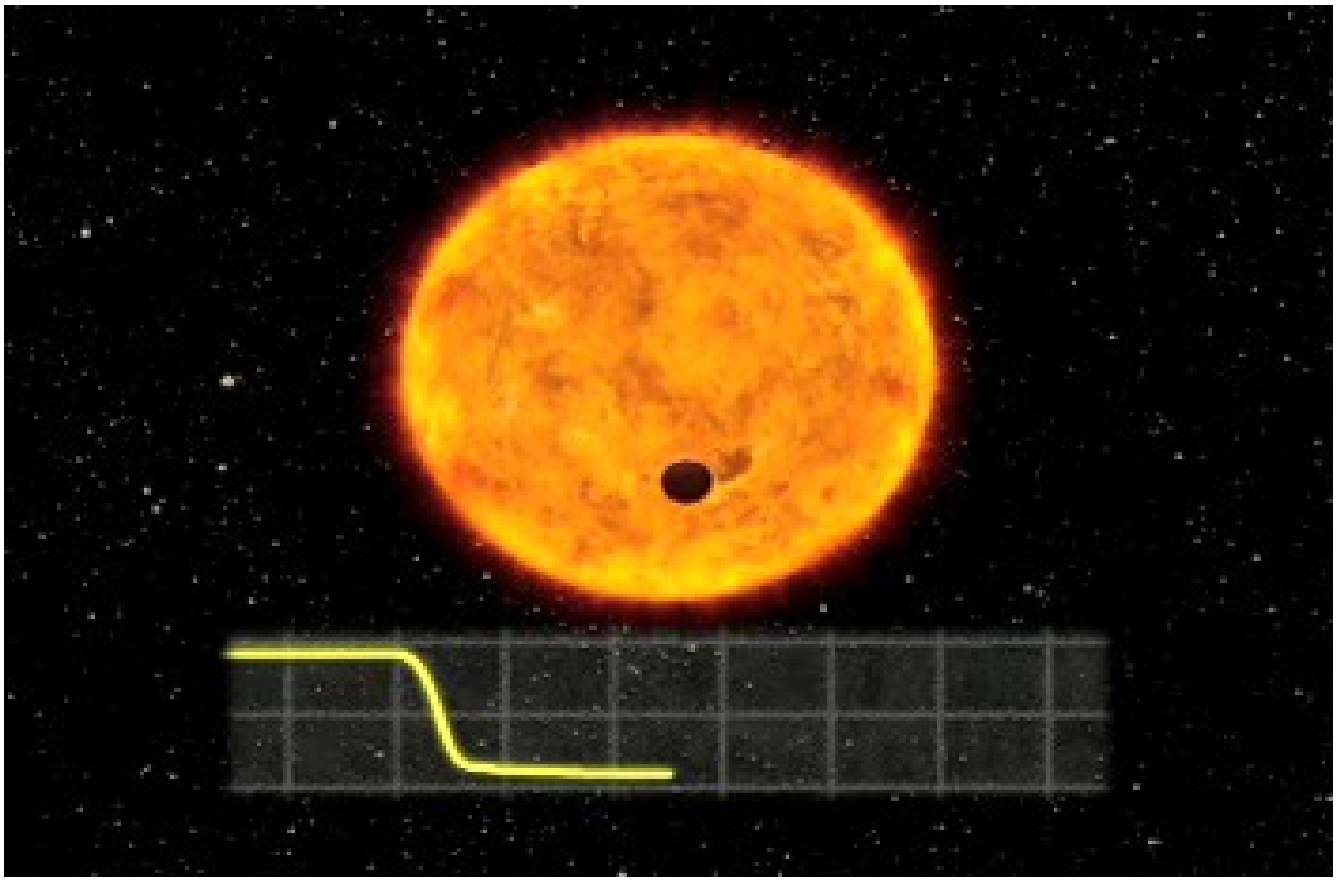
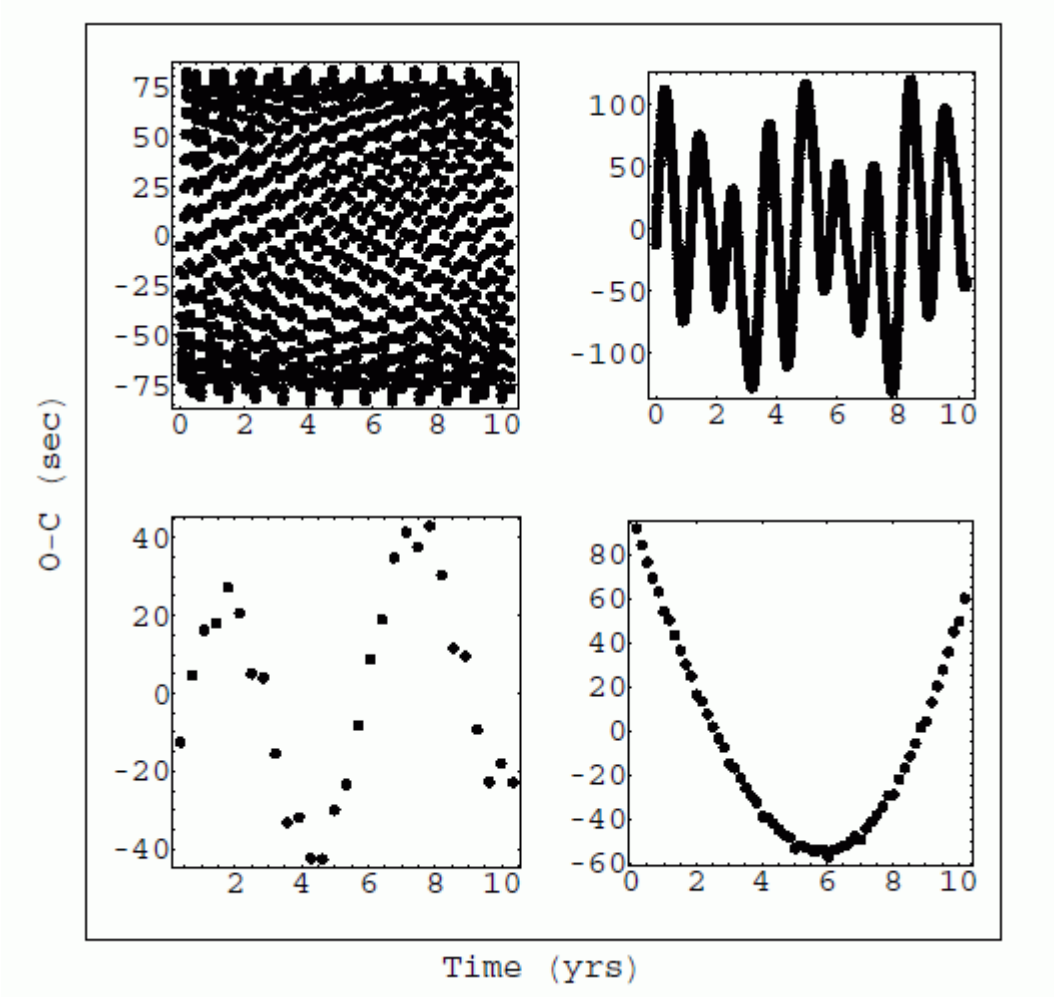
Transit Timing Variations
of
WASP-3b and WASP-10b

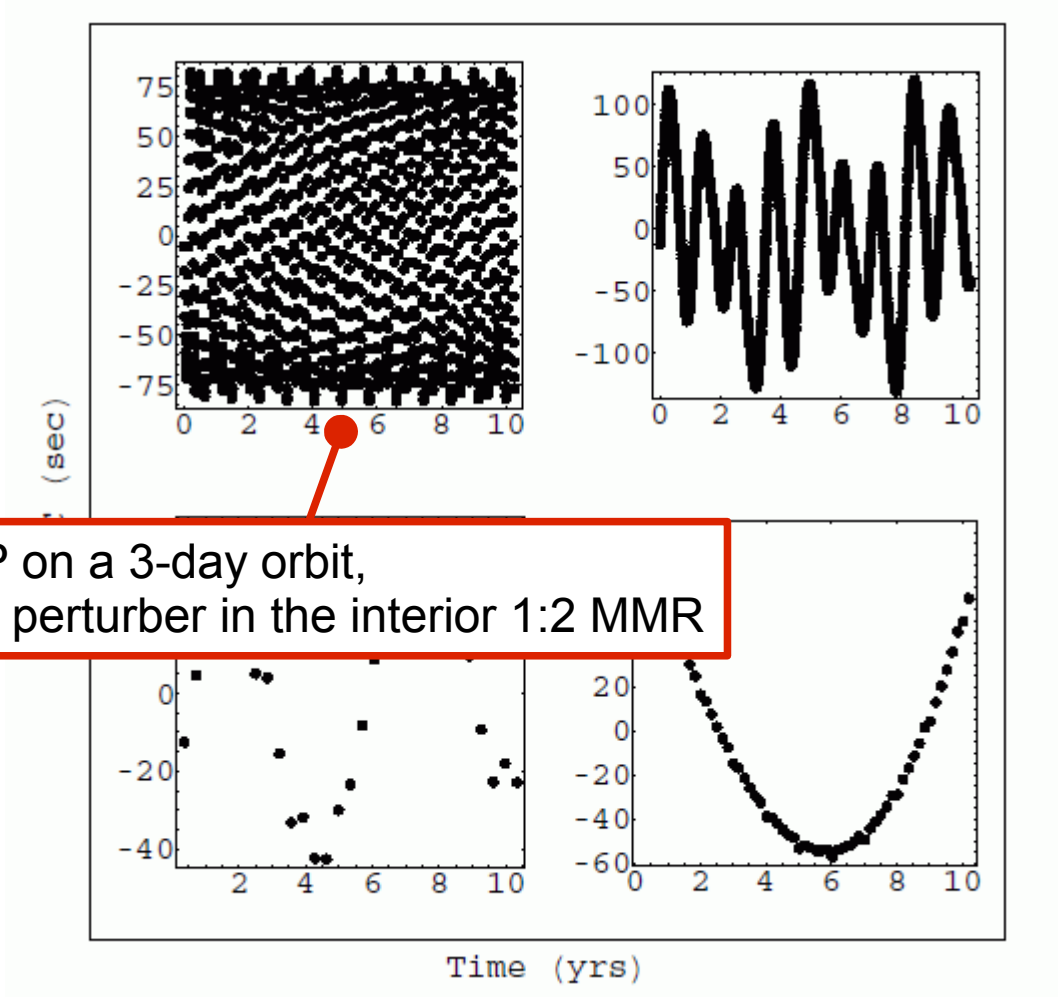


Credit: NASA, ESA, and G. Bacon (STScI), STScI-2006-34

Analysis of O-C (observed – calculated) diagrams – TTV (Steffen et al. 2007)

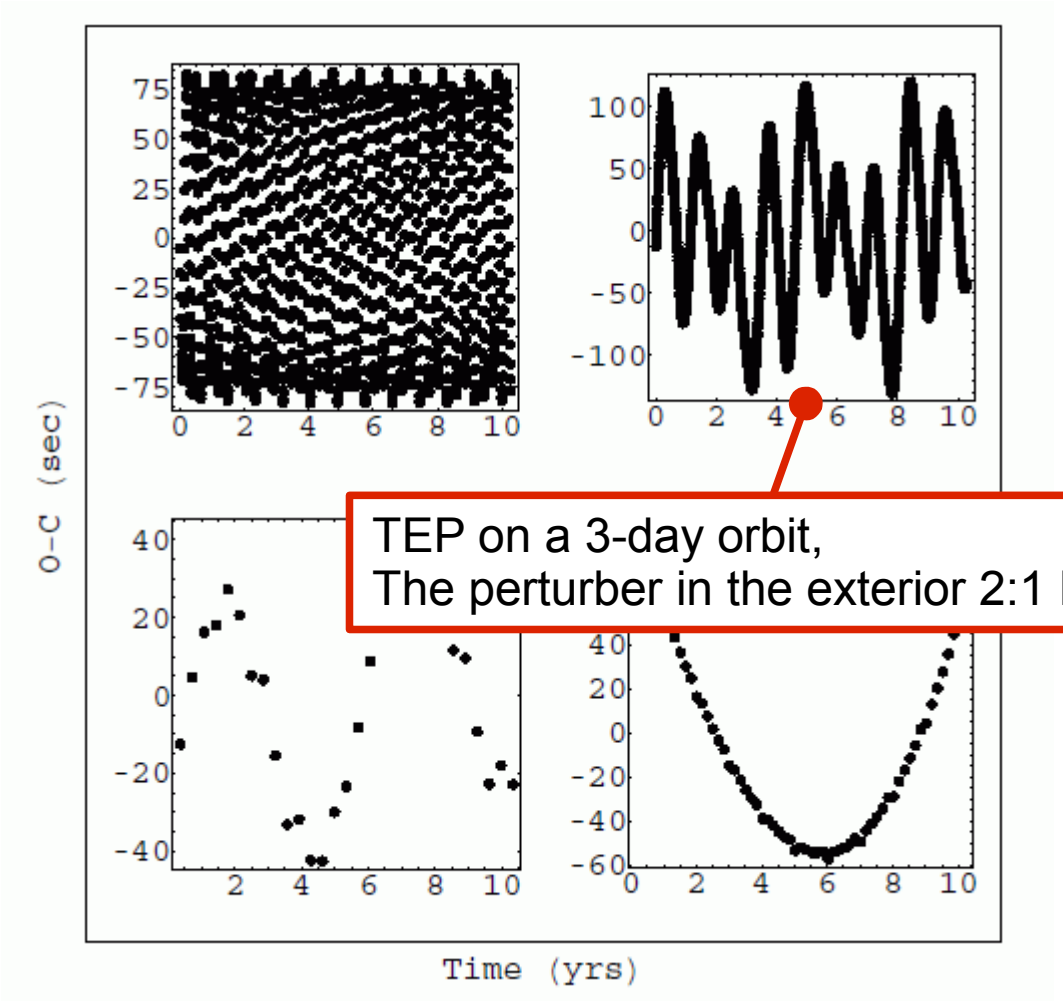


Analysis of O-C (observed – calculated) diagrams – TTV (Steffen et al. 2007)

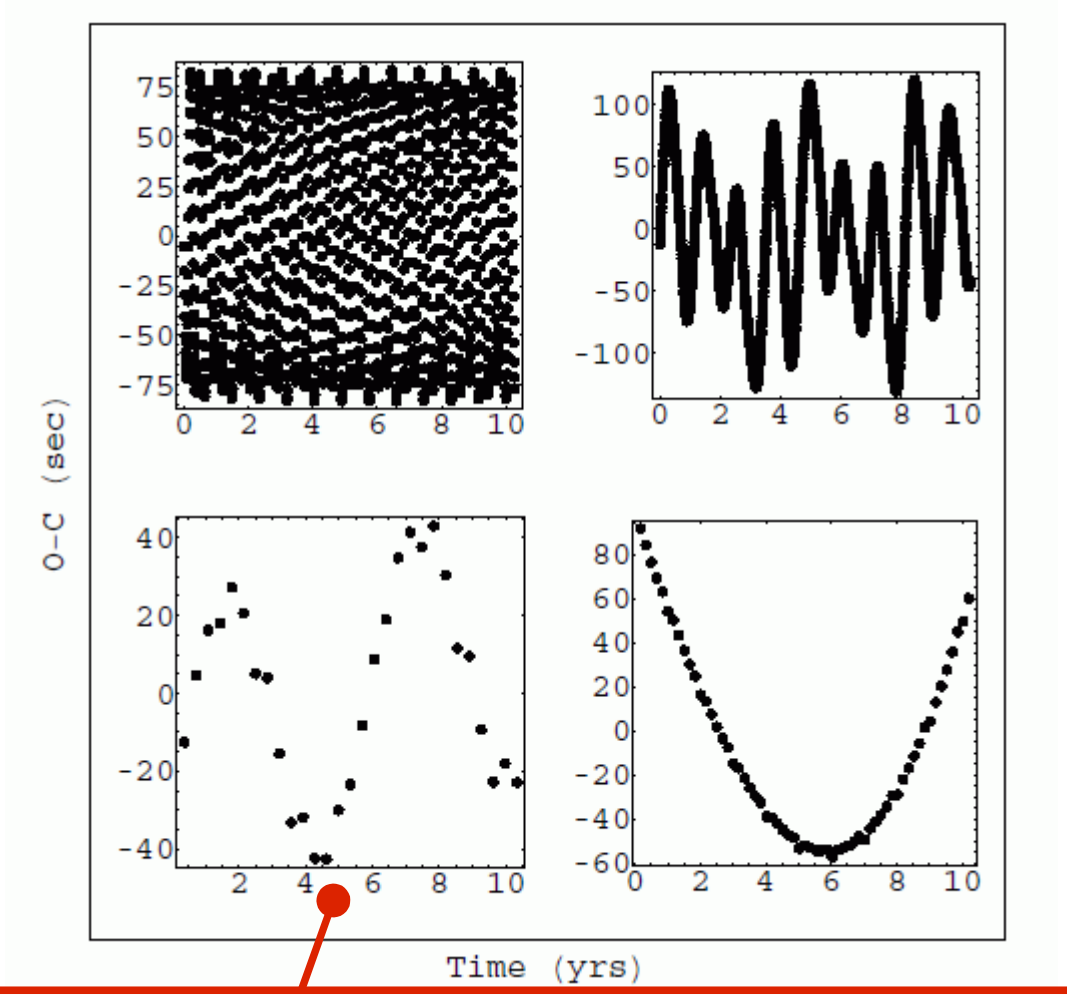


TEP on a 3-day orbit,
The perturber in the interior 1:2 MMR

Analysis of O-C (observed – calculated) diagrams – TTV (Steffen et al. 2007)

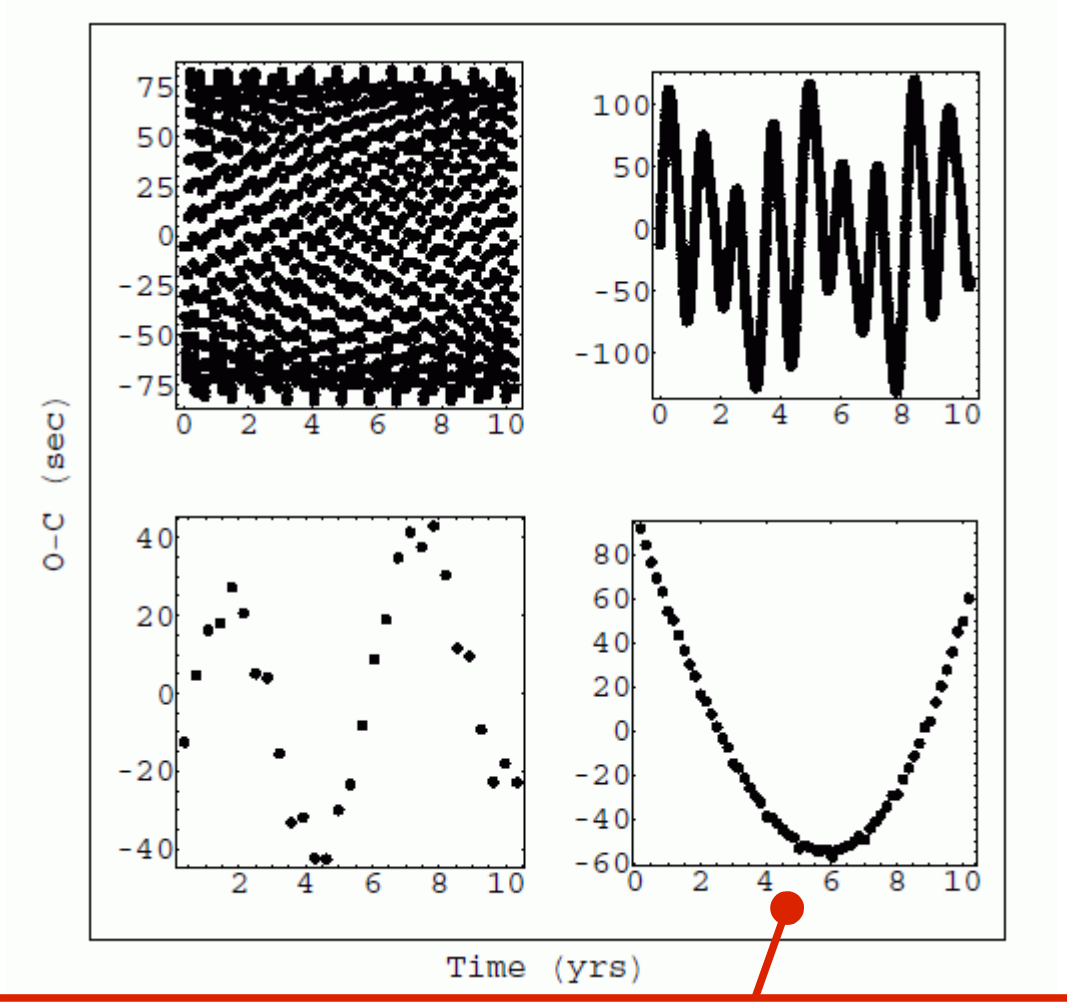


Analysis of O-C (observed – calculated) diagrams – TTV (Steffen et al. 2007)



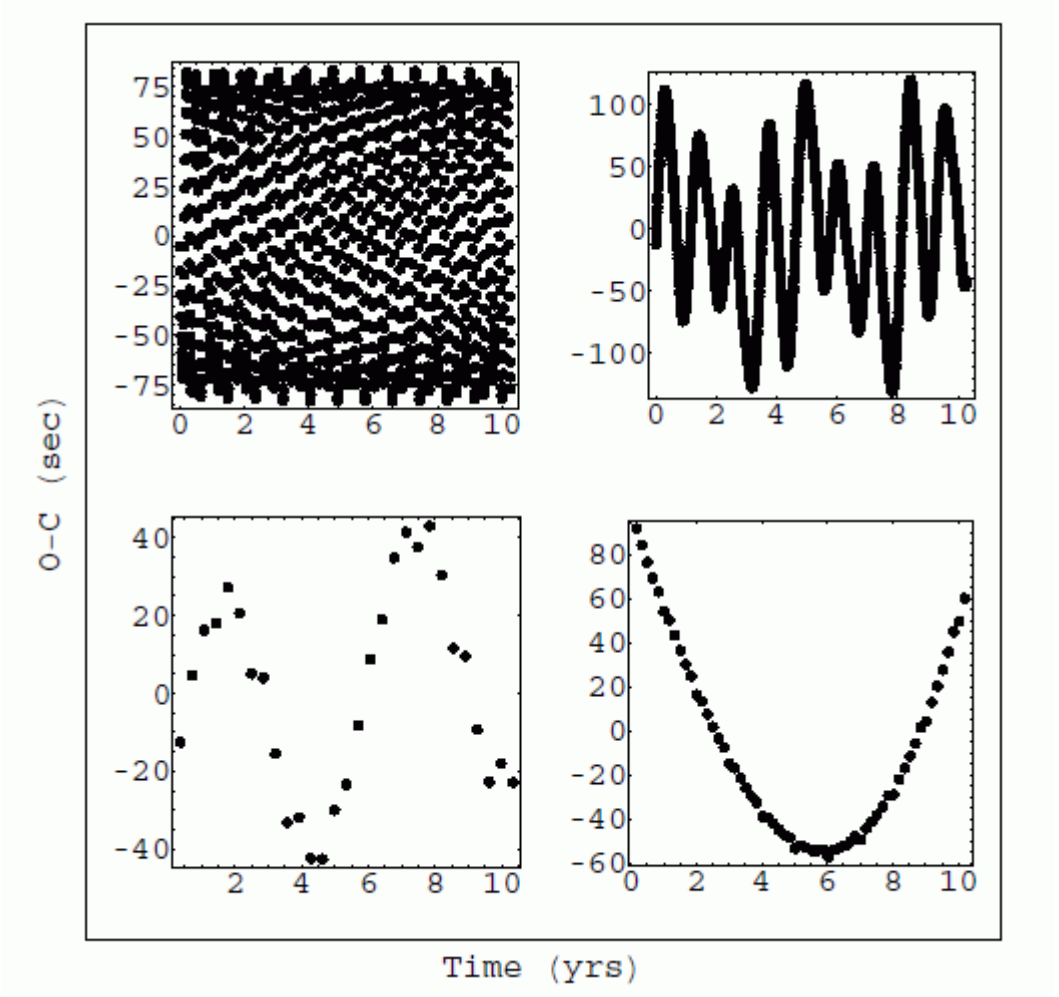
TEP has a period of 130 d, both planets have an eccentricity of 0.05, and the perturber orbits at 1 AU, not in MMR

Analysis of O-C (observed – calculated) diagrams – TTV (Steffen et al. 2007)



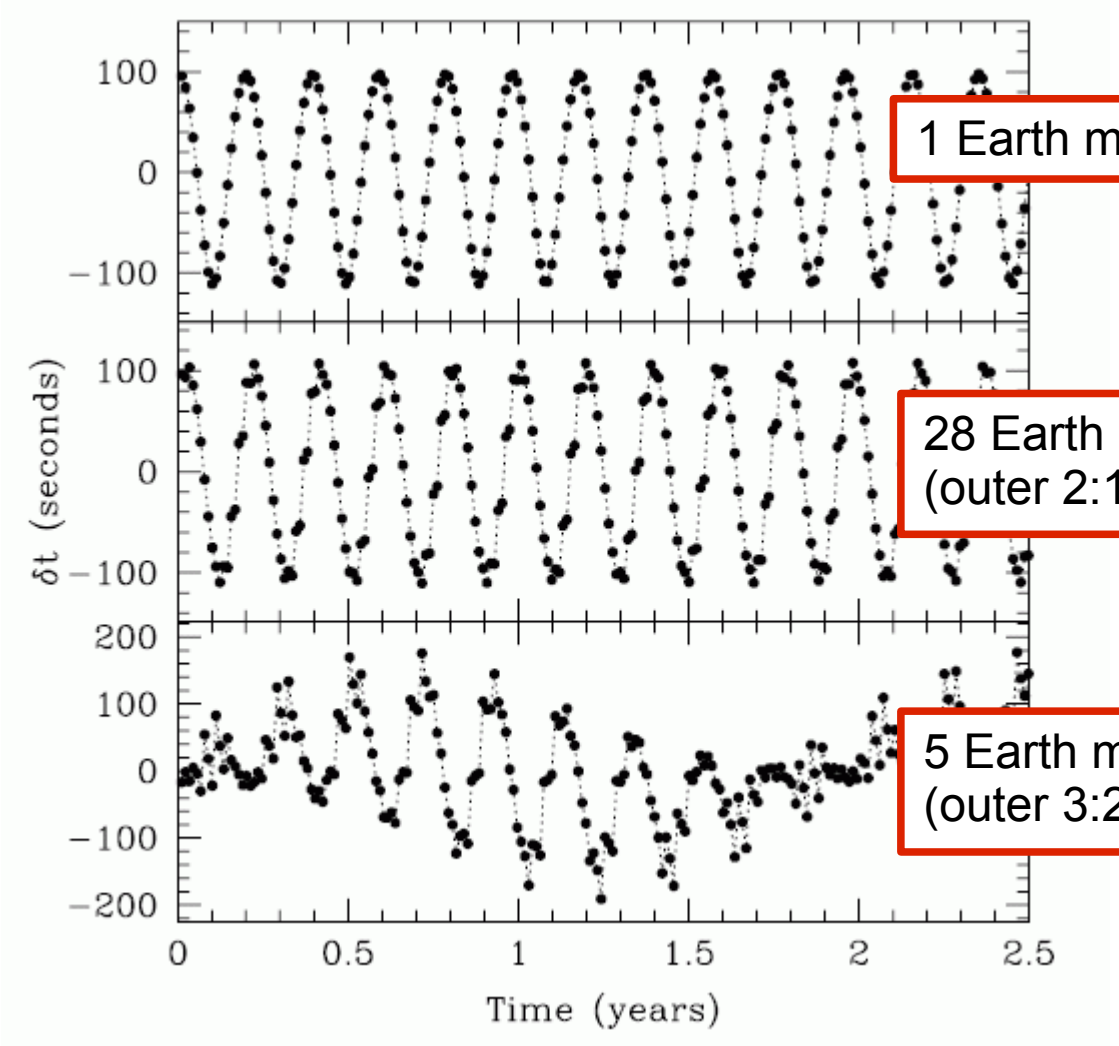
TEP has an eccentricity of 0.15,
the perturber has eccentricity of 0.25, orbits at 1 AU in the exterior 6:1 MMR

Analysis of O-C (observed – calculated) diagrams – TTV (Steffen et al. 2007)



Different systems – the similar signal in O-C diagrams (Ford & Holman 2007)

Transiting hot Jupiter-like planet (period: ~4 d, mass: 0,5 Jupiter mass) + ...

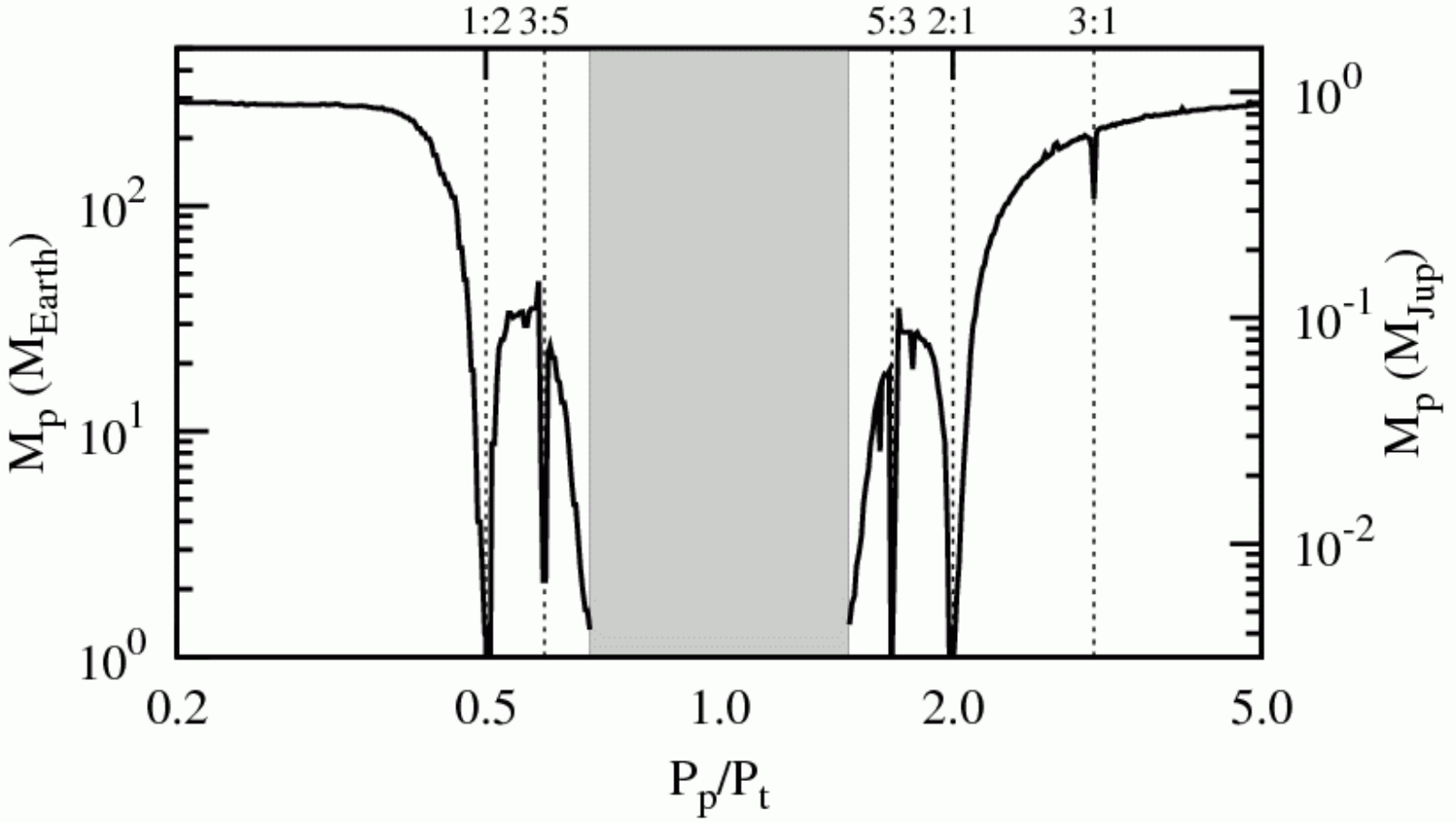


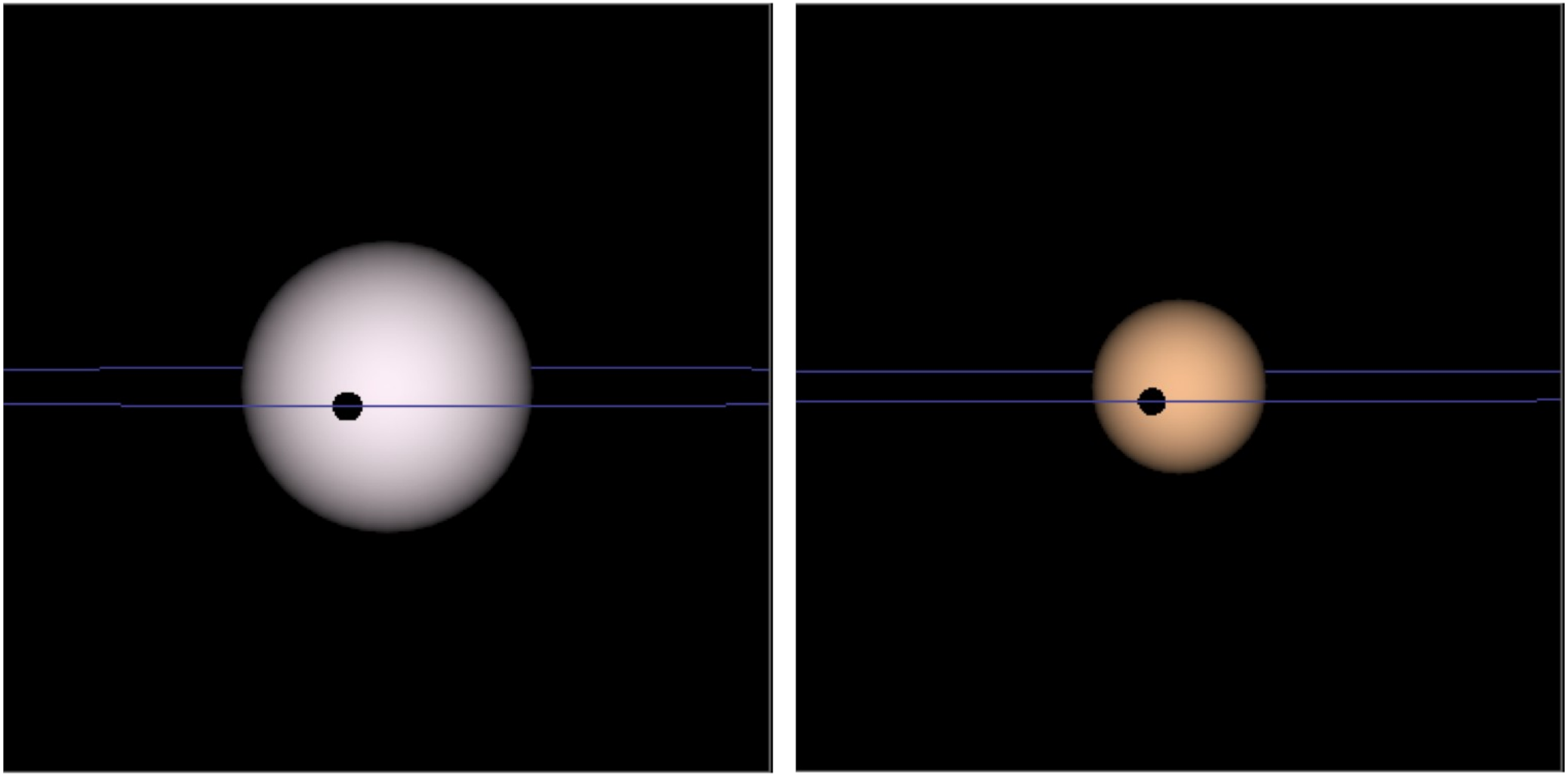
1 Earth mass Trojan planet

28 Earth mass planet, orbital period: ~8 d (outer 2:1 resonance)

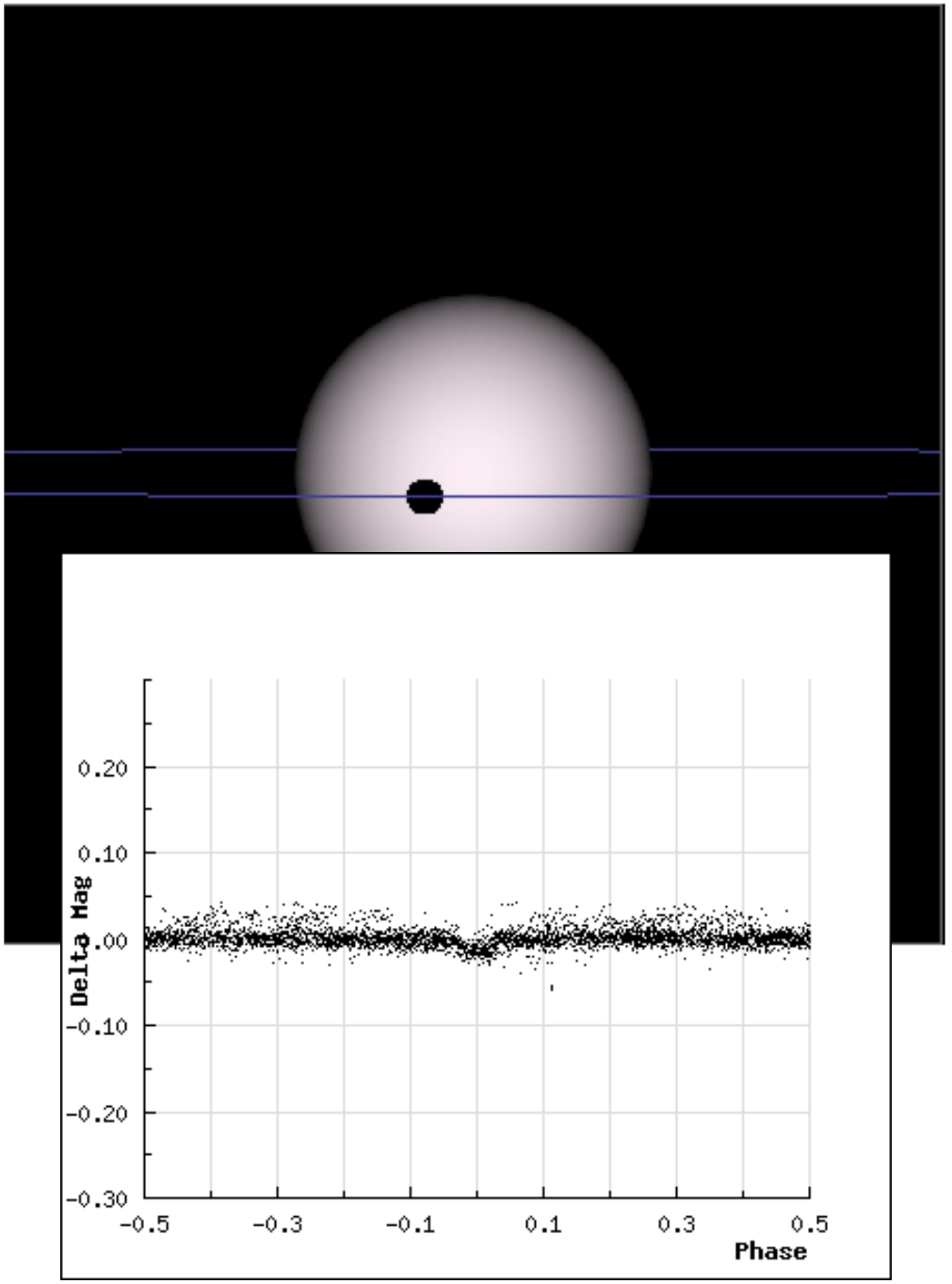
5 Earth mass planet, orbital period: ~6 d (outer 3:2 resonance)

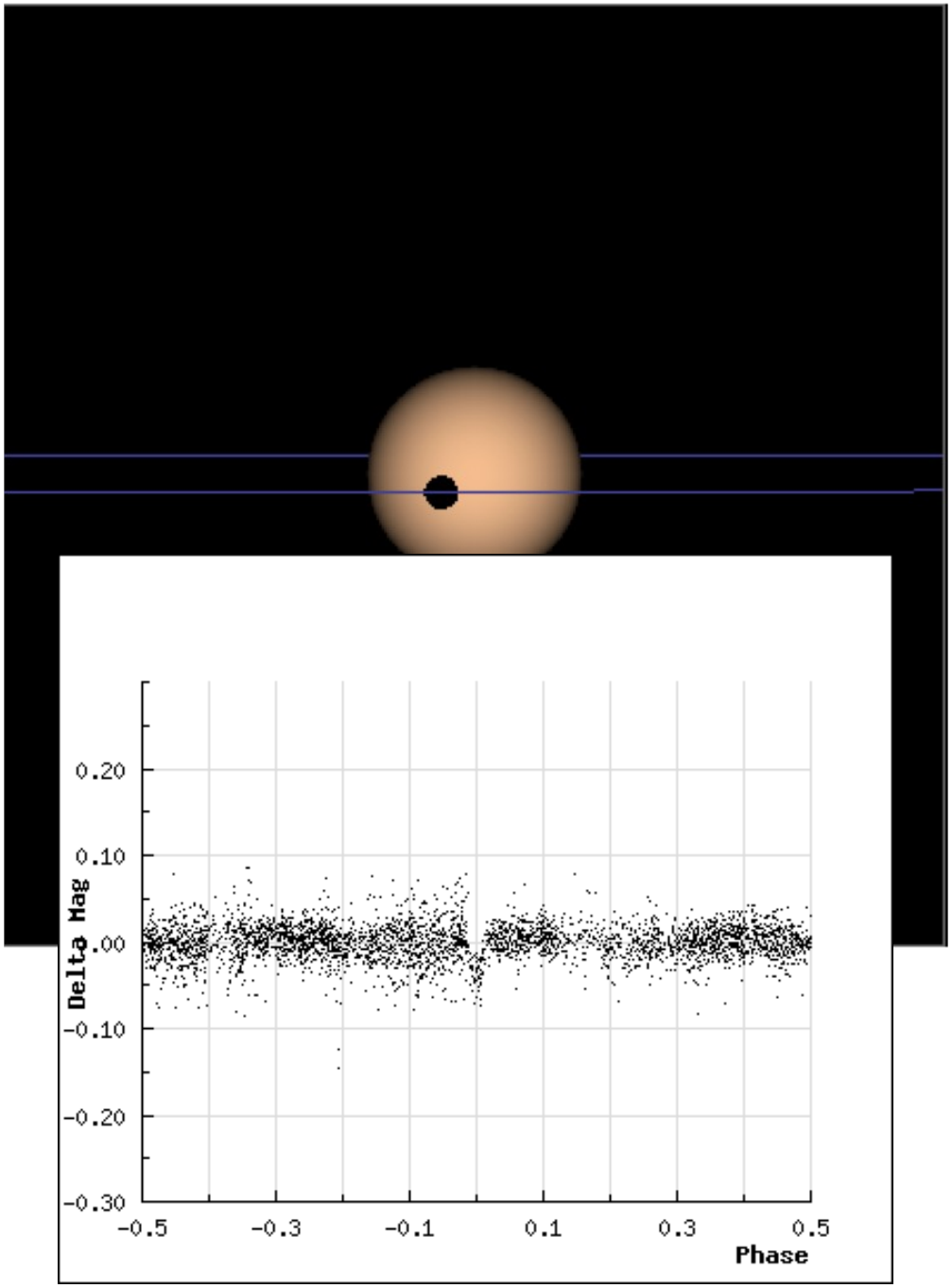
For a given TTV amplitude...





Credit: http://www.superwasp.org/





Credit: http://www.superwasp.org/

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doi:10.1111/j.1365-2966.2010.17099.x

Transit timing variation in exoplanet WASP-3b*

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Ch. Ginski,[1] Ch. Adam,[1] C. Marka,[1] M. Moualla[1] and M. Mugrauer[1]

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[2]*Toruń Centre for Astronomy, N. Copernicus University, Gagarina 11, PL-87100 Toruń, Poland*
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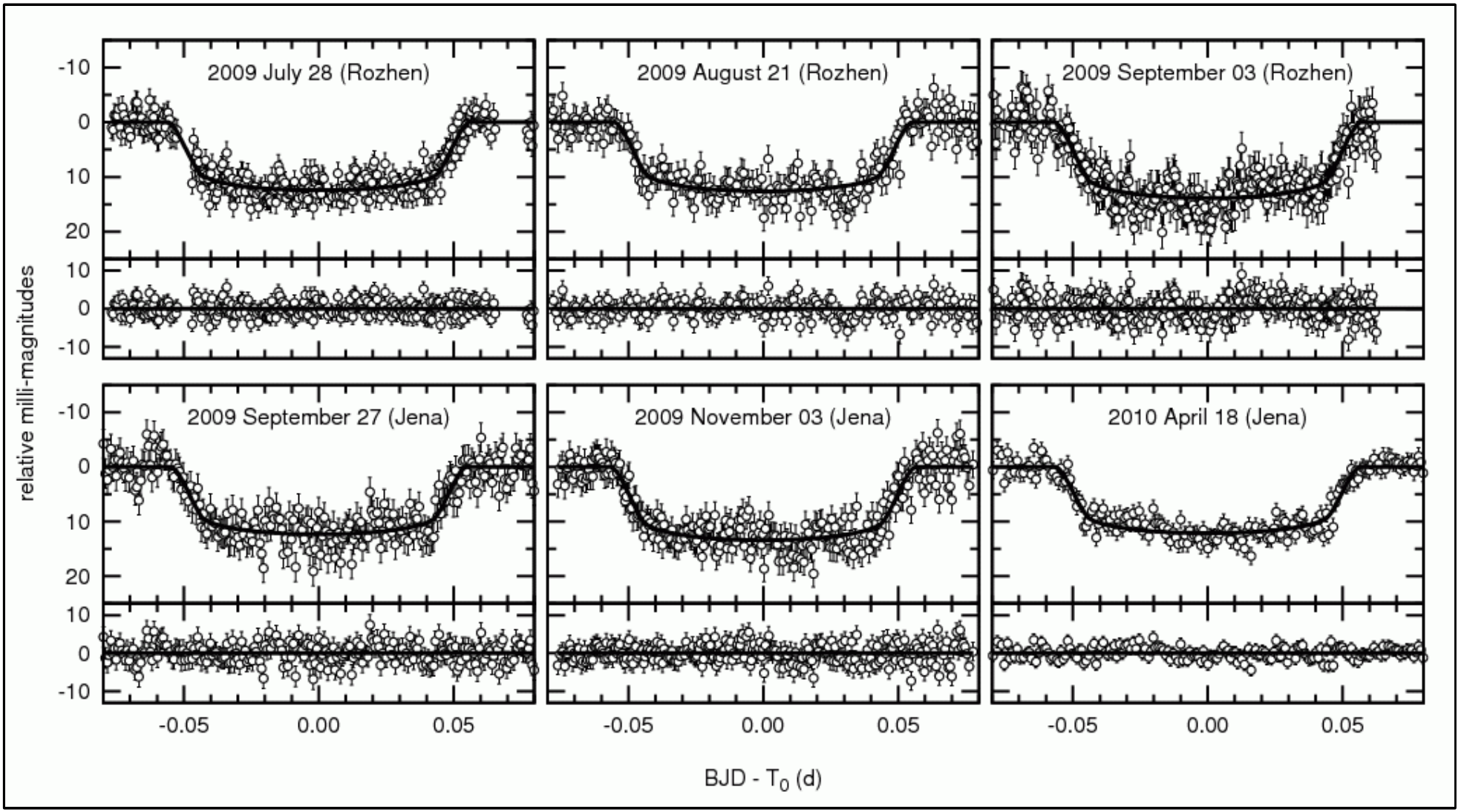
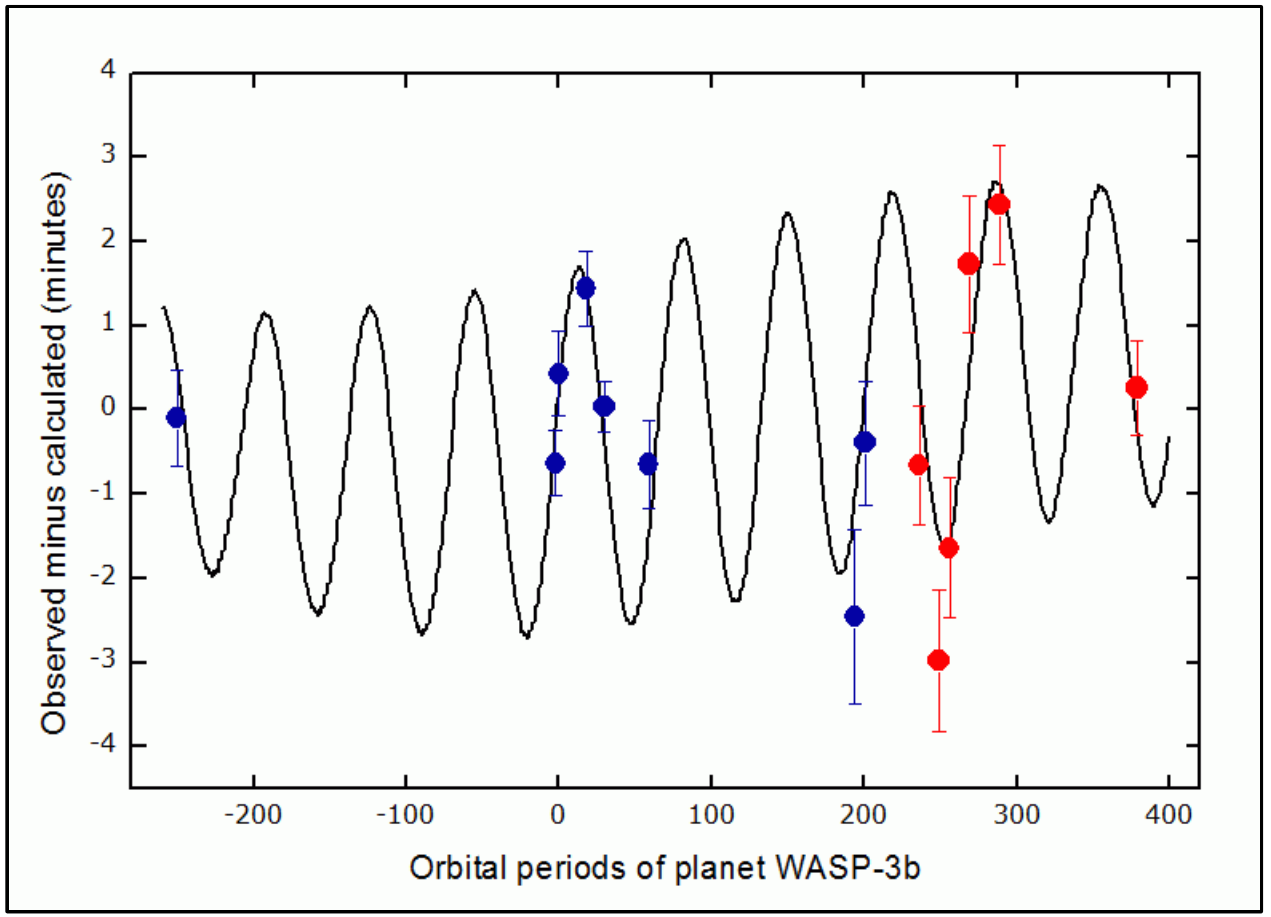
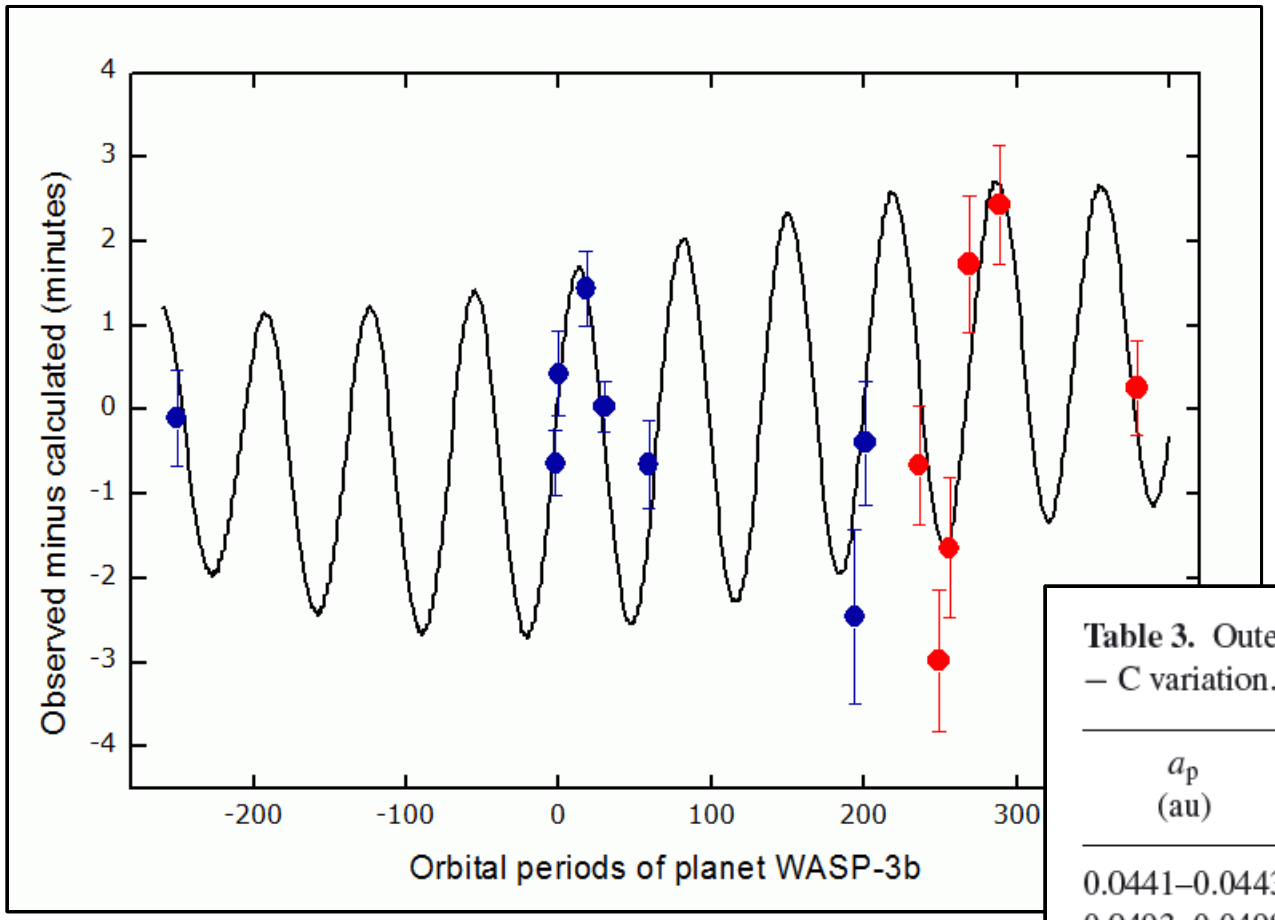
ABSTRACT

Photometric follow-ups of transiting exoplanets may lead to discoveries of additional, less massive bodies in extrasolar systems. This is possible by detecting and then analysing variations in transit timing of transiting exoplanets. We present photometric observations gathered in 2009 and 2010 for exoplanet WASP-3b during the dedicated transit-timing-variation campaign. The observed transit timing cannot be explained by a constant period but by a periodic variation in the observations minus calculations diagram. Simplified models assuming the existence of a perturbing planet in the system and reproducing the observed variations of timing residuals were identified by three-body simulations. We found that the configuration with the hypothetical second planet of mass $\sim 15\,M_{\oplus}$, located close to the outer 2:1 mean-motion resonance, is the most likely scenario reproducing observed transit timing. We emphasize, however, that more observations are required to constrain better the parameters of the hypothetical second planet in the WASP-3 system. For final interpretation not only transit timing but also photometric observations of the transit of the predicted second planet and high-precision radial velocity data are needed.

Key words: stars: individual: WASP-3 – planetary systems.


2009 July 28 (Rozhen)
2009 August 21 (Rozhen)
2009 September 03 (Rozhen)
2009 September 27 (Jena)
2009 November 03 (Jena)
2010 April 18 (Jena)
relative milli-magnitudes
BJD - T0 (d)
-10
0
10
20
-0.05
0.00
0.05


Observed minus calculated (minutes)
4
3
2
1
0
-1
-2
-3
-4
-200
-100
0
100
200
300
400
Orbital periods of planet WASP-3b



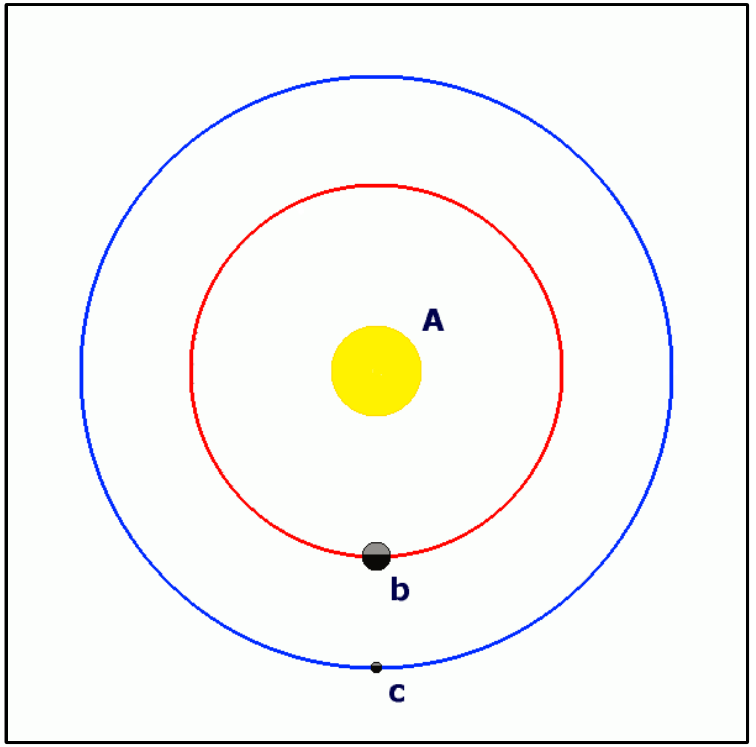
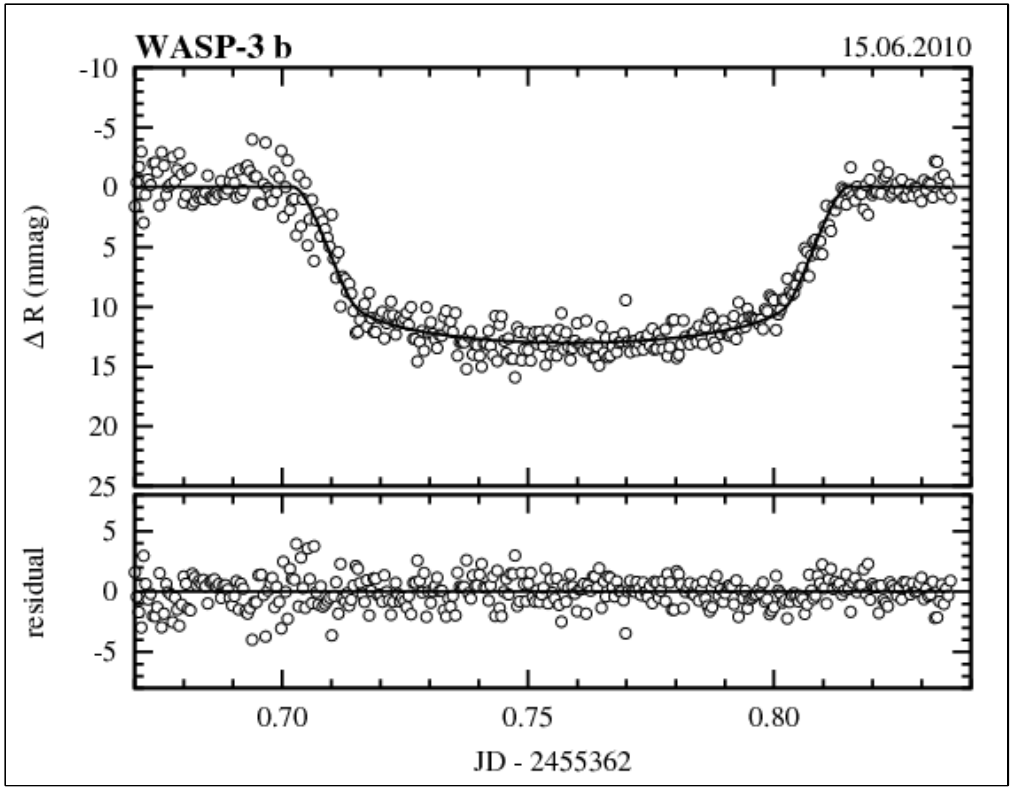
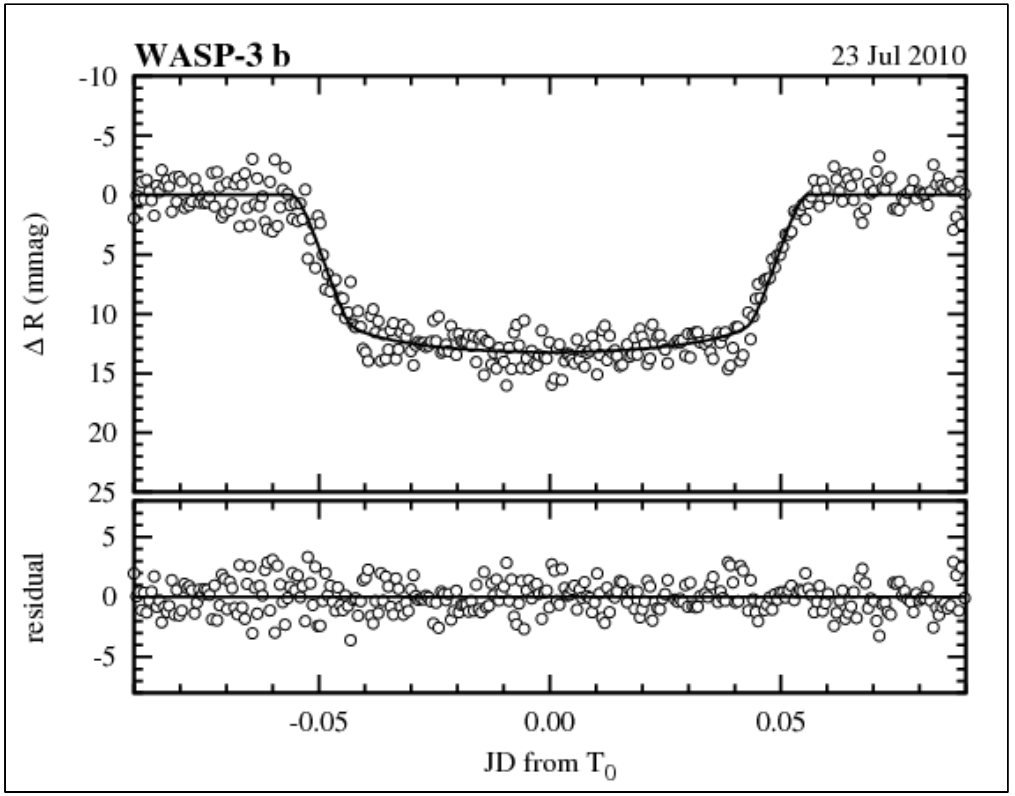


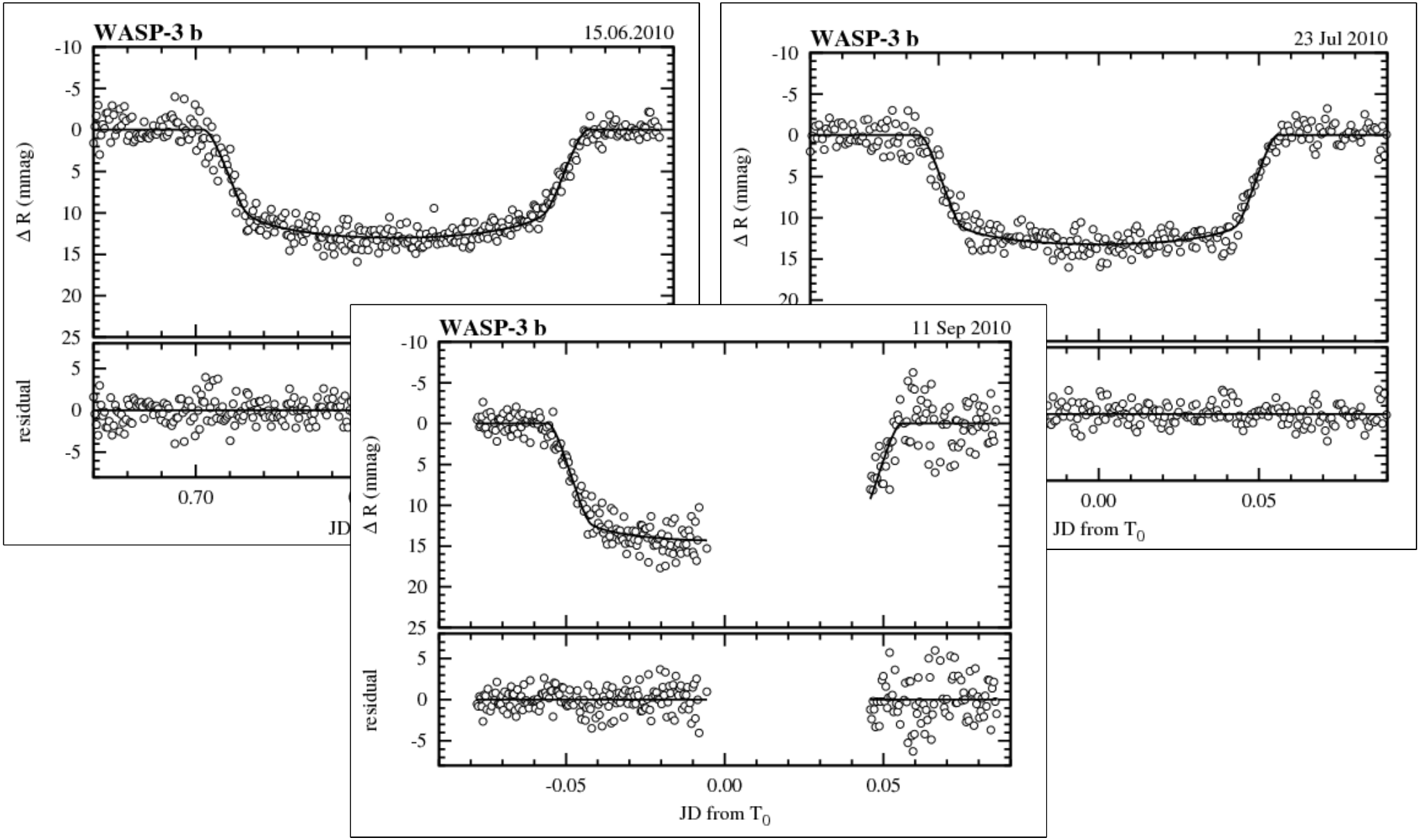
Table 3. Outer-perturber solutions which reproduce the observed O − C variation.

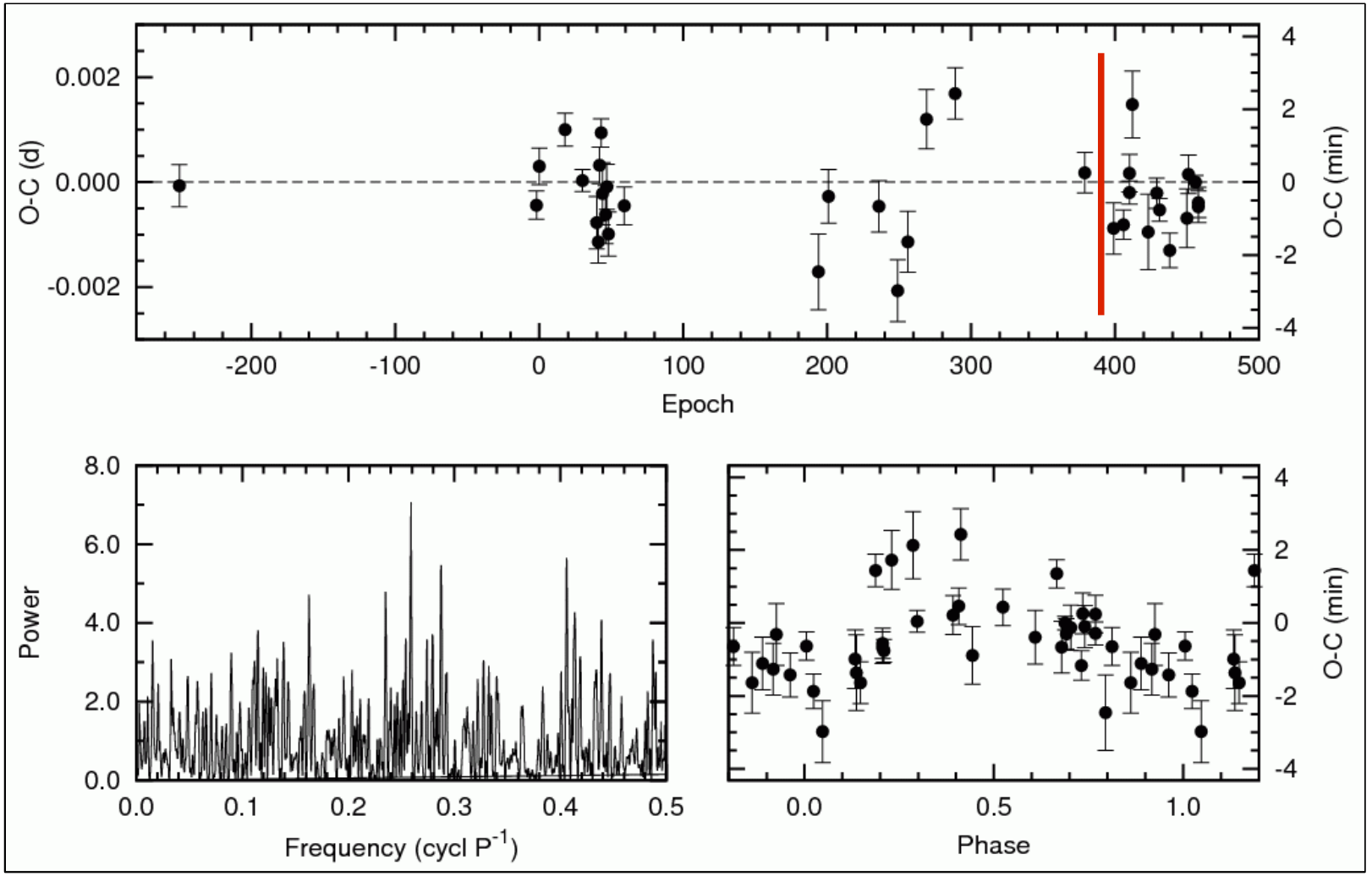
a_p (au)	M_p ($M_\oplus$)	P_p (d)	K_p ($m\,s^{-1}$)	χ^2_{red}
0.0441–0.0443	6–10	3.03–3.05	2.3–3.8	2.4
0.0493–0.0498	10	3.58–3.64	3.7	2.8
0.0506–0.0511	15	3.72–3.78	5.3	1.5

Note: a_p denotes the semimajor axis of the perturbing planet, M_p is its mass, P_p is its orbital period, K_p is the expected semi-amplitude of the radial velocity variation and χ^2_{red} is the lowest value of reduced χ^2 for direct model fitting.


WASP-3 b
15.06.2010
Δ R (mmag)
residual
JD - 2455362


WASP-3 b
23 Jul 2010
Δ R (mmag)
residual
JD from T0


WASP-3 b
15.06.2010
WASP-3 b
23 Jul 2010
WASP-3 b
11 Sep 2010
Δ R (mmag)
residual
JD from T0


O-C (d)
0.002
0.000
-0.002
-200
-100
0
100
200
300
400
500
Epoch
4
2
0
-2
-4
O-C (min)
Power
8.0
6.0
4.0
2.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
Frequency (cycl P-1)
0.0
0.5
1.0
Phase

Mon. Not. R. Astron. Soc. **000**, 1–10 (2010) Printed 24 September 2010 (MN LATEX style file v2.2)

Transit timing variation and activity in the WASP-10 planetary system*

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[7] *Astronomical Institute of the Slovak Academy of Sciencies, 059 60 Tatranská Lomnica, Slovak Republic*
[8] *Main Astronomical Observatory of National Academy of Sciences of Ukraine, 27 Akademika Zabolotnoho St., 03680 Kyiv, Ukraine*
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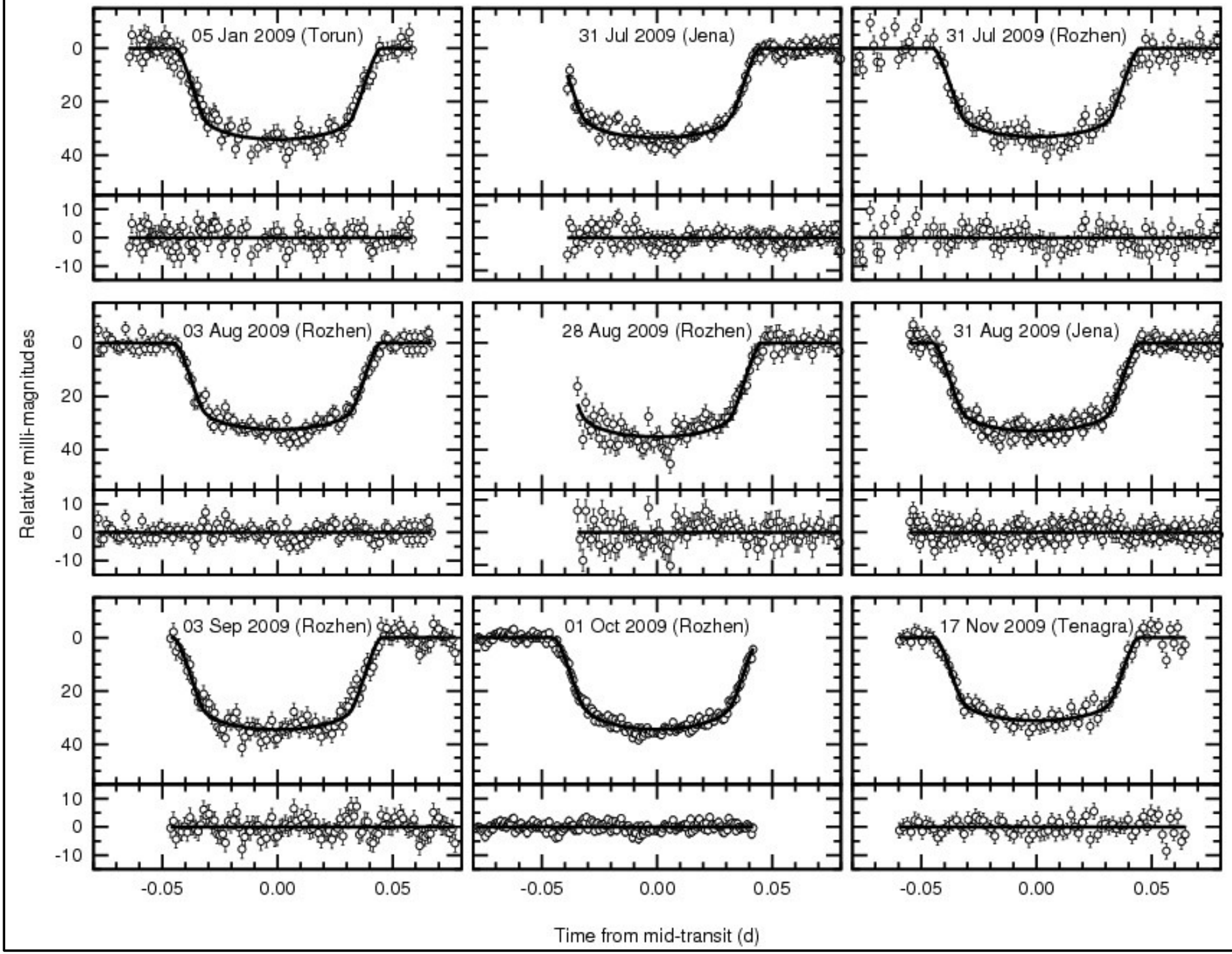
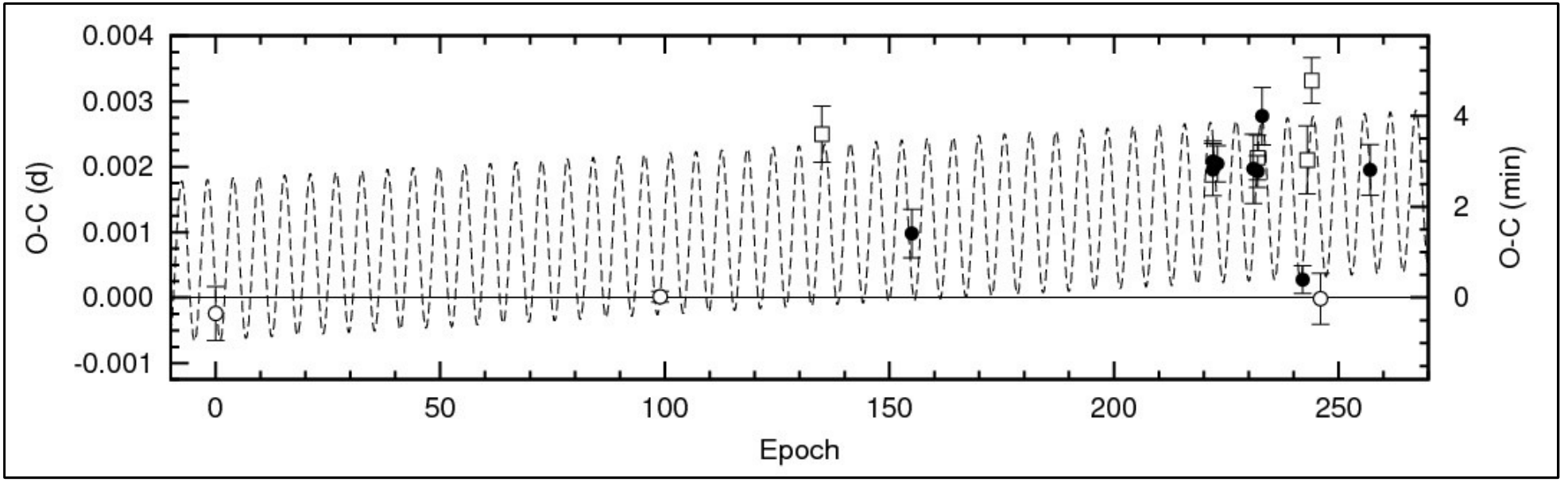
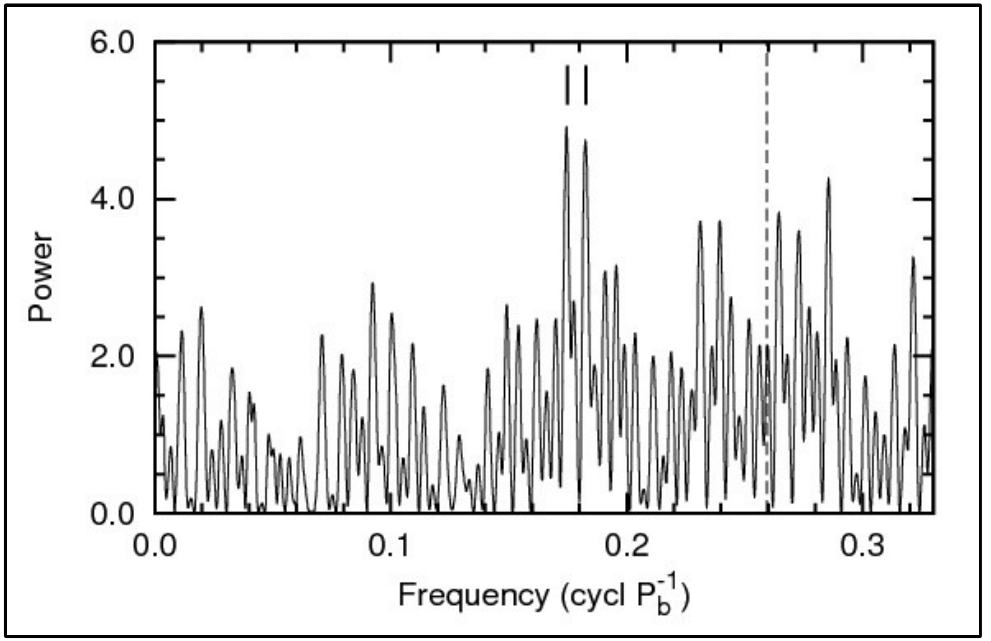
Accepted. Received ; in original form

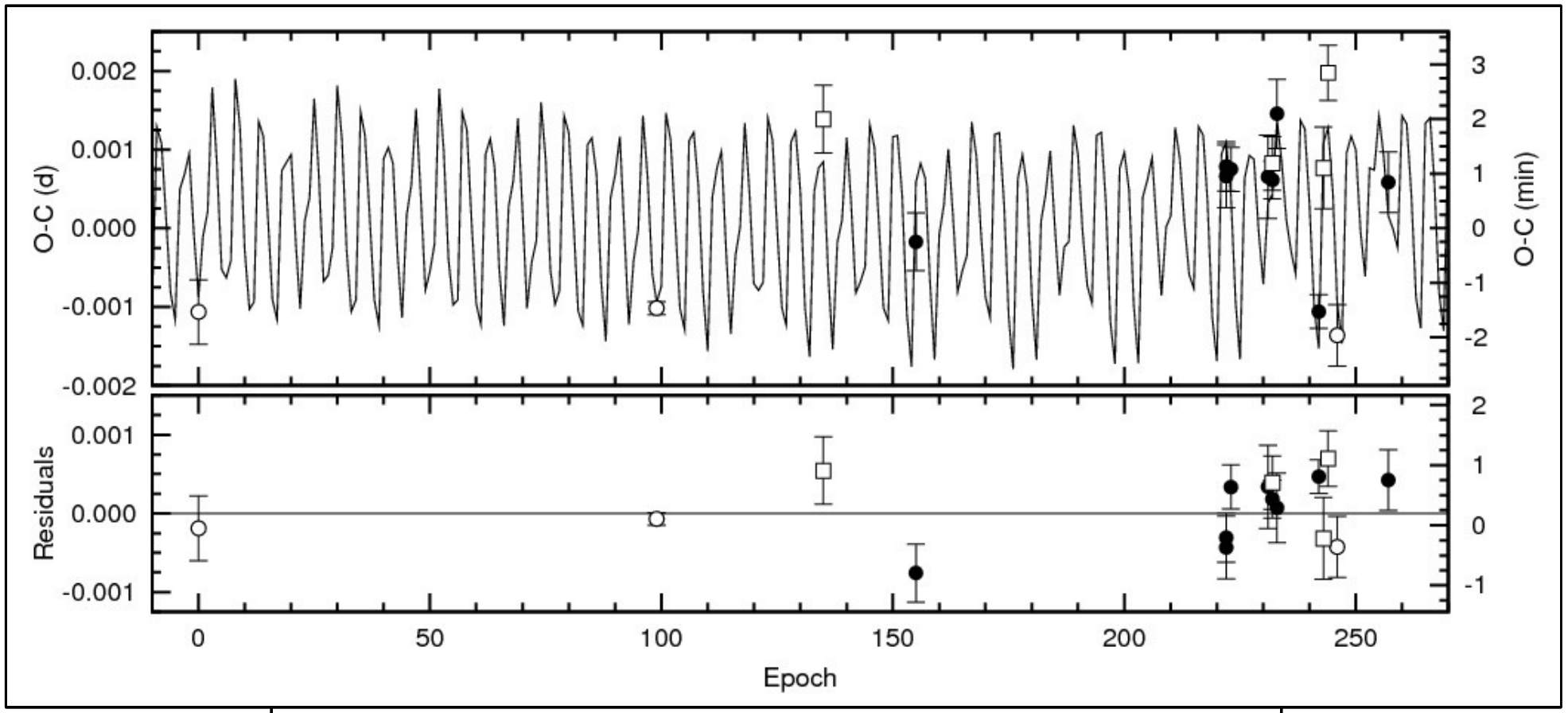
ABSTRACT

Transit timing analysis may be an effective method of discovering additional bodies in extrasolar systems which harbour transiting exoplanets. The deviations from the Keplerian motion, caused by mutual gravitational interactions between planets, are expected to generate transit timing variations of transiting exoplanets. In 2009 we collected 9 light curves of 8 transits of the exoplanet WASP-10b. Combining these data with published ones, we found that transit timing cannot be explained by a constant period but by a periodic variation. Simplified three-body models which reproduce the observed variations of timing residuals were identified by numerical simulations. We found that the configuration with an additional planet of mass of $\sim$0.1 $M_{\rm J}$ and orbital period of $\sim$5.23 d, located close to the outer 5:3 mean motion resonance, is the most likely scenario. If the second planet is a transiter, the estimated flux drop will be $\sim$0.3

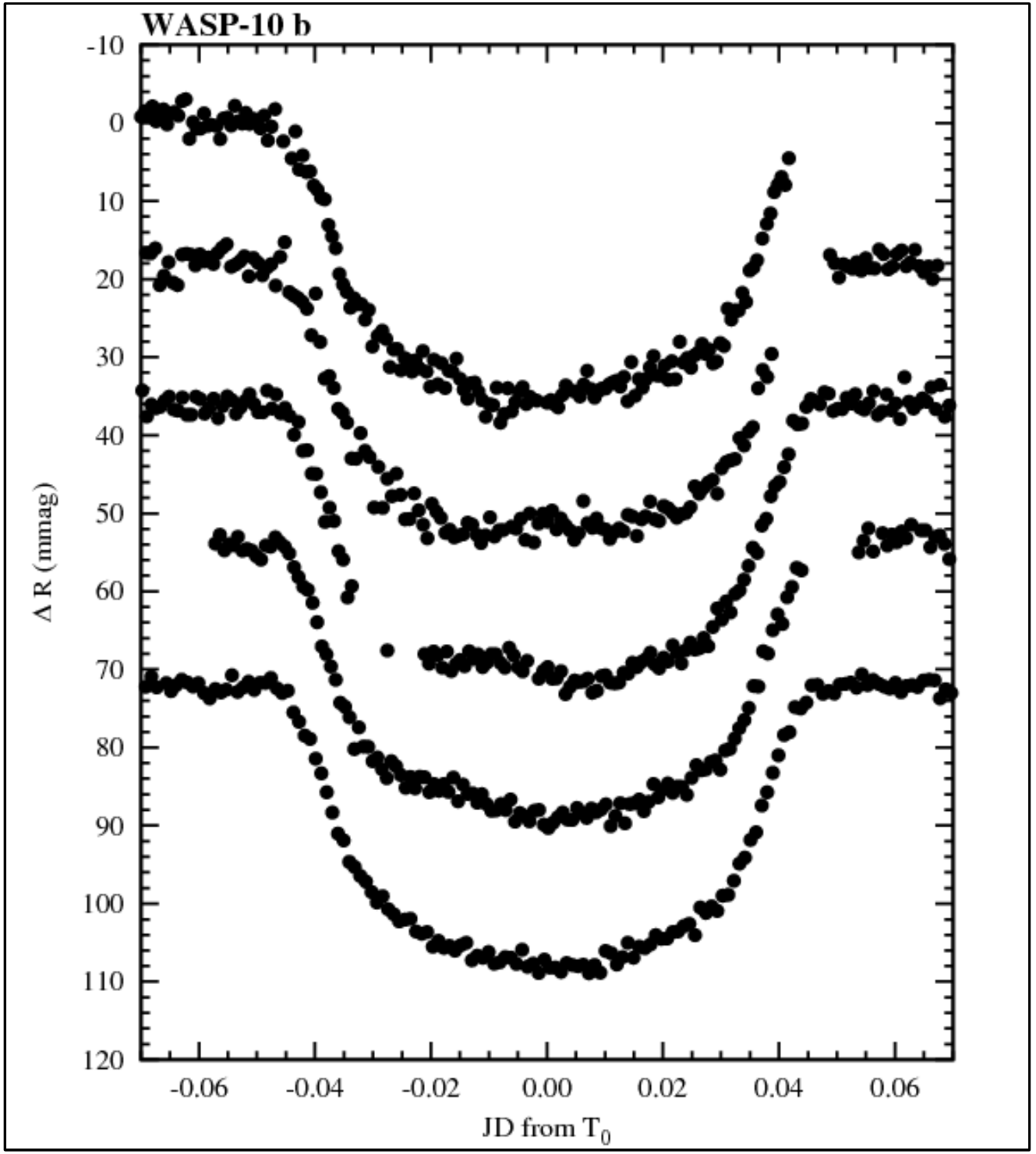

05 Jan 2009 (Torun)
31 Jul 2009 (Jena)
31 Jul 2009 (Rozhen)
03 Aug 2009 (Rozhen)
28 Aug 2009 (Rozhen)
31 Aug 2009 (Jena)
03 Sep 2009 (Rozhen)
01 Oct 2009 (Rozhen)
17 Nov 2009 (Tenagra)
Relative milli-magnitudes
Time from mid-transit (d)

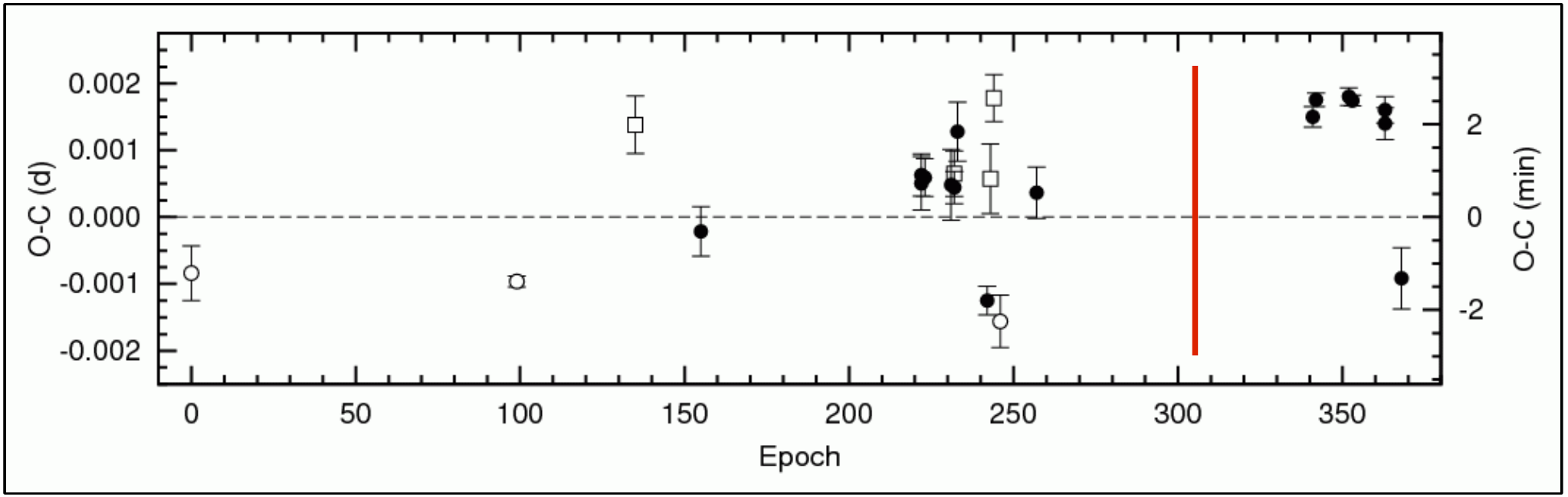

0.004
0.003
0.002
0.001
0.000
-0.001
O-C (d)
4
2
0
O-C (min)
0
50
100
150
200
250
Epoch


6.0
4.0
2.0
0.0
Power
0.0
0.1
0.2
0.3
Frequency (cycl P_b^{-1})



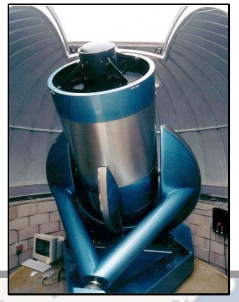
No.	$P^{\rm ttv}$	$a_{\rm c}$ (au)	$M_{\rm c}$ ($M_{\rm J}$)	$P_{\rm c}$ (d)	$K_{\rm c}$ (m s^{-1})	$\chi^2_{\rm red}$
1	1	0.0536	0.10	5.2293	14.2	1.5
2	2	0.0539	0.10	5.2647	14.1	2.5
3	2	0.0682	0.55	7.4962	69.1	2.8
4	1	0.0686	0.55	7.5677	68.9	2.8


WASP-10 b
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
Δ R (mmag)
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
JD from T0

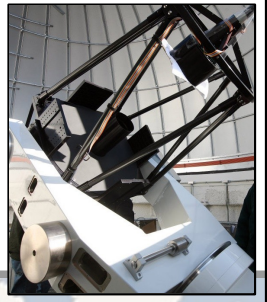

0.002
0.001
0.000
-0.001
-0.002
O-C (d)
2
0
-2
O-C (min)
0
50
100
150
200
250
300
350
Epoch

Pomona College
Table Mountain Facility
1.0-m telescope

Tenagra II
Tenagra Observatory
0.8-m telescope

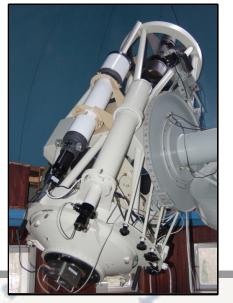


Swarthmore
Peter van de Kamp Observ.
0.6-m telescope



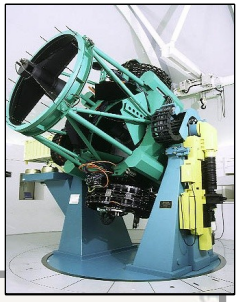
Jena
Astrophysical Institute
0.9-m telescope

Toruń
Centre for Astronomy
0.6- and 0.9-m telescopes

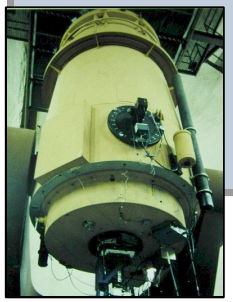


Stara Lesna
Slovak Acad. of Sciences
0.5-m telescope

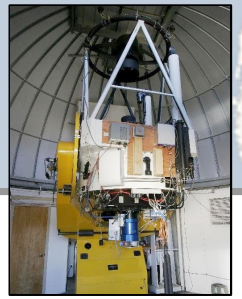
Gunma
Astronomical Observatory
1.5-m telescope



Mauna Kea
University of Hawaii
2.2-m telescope

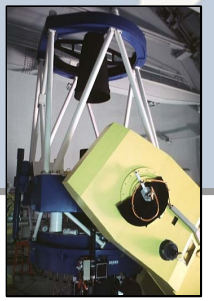


F.L.Wipple Observ.
Harvard-Smithsonian CfA
1.2-m telescope

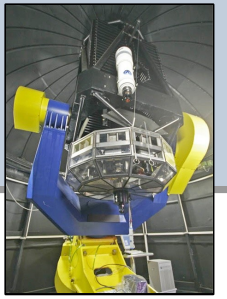


Van Vleck Observ.
Wesleyan University
0.6-m telescope

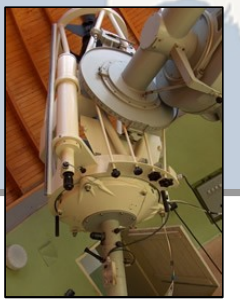
Calar Alto
Astronomical Observatory
2.2-m telescope



Trebur
M.Adrian Observatory
1.2-m telescope



Rozhen
Astronomical Observatory
0.6- and 2.0-m telescopes



Ankara
University Observatory
0.4-m telescope