6th Workshop of Young Researchers in Astronomy and Astrophysics

The Multi-wavelength Universe

From Starbirth to Star Death

3-6 September 2012 - Budapest, Hungary

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Dynamical masses, absolute radii, and 3D orbits of the triply eclipsing HD 181068 from Kepler photometry

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[3] ELTE Gothard-Lendület Research Group, Szombathely
[4] Sydney Institut for Astronomy
[5] Eötvös University, Astron. Dept., Budapest
[6] NASA Ames Research Center

TRINITY – A short history

System characteristics:

Discovered by Alíz Derekas in Q1, Q2 data

– Triply eclipsing,very close hierarchical triple system
– Close binary: two late G, early K dwarves, with
P_{Bab} ~ 0.905677 days; e_{Bab} = 0.0
– Wide component: chromospherically active G8 giant,
P_{AB} ~ 45.5 days; e_{AB} = 0.0

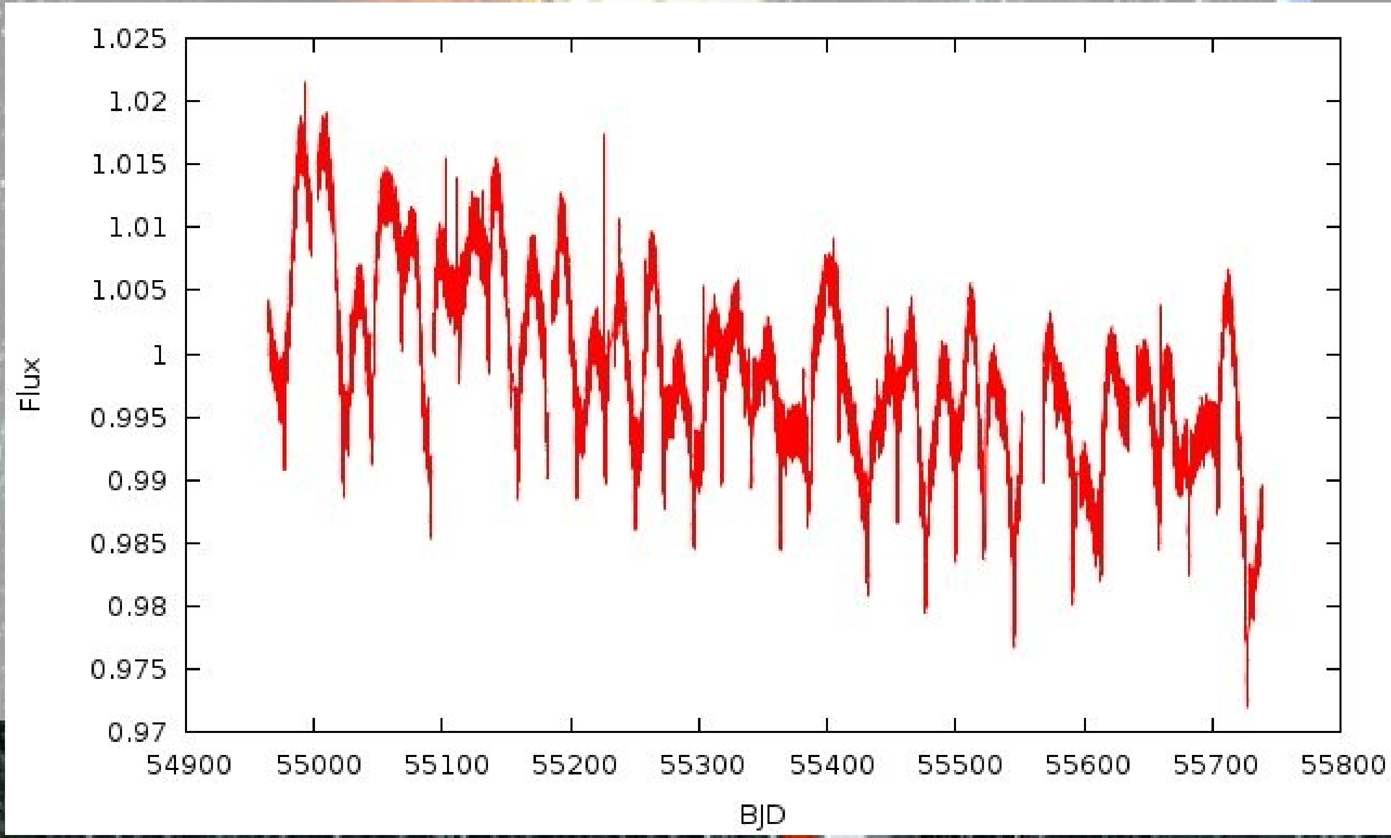
Masses, temperatures, metallicity,radii, distance are from:
Spectroscopy (NOT, DAO, Tautenburg, McD)
PAVO/CHARA interferometry

(Derekas et al. 2011, Sci, 332, 216)

TRINITY – All inclusive

Light-curve on different time-scales:

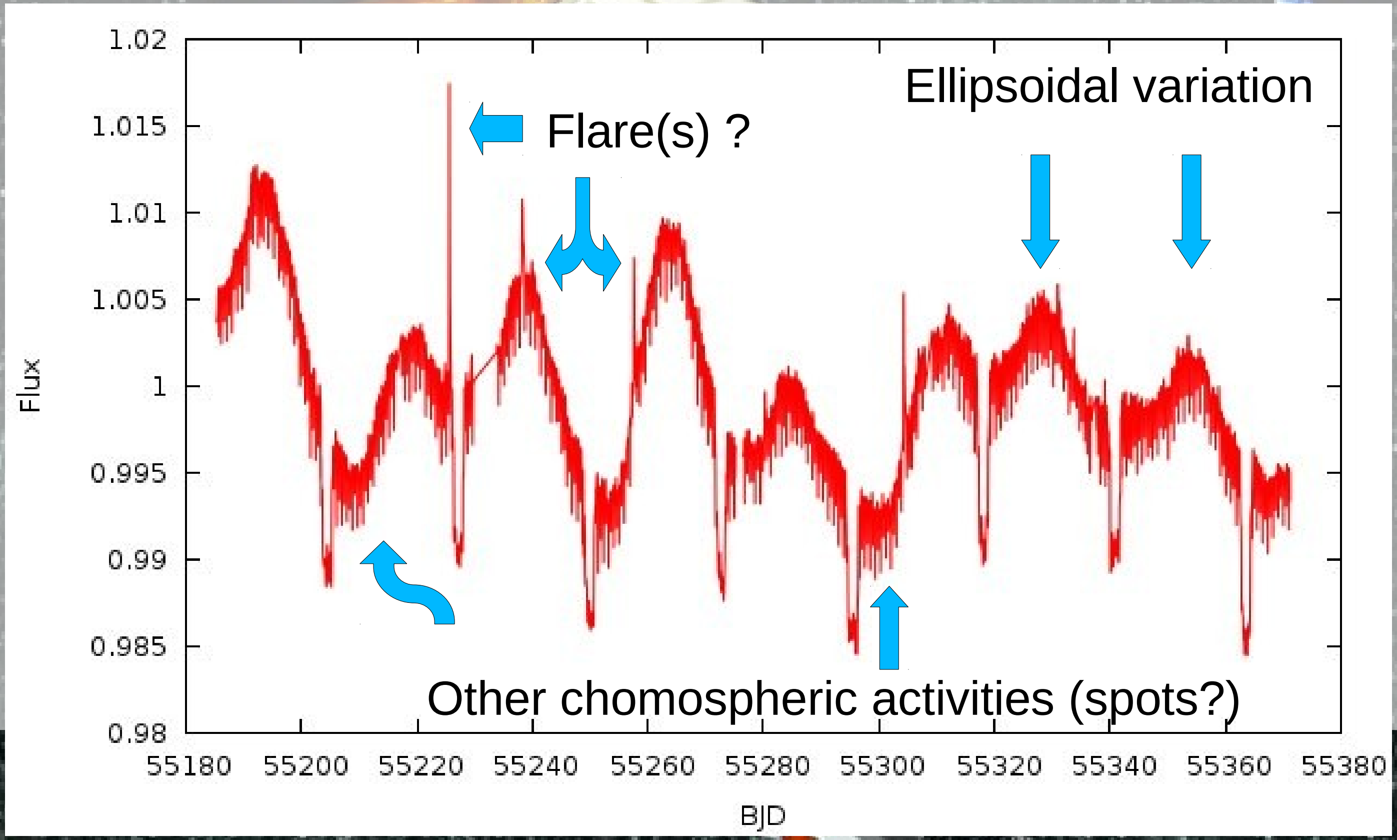
Q1 – Q9



TRINITY – All inclusive

Light-curve on different time-scales:

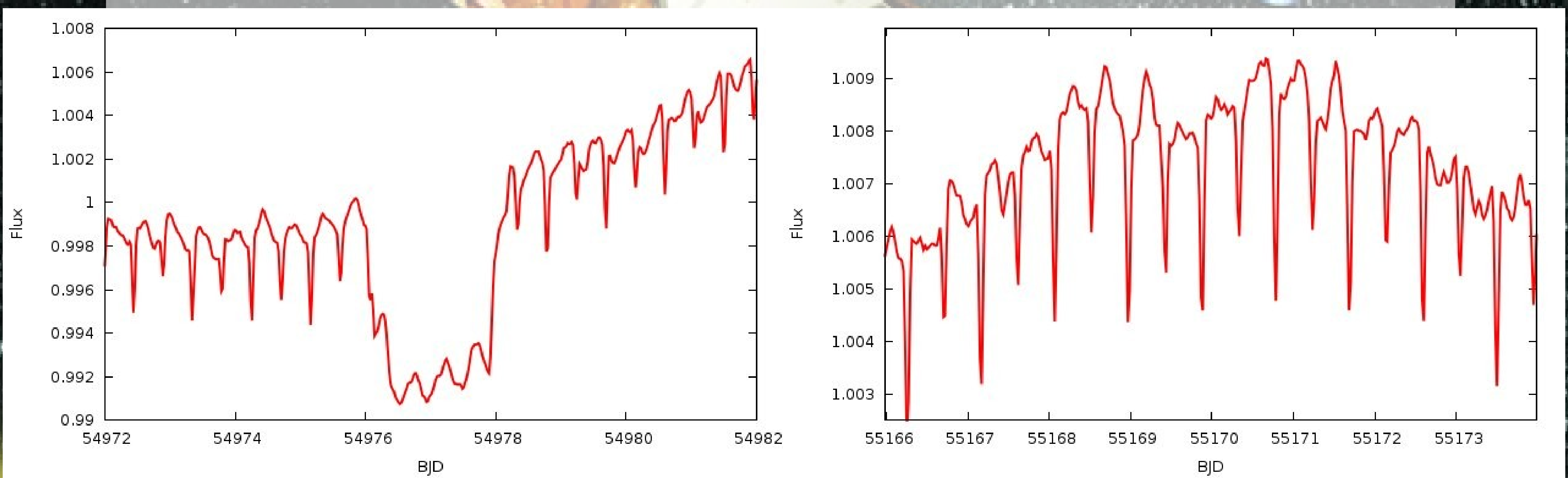
One Q



TRINITY – All inclusive

Light-curve on different time-scales:

Within One Q

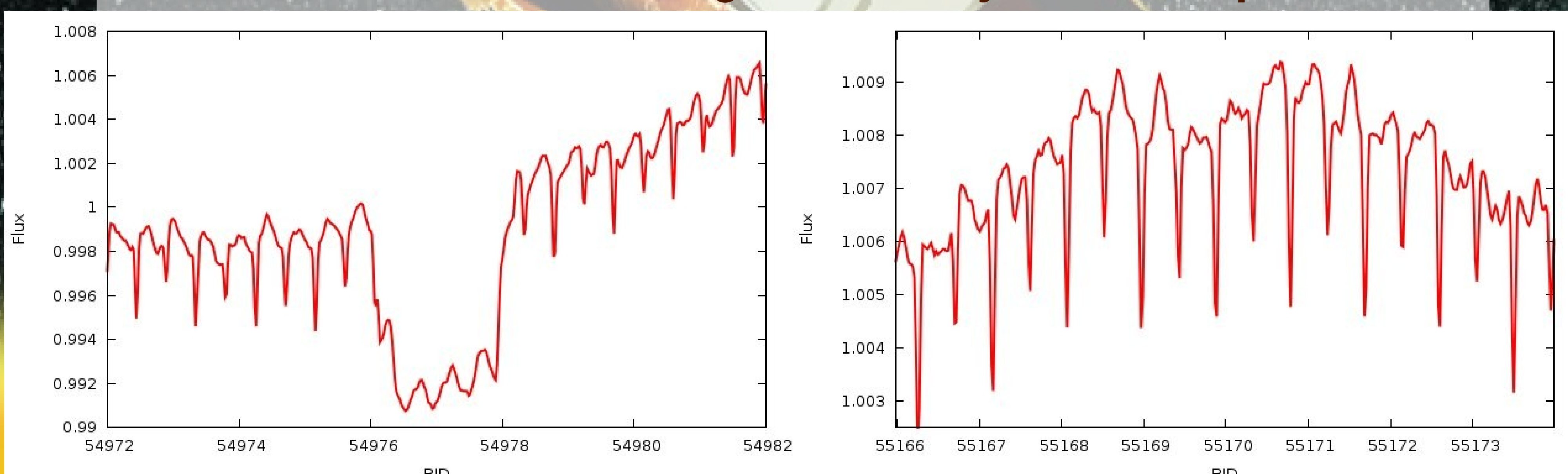


TRINITY – What We See – Questions and Answers

New question(s) – and answer(s)

– A not so easy one: if the close binary totally eclipsed in secondary minimum, why we see a light variation with its orbital half-period during totality?

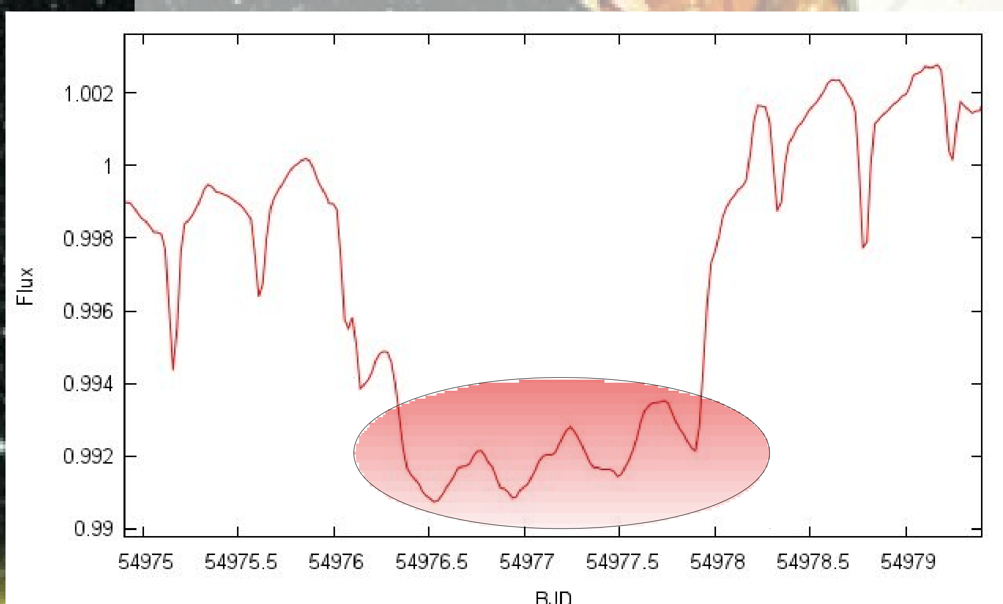
Tidal oscillations on the giant, with synodic half-period!

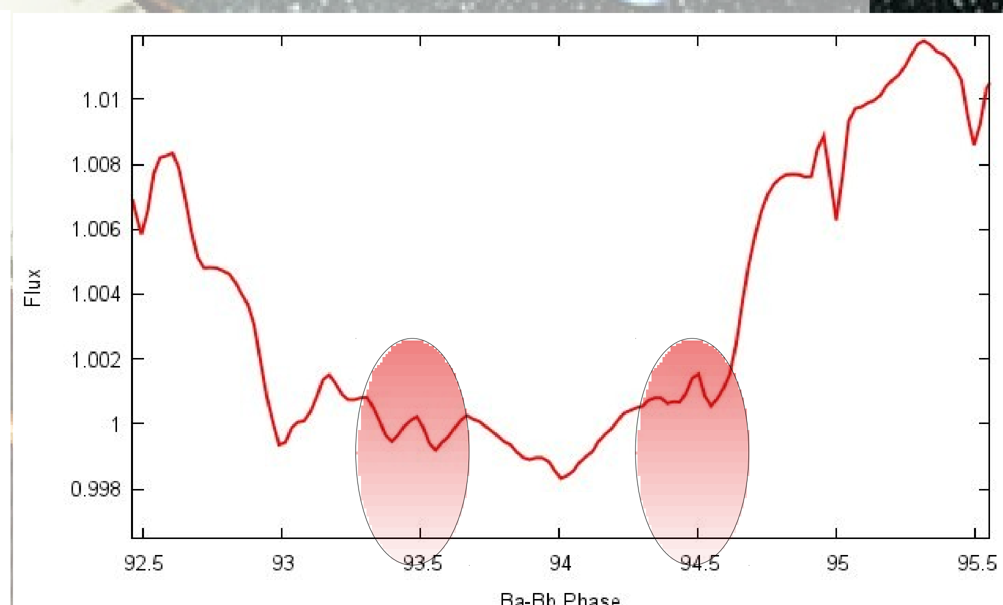


TRINITY – All inclusive

Light-curve on different time-scales:

Great Minima





TRINITY – All inclusive

Light-curve on different time-scales:

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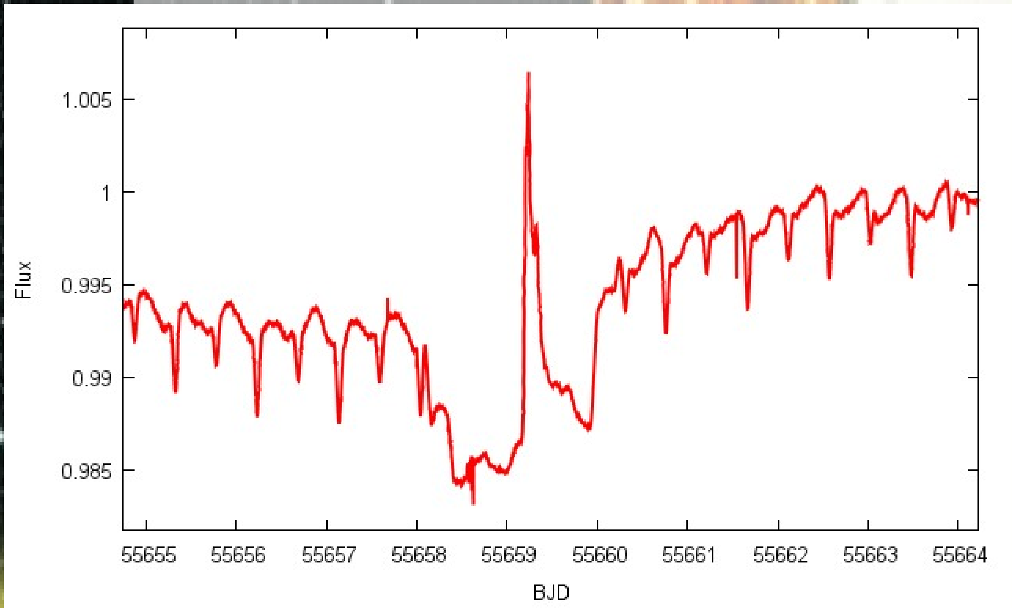
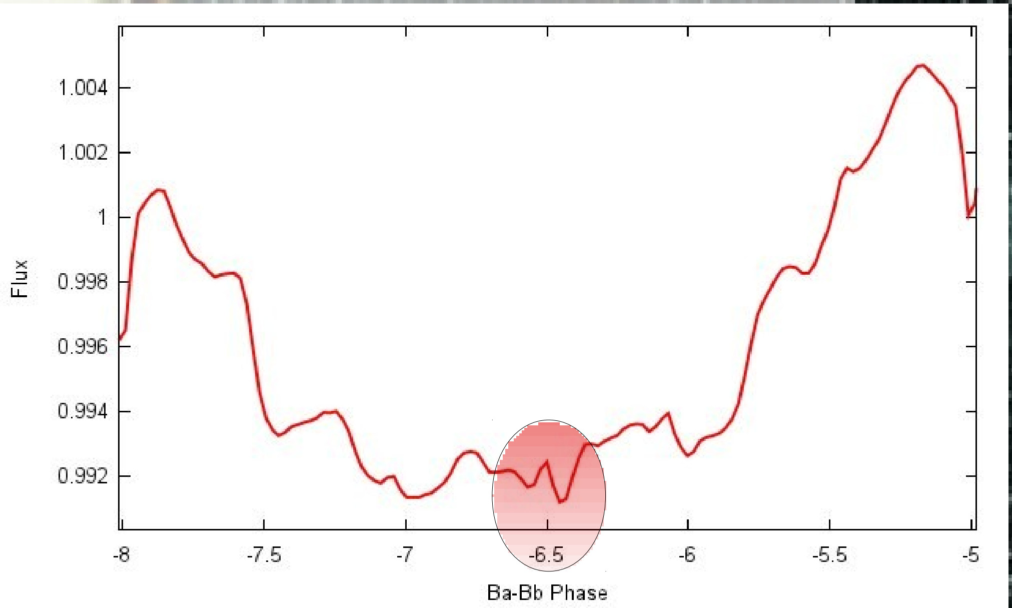
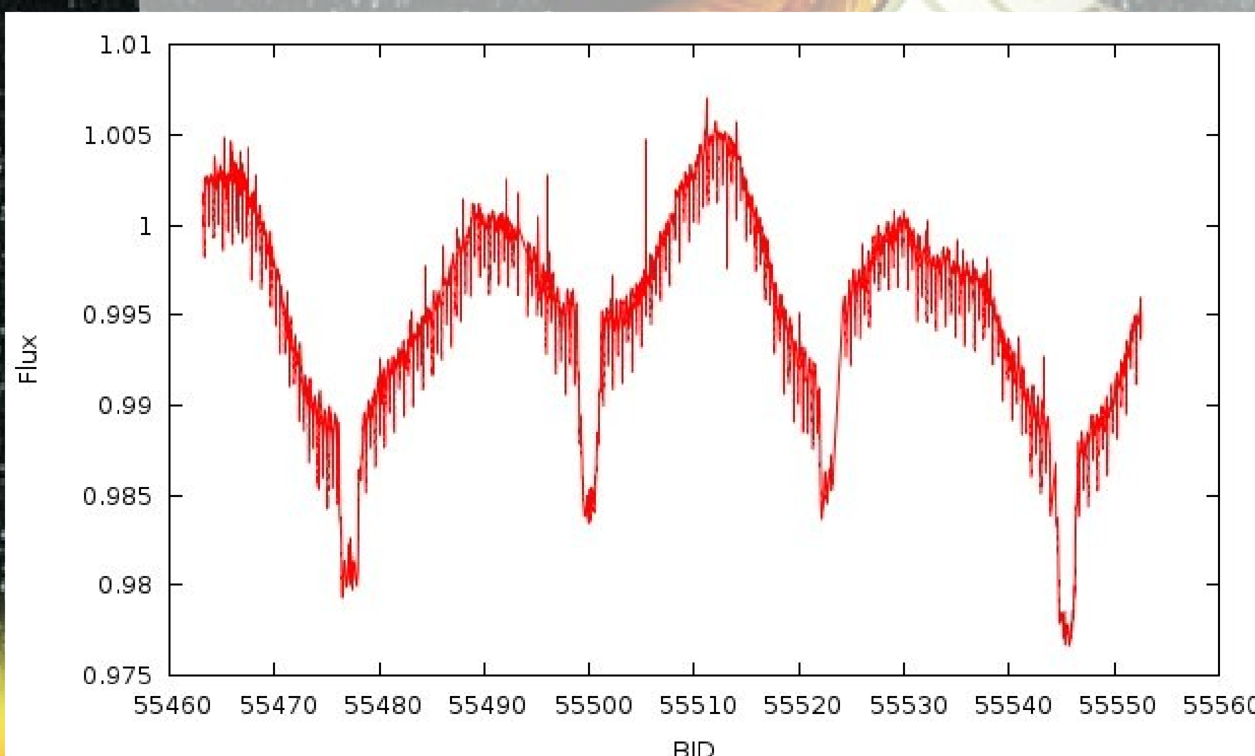
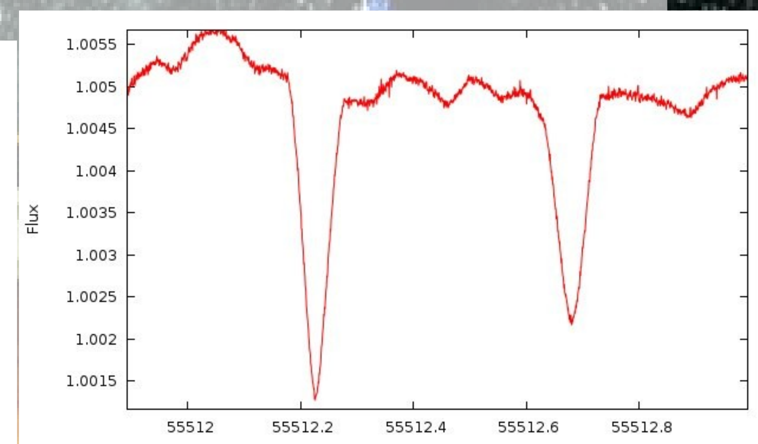


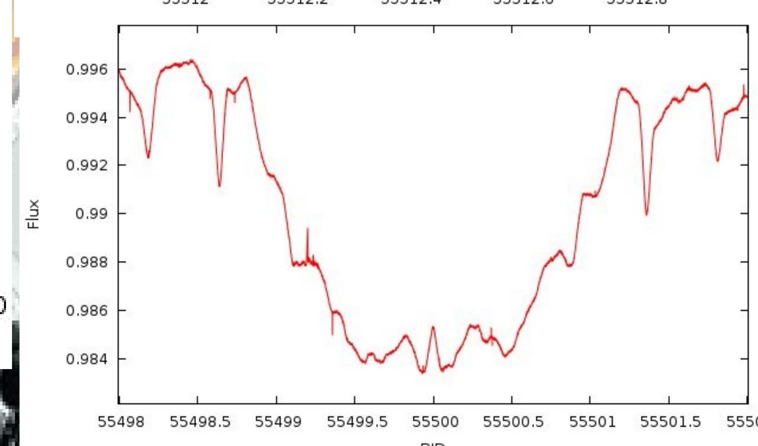


TRINITY – The last year...

– Q7-Q9 short cadence observations







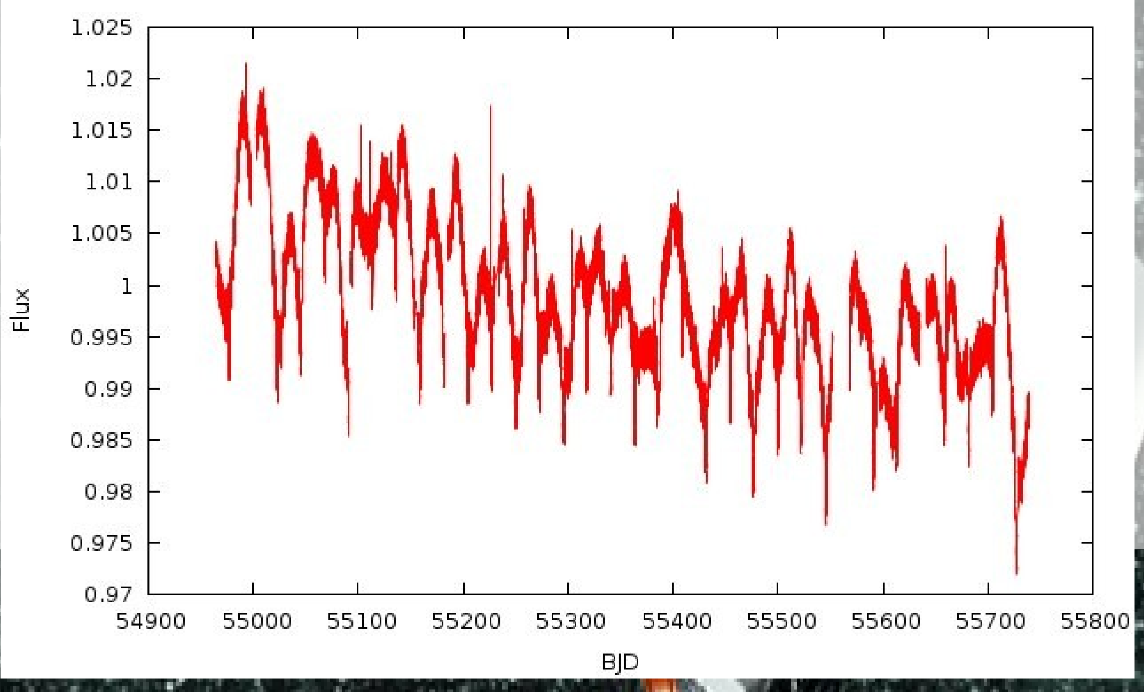
Q7 SC data

TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

(Her maiden name: O–C analysis)

– Time interval covered (Q1–Q9): MBJD 54964 – 55739
- ~ 775 days ~ 2.1 years
- ~ 855 Ba-Bb (inner binary) cycles (most eclipses were observed)
- ~ 17 A-B (outer pair) cycles



TRINITY – Period Study

Eclipse Timing Variation (ETV) Study
(Her maiden name: O–C analysis)

– What is expected?

Light-time effect:

$$O-C_{\mathrm{LITE}}=\frac{a_{\mathrm{B}}\sin i_2}{c}\,\frac{\left(1-e_2^2\right)\sin(u_{\mathrm{B}})}{1+e_2\cos v_2},$$

$$A_{\mathrm{LITE}}\approx 1^{\mathrm{d}}1\times 10^{-4}\,\frac{m_{\mathrm{A}}}{m_{\mathrm{AB}}^{2/3}}\sin i_2 P_2^{2/3}\left(1-e_2^2\cos^2\omega_{\mathrm{B}}\right)^{1/2},$$

(e.g. Irwin 1959; Kopal 1978)

Dynamical effects (perturbations):

Circular, non-coplanar case!

$$\begin{aligned}O-C_{\mathrm{dyn}} &= \frac{3}{8\pi}\frac{m_{\mathrm{A}}}{m_{\mathrm{AB}}}\frac{P_1^2}{P_2}\left\{\sin^2 i_{\mathrm{m}}\sin 2(u_2-u_{\mathrm{m}2})\right.\\ &\quad+\frac{1}{2}\cot i_1\sin i_{\mathrm{m}}\left[\sin u_{\mathrm{m}1}\cos 2(u_2-u_{\mathrm{m}2})\right.\\ &\quad\left.\left.+\cos i_{\mathrm{m}}\cos u_{\mathrm{m}1}\sin 2(u_2-u_{\mathrm{m}2})\right]\right\}\end{aligned}$$

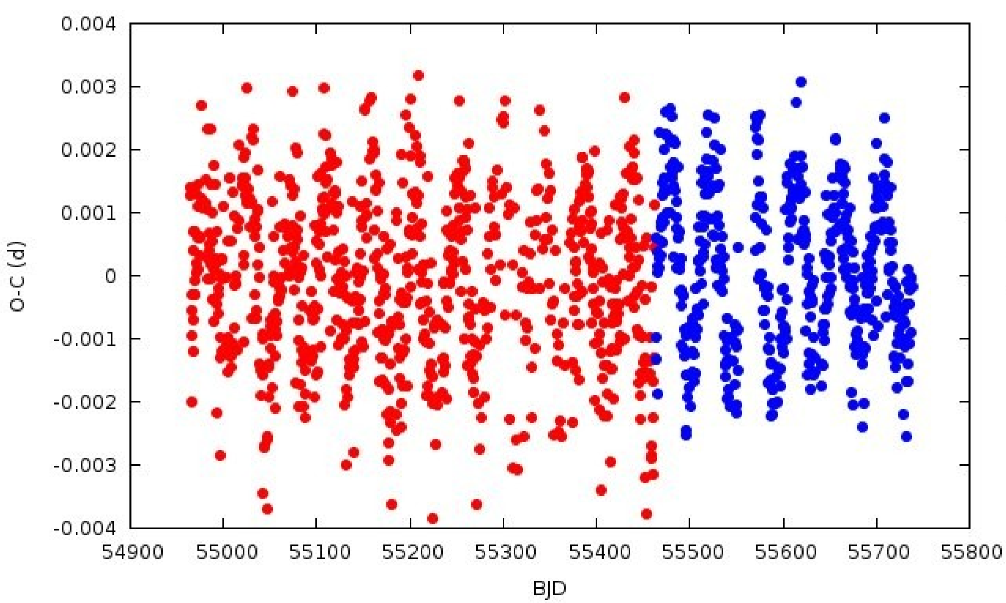
$$A_{\mathrm{dyn}}\sim\frac{1}{2\pi}\frac{m_{\mathrm{A}}}{m_{\mathrm{AB}}}\frac{P_1^2}{P_2}\frac{\left(1-e_1^2\right)^{1/2}}{\left(1-e_2^2\right)^{3/2}}$$

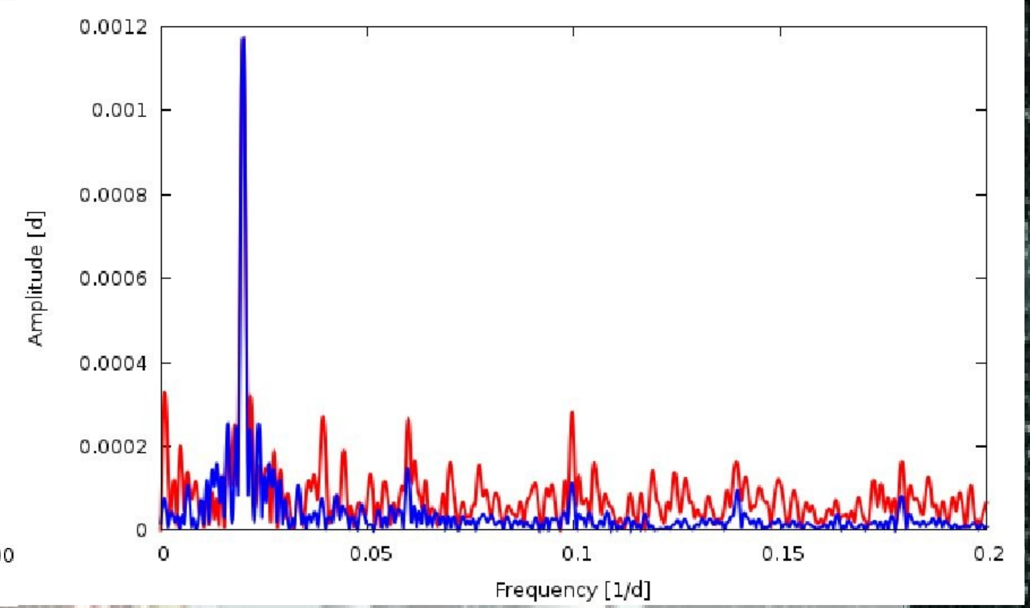
(Söderhjelm 1975; Borkovits et al. 2003, 2011; Agol et al. 2005)

TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

Discrete Fourier Transform



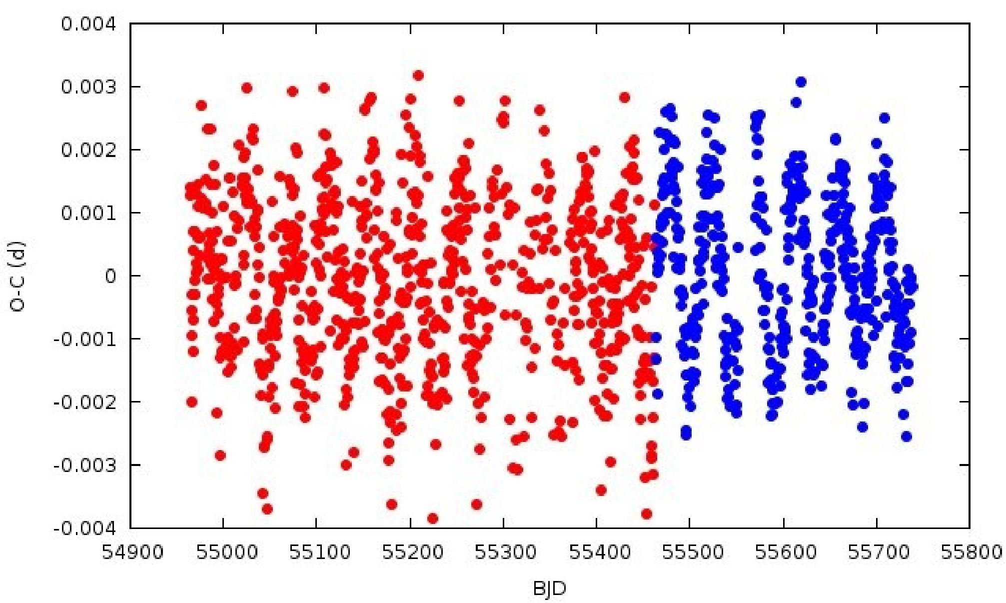


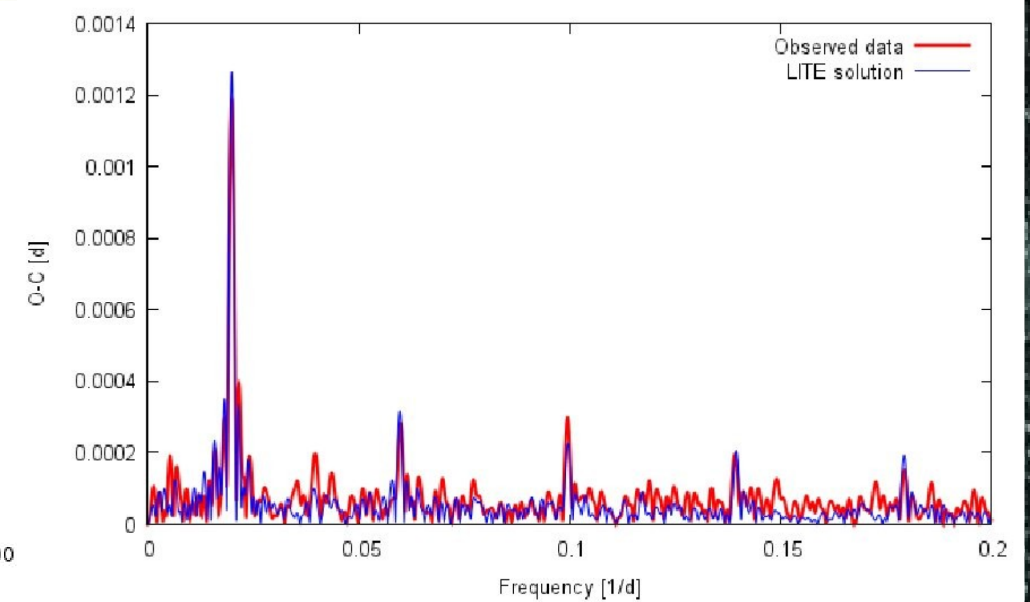
Red: Q1-6 (LC) Blue: Q7-9 (SC) **Red: O–C Blue: window**

TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

Discrete Fourier Transform



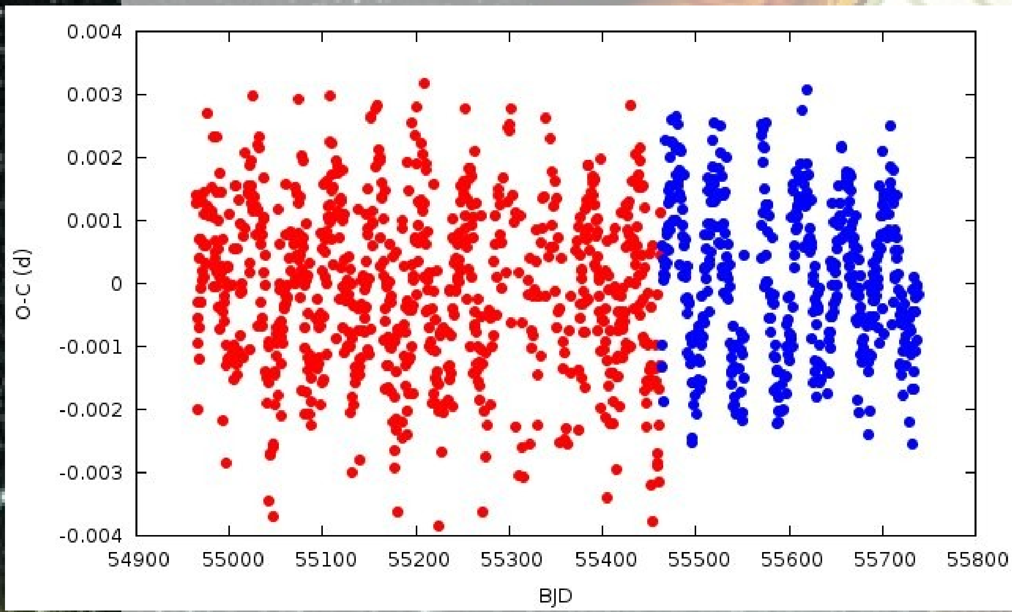


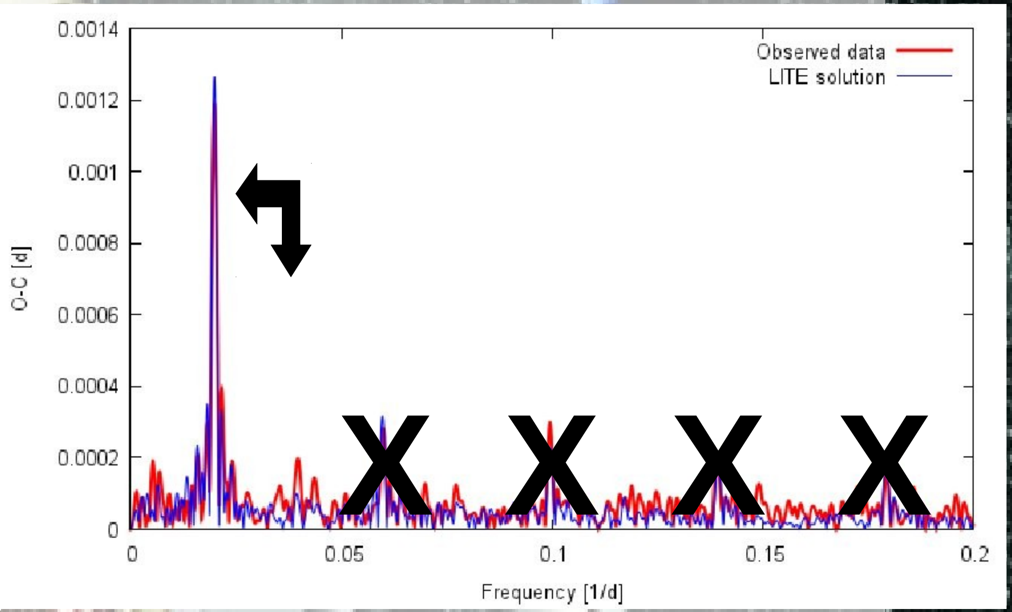
Red: Q1-6 (LC) Blue: Q7-9 (SC) **Red: O–C Blue: LITE**

TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

Discrete Fourier Transform





Red: Q1-6 (LC) Blue: Q7-9 (SC)   **Red: O–C Blue: LITE**

TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

General Linear Least Squares

$$f(E) = c_0 + c_1 E + c_2 E^2 + \sum_{j=1}^{2} (a_j \sin j\omega E + b_j \cos \omega E)$$

$(\omega = 2\pi\ P_1/P_2)$

– polynomal terms: zero shift, refined period, secular period change
– periodic terms:

j = 1

LITE → from amplitude: $a_B \sin i_2$ → from phase: outer orbital phase

From RV solution : $a_A \sin i_2$!!!

↓

LITE makes this SB1 system to SB2 → *MASSES!!!!*

TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

General Linear Least Squares

$$f(E) = c_0 + c_1 E + c_2 E^2 + \sum_{j=1}^{2} (a_j \sin j\omega E + b_j \cos \omega E)$$

$(\omega = 2\pi\ P_1/P_2)$

– polynomal terms: zero shift, refined period, secular period change
– periodic terms:

j = 1
LITE → from amplitude: $a_B \sin i_2$ → from phase: outer orbital phase

j = 2
dynamical term → from amplitude: mutual inclination (i_m)
from phase: $\Delta\Omega$ → complete 3D orbit

Tamás Borkovits et al. – New results on Trinity

TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

Results

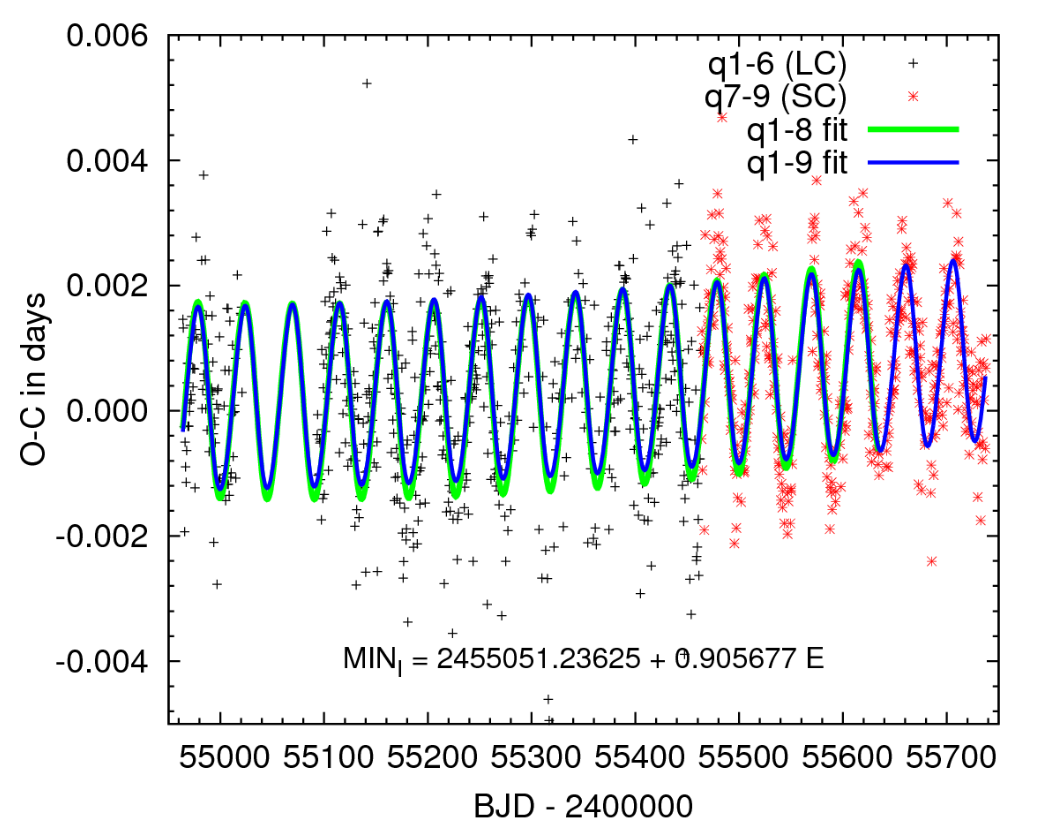


Table 1. Adjusted and derived parameters (and their formal errors) from the general linear least-squares fit of the ETV curve.

Parameter	$q1-q9$	$q7-q9$
c_0	−0.000018(51)	0.004275(1206)
c_1	−0.0000002(3)	−0.0000125(40)
c_2	$0.5(4) \times 10^{-9}$	$10.8(33) \times 10^{-9}$
a_1	0.001040(28)	0.001128(34)
b_1	−0.001004(27)	−0.001028(33)
a_2	−0.000001(29)	0.000006(35)
b_2	0.000089(26)	0.000067(31)
$a_B \sin i_2$ [$R_\odot$]	54(1)	57(1)
$(u_{AB})_0$ [°]	−44(1)	−42(1)
$T_{AB-\mathrm{prim\,in}}$ [BJD]	55045.4(1)	55045.2(2)
$a_A \sin i_2^a$ [$R_\odot$]	33.43(5)	
m_A/m_{AB}	0.617(5)	0.629(5)
$m_{AB} \sin^3 i_2$ [$M_\odot$]	4.30(15)	4.76(20)
$m_A \sin^3 i_2$ [$M_\odot$]	2.65(10)	3.00(13)
$m_A/m_{AB} \sin^2 i_m$	0.042(12)	0.031(14)
i_m^b [°]	15(2)	13(3)
u_{m2} [°]	91(9) or 271(9)	95(15) or 275(15)
i_2^c [°]	87.7	
$i_1^{b,d}$ [°]	88(2) or 88(2)	87(3) or 89(3)
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[a]: taken from Derekas et al. (2011);
[b]: $180° - i_m, 180° - i_1, 180° - \Delta\Omega$ gives an equivalent solution;
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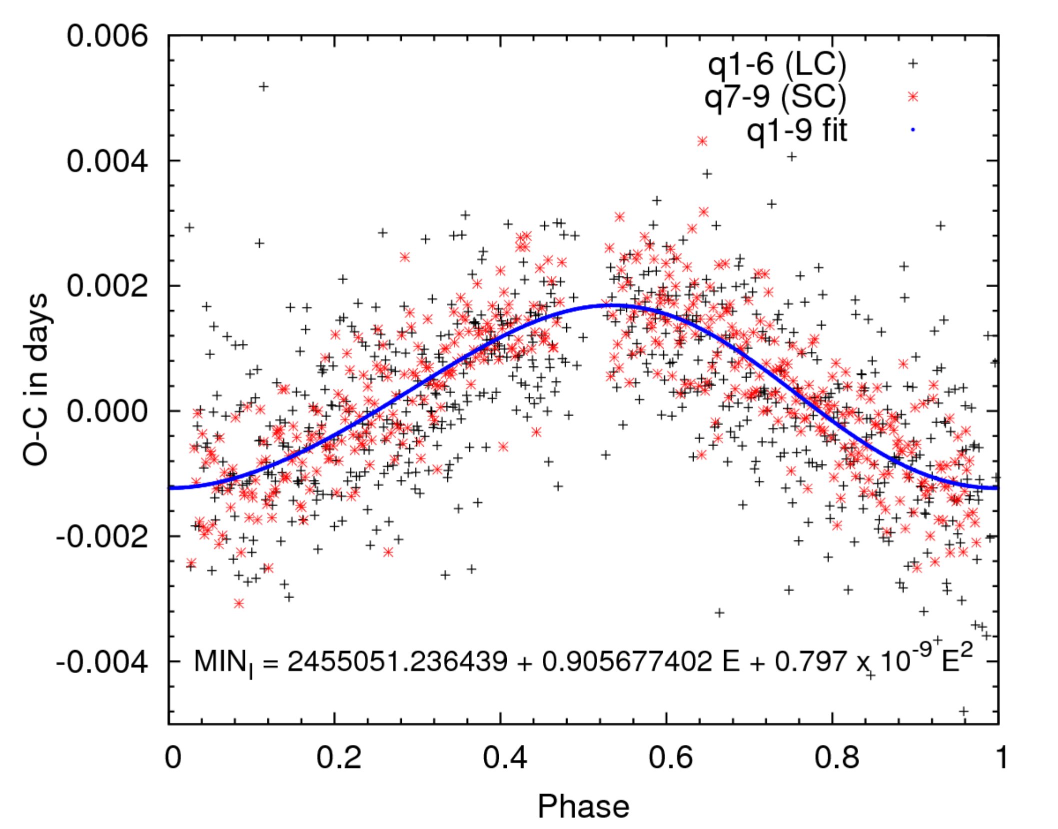
[d]: Second values are valid for $u_{m2} + 180°$.

TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

Results



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TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

Results

Masses in good correspondance with astrophysical expectations, and previous results

H U R R A Y!

Table 1. Adjusted and derived parameters (and their formal errors) from the general linear least-squares fit of the ETV curve.

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[c]: fixed from light-curve solution;
[d]: Second values are valid for $u_{m2} + 180°$.

TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

Results

For first glance:

it seems to be consistent (phase term)
it would predict precession with
P_{prec} ~ 13 – 14 years;
A_{prec} ~ 26° – 28° (full amplitude)

This can explain the secular period variation not only qualitatively, but even quantitavely, too !

H U R R A Y ???

(Formulae in Borkovits et al. 2007)

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TRINITY – Period Study

Eclipse Timing Variation (ETV) Study

Results

H U R R A Y ???

Unfortunately NOT!

In the last two years the inner inclination (i_1) should have to change by ~ 10°, But we do not see any eclipse depth variation, i. e. there is no observable precession!

Table 1. Adjusted and derived parameters (and their formal errors) from the general linear least-squares fit of the ETV curve.

Parameter	$g1-g9$	$g7-g9$
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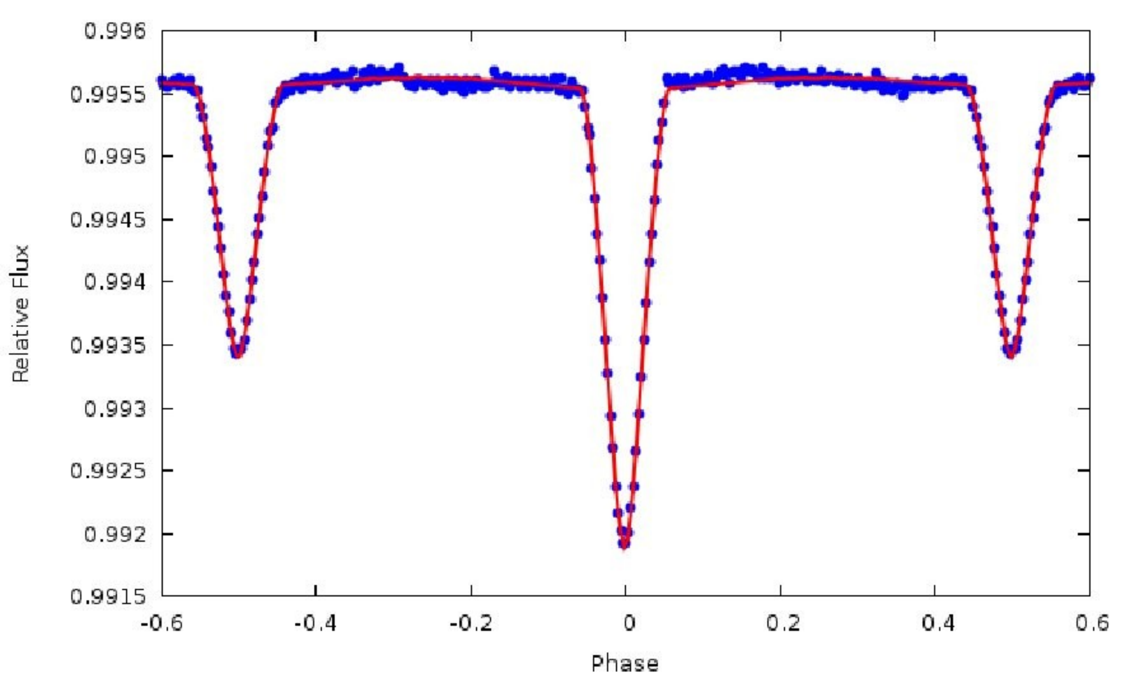
TRINITY – Light Curve Study

Aim: disentangling the different variations

1. **Close binary**

   – **More than 885 cycles: let's average simply!**



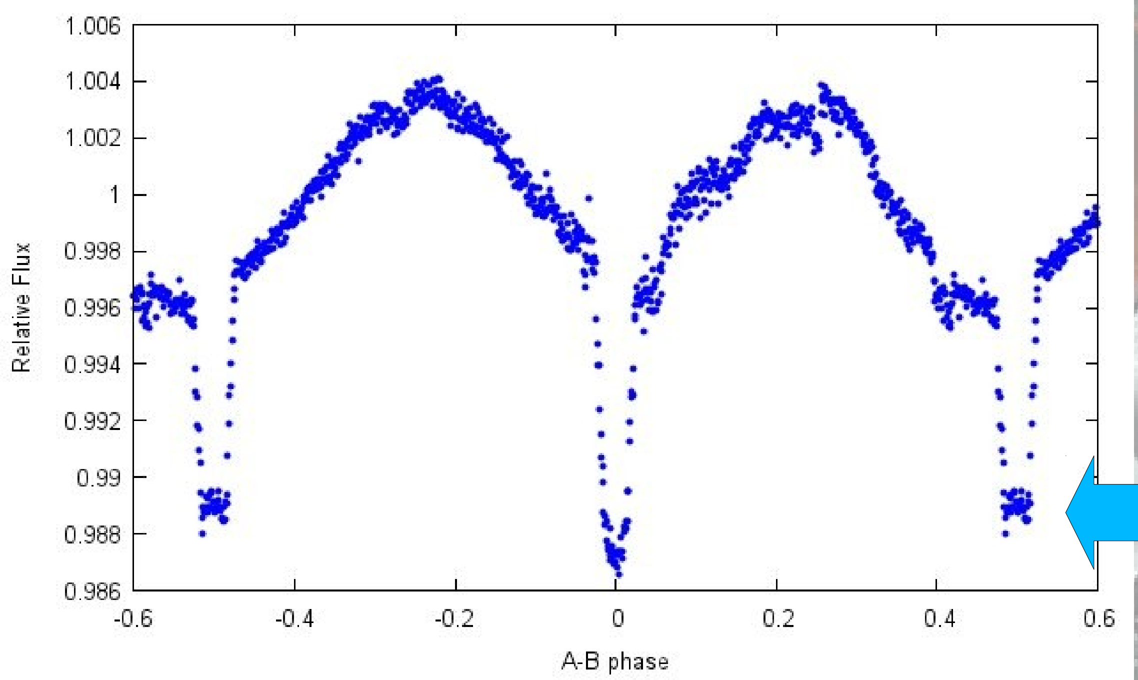
√

TRINITY – Light Curve Study

Aim: disentangling the different variations

2. Wide binary

– The same receipt? Only 17 cycles!



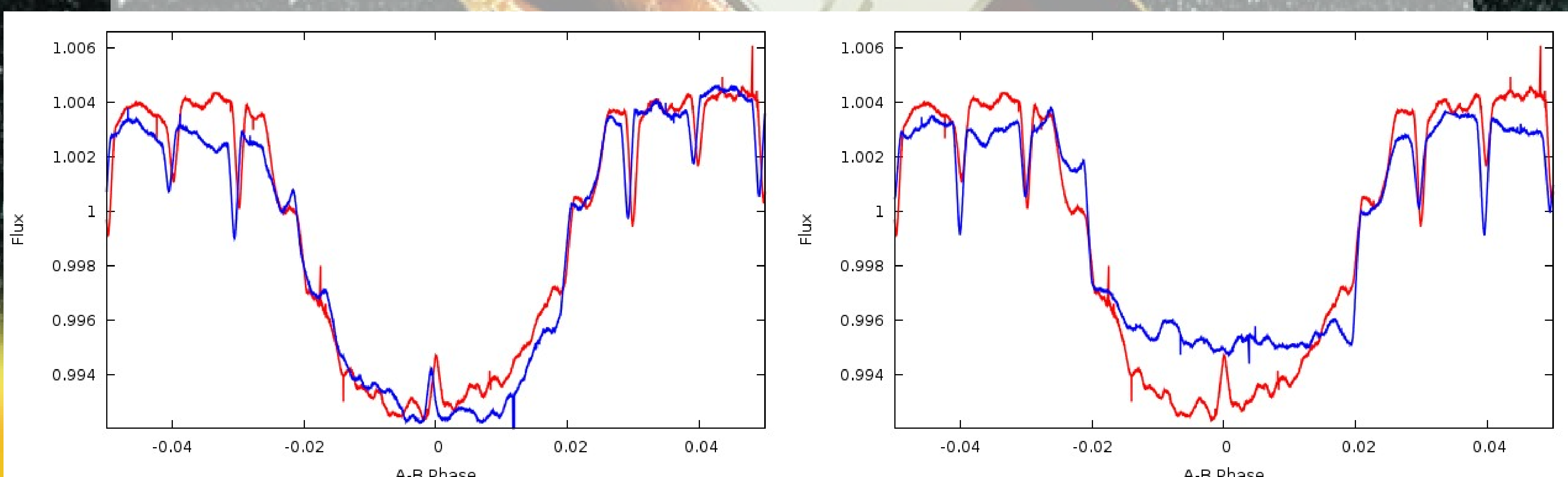
We lost the most important information!

TRINITY – Light Curve Study

Aim: disentangling the different variations

2. Wide binary

- **What are these most important information, and their carrier?**
  The shoulders
  And, especially, the ~5:251 mean-motion resonance



TRINITY – Light Curve Study

Aim: disentangling the different variations

2. Wide binary

Instead: simultaneous light-curve synthesis
with a new code (based on WD and Andrej's Phoebe)
Main differences:

- **simultaneous treatment of inner and outer binaries,**
  incl. momentarily varying tidal field
  (i. e. „dancing” of two bulges on the giant)
  linear approximation, instead of Roche model:

$$r = R\left(1 + \sum_{j=2}^{4} f_j + g_2\right), \qquad \text{(B1)}$$

where the amplitudes of the first order tidal distortions caused by star k on star i are

$$f_j^{(i<-k)} = \left(1 + 2k_j^{(i)}\right)\frac{m_k}{m_i}\left(\frac{R_i}{\rho_{ik}}\right)^{j+1} P_j\left(\lambda''_{ik}\right), \qquad \text{(B2)}$$

while the amplitude of the rotational distortion of star i is

$$g_2^{(i)} = -\frac{\omega_i^2 R_i^3}{3Gm_i} P_2\left(\nu'_i\right). \qquad \text{(B3)}$$

(e.g. Kopal, 1978)

TRINITY – Light Curve Study

Aim: disentangling the different variations

2. Wide binary

Instead: simultaneous light-curve synthesis
with a new code (based on WD and Andrej's Phoebe)
Main differences:
– simultaneous treatment of inner and outer binaries,
incl. momentarily varying tidal field
light-time effect
(calculating stellar positions in different moments)

TRINITY – Light Curve Study

Aim: disentangling the different variations

2. Wide binary

Instead: simultaneous light-curve synthesis
with a new code (based on WD and Andrej's Phoebe)
Main differences:
– simultaneous treatment of inner and outer binaries,
incl. momentarily varying tidal field
light-time effect
– other extras: Doppler-beaming
(calculates for each cells, incl. rotation)

TRINITY – Light Curve Study

Aim: disentangling the different variations

2. Wide binary

Instead: simultaneous light-curve synthesis
with a new code (based on WD and Andrej's Phoebe)
Main differences:
– simultaneous treatment of inner and outer binaries,
incl. momentarily varying tidal field
light-time effect
– other extras: Doppler-beaming
Additional Fourier terms to describe intrinsic variations

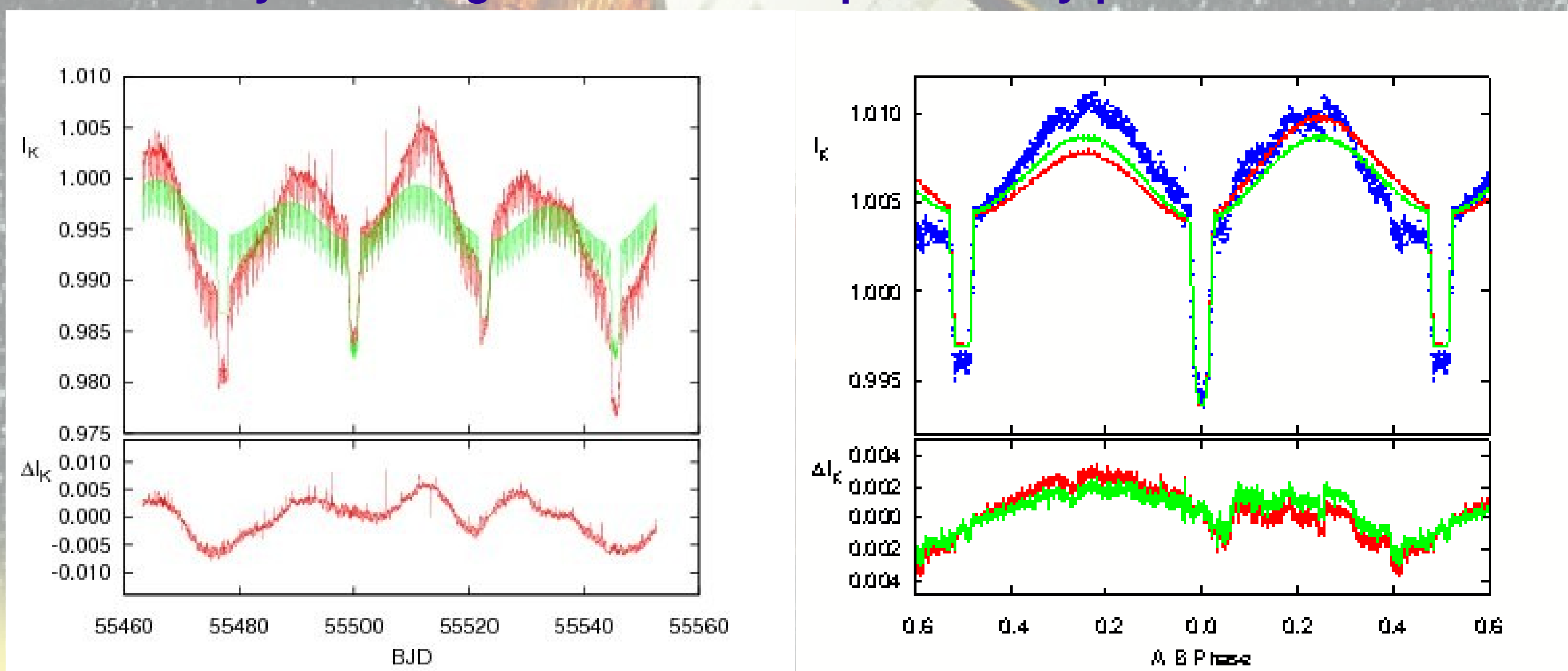
No spot modelling – yet

TRINITY – Light Curve Study

Aim: disentangling the different variations

Steps of the modelling/fitting process

1. Synthetic light-curve fit with preliminary parameter set

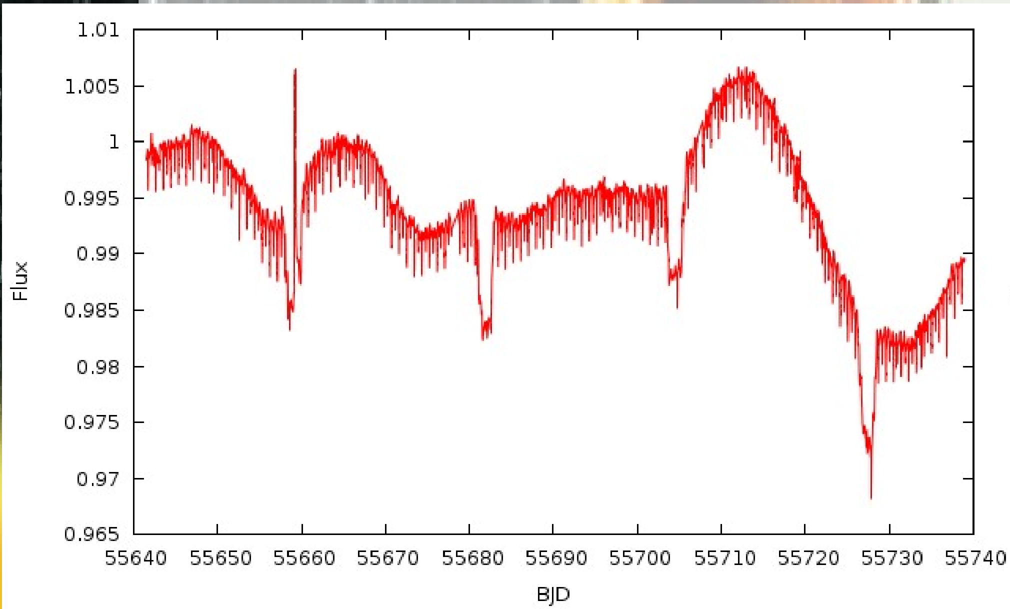


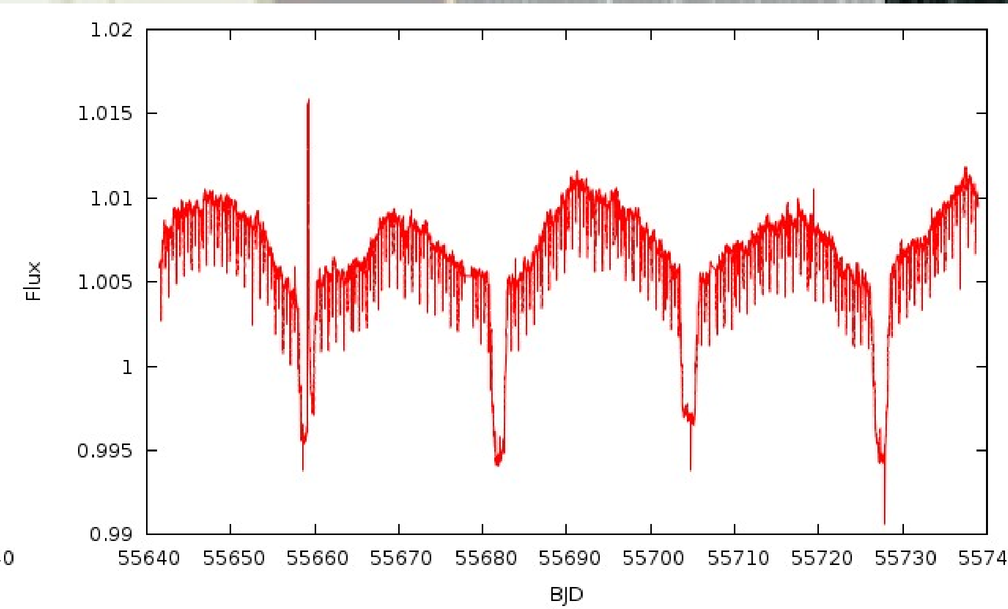
TRINITY – Light Curve Study

Aim: disentangling the different variations

Steps of the modelling/fitting process

1. Synthetic light-curve fit with preliminary parameter set
2. Modeling of residual curves with Fourier terms
3. Removal of this model from Q by Q





TRINITY – Light Curve Study

Aim: disentangling the different variations

Steps of the modelling/fitting process

1. Synthetic light-curve fit with preliminary parameter set
2. Modeling of residual curves with Fourier terms
3. Removal of this model from Q by Q
4. Light-curve fit with some numerical methods
   (e.g. MCMC – next week?) – now simple grid search
5. Optional: go to 2. – refinement

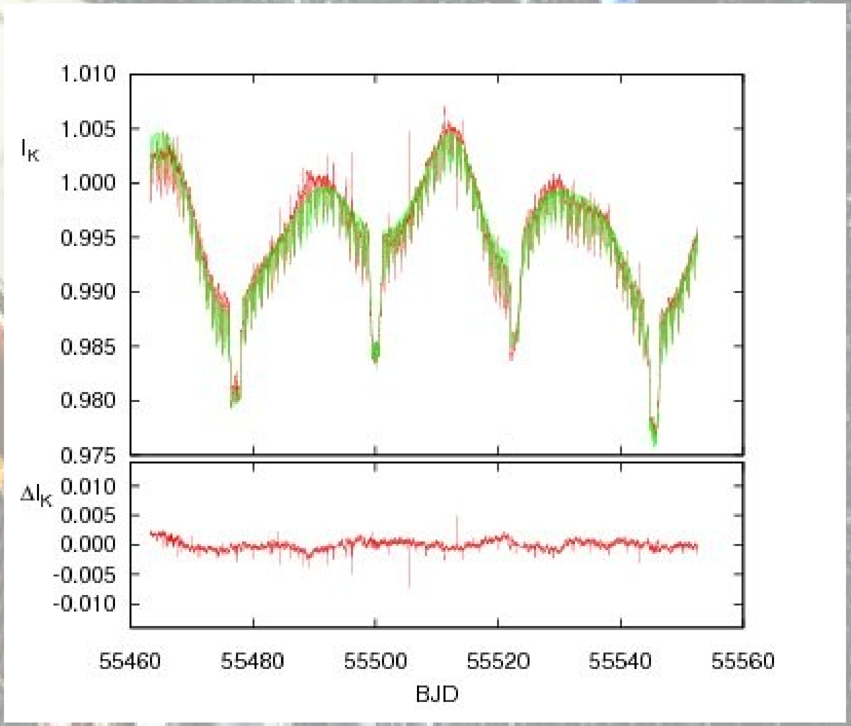
TRINITY – Light Curve Study

Some results

Table 2. Stellar and orbital parameters derived from the combined *ETV* and synthetic light curve analysis

orbital parameters		
	subsystem	
	Ba–Bb	A–B
P [d]	0.9056768(2)	45.4715()
$T_{\rm MINI}$ [BJD]	2455051.23623(5)	2455499.996()
a [$R_\odot$]	4.74()	89.61()
e	0.0	0.0
ω	–	–
i [deg]	85.35(5)	87.4(1)
$\Delta\Omega$ [deg]	0.0(5)	
$i_{\rm rel}$ [deg]	2.05()	
q	0.920(5)	0.595(5)
$L_{\rm sec}/L_{\rm TOT}$	0.3468	0.0078

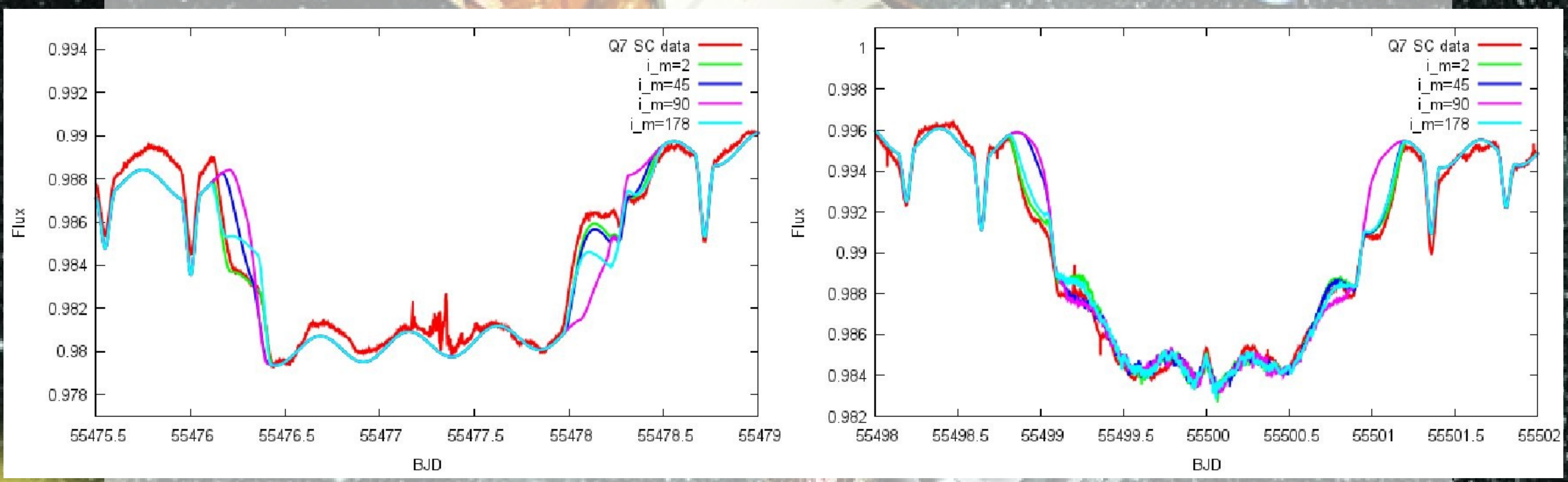
stellar parameters			
	Ba	Bb	A
m [$R_\odot$]	0.927()	0.830()	3.0(1)
R [$R_\odot$]	0.875(5)	0.815(5)	12.60(5)
$T_{\rm eff}$ [K]	5200()	4685(25)	5120(20)
$\log g$ [dex]	4.52	4.54	2.71



TRINITY – Light Curve Study

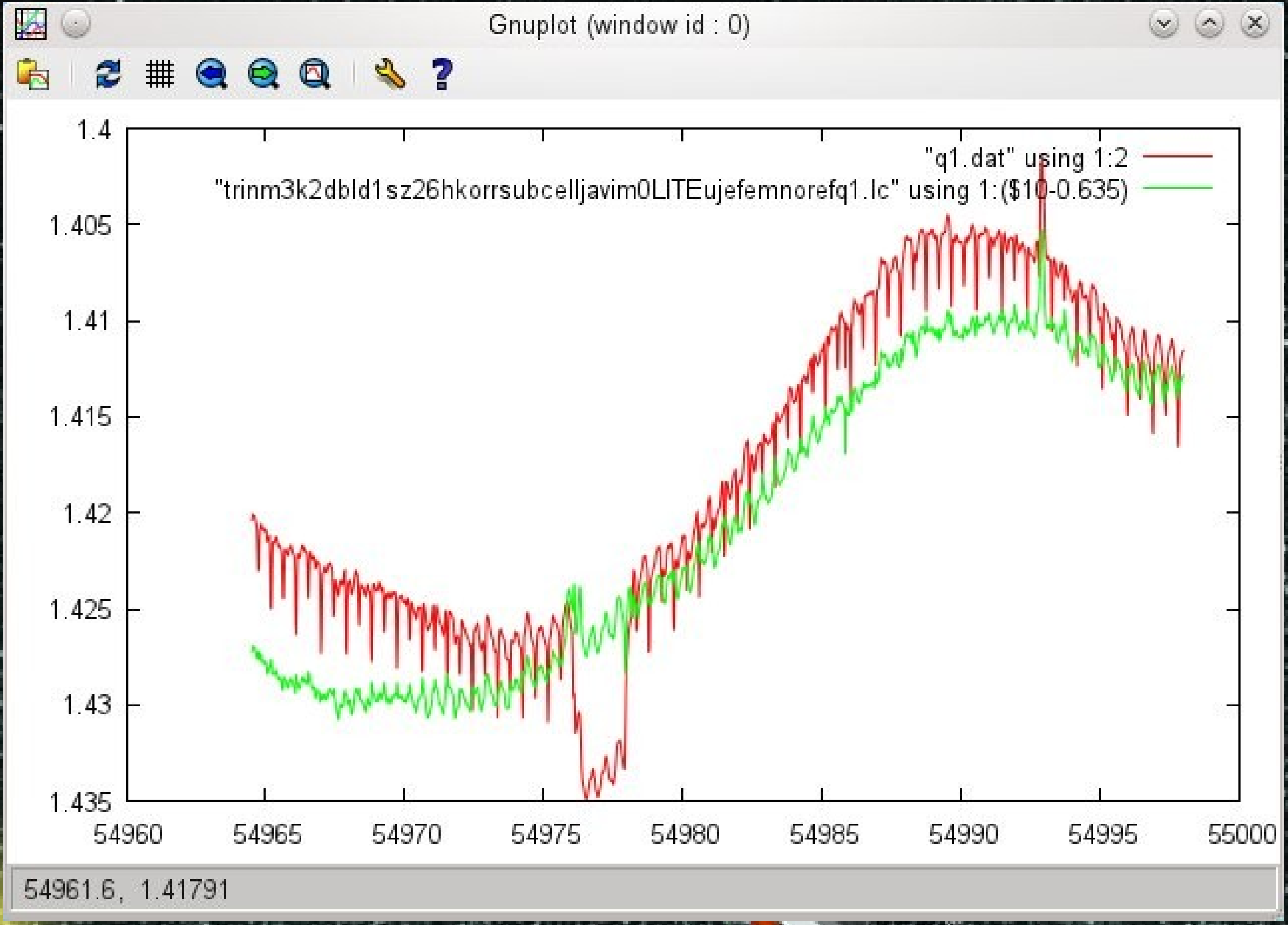
Some results

3-D orbits – resolving inclination ambiguity

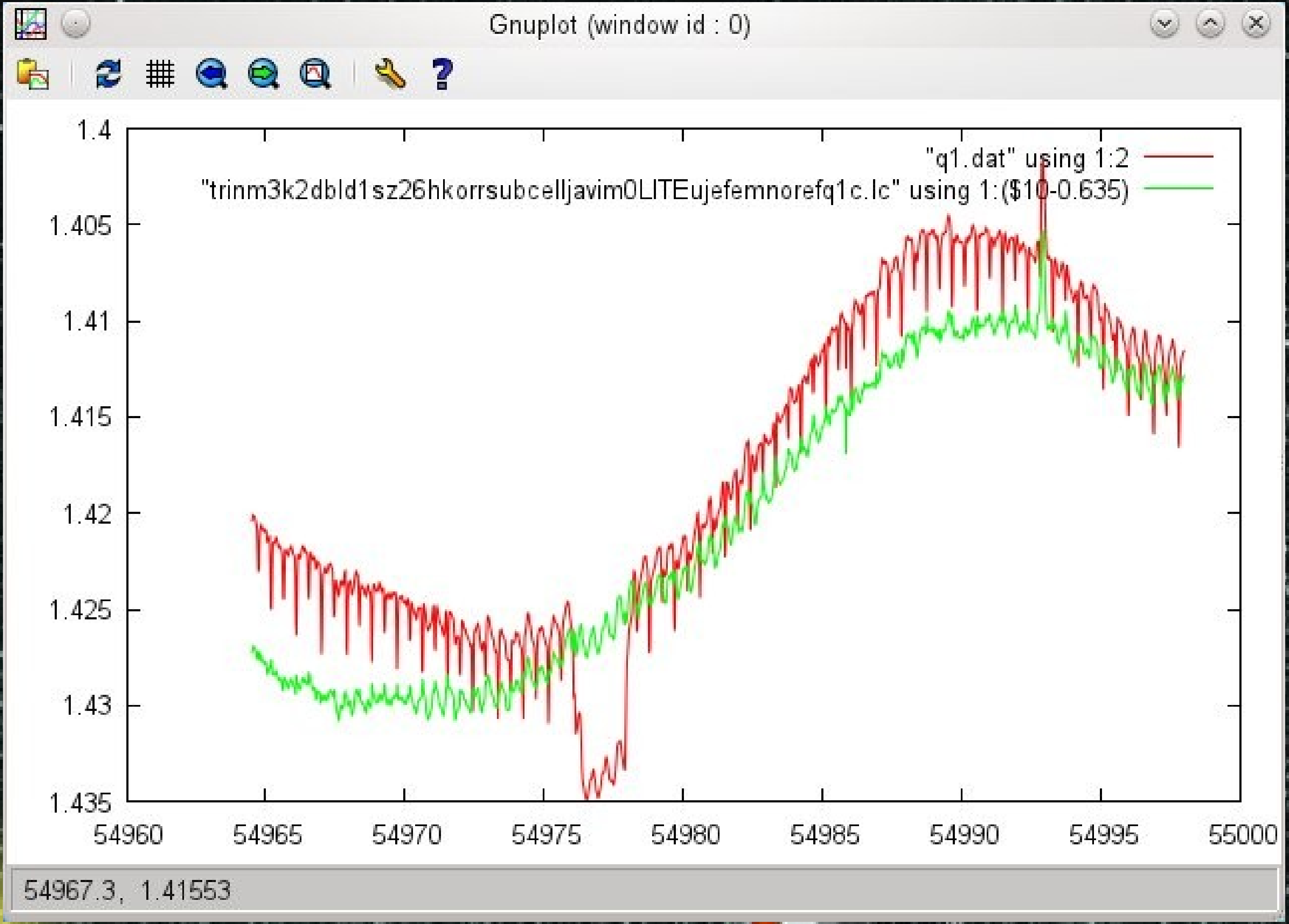


Not simply coplanar, but prograde, too!

TRINITY – clock fine tuning



TRINITY – 45 day 11 hour 19 min 40 sec



TRINITY – Conclusions/Continuation

– Combination of LITE solution from ETV with previous SB1 radial velocity data resulted SB2-type mass data

– Simultaneous light curve fit for both the close and the wide eclipsing binaries resulted not only the usual relative (scaled) stellar parameters, but physical ones

– 3D orbits were determined, and inclination ambiguity were also resolved

Next stage: study of tidal oscillations and flares