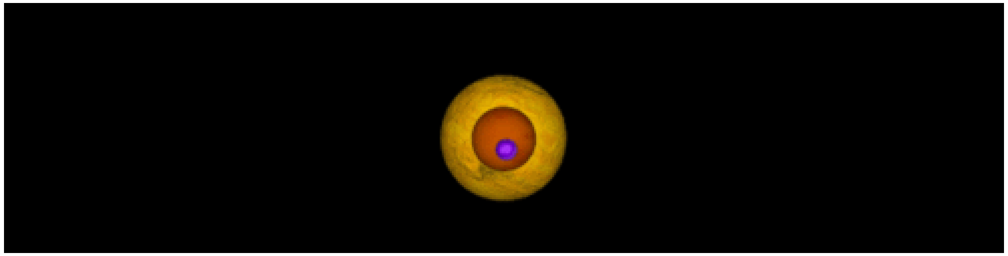
# Searching for planets around eclipsing binary stars using ‘TIMING’ method



Artistic impression of the Kepler-16-system with Kepler-16A in yellow, Kepler-16B in reddish-orange and Kepler-16 (AB)-b in violet.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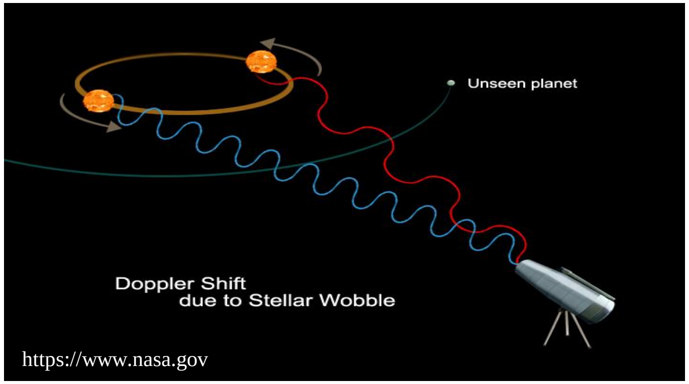
**EWASS-2017**

**Prague, June 26, 2017**

# Ways to find Planets

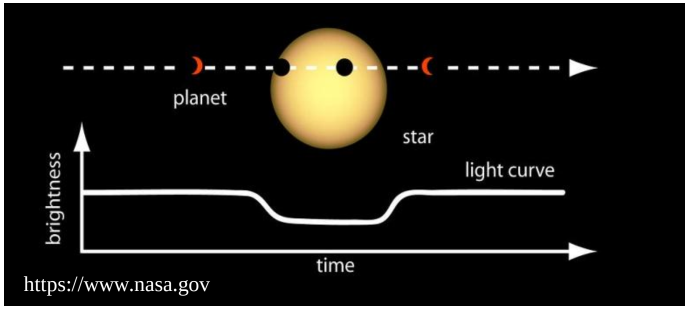
- Radial Velocity,
- Transit
- Direct Imaging
- **Timing Variations**
- Microlensing
- Astrometry

**Radial Velocity:** 638 Planet discovered




planet causes stars to wobble in space,
changing the color of the observed light

**Transit Method:** **2732 Planets discovered**




planet dims the star's light when it passes
beetwen star and the Earth

# Timing

→ **"Timing"** observations,
**2009...** Evidence for planets around some binary systems

(Lee et al. 2009)

→**KEPLER**, Transit Method
**2011 ...** Discovery of a circumbinary planet transiting a close binary system

(Doyle et al. 2011)

**Timing Method:**
**Light Travel Time (LTT) effect:** the variations in the timings of eclipse minima w.r.t. the linear ephemeris (O–C), orbital period.

**Eclipsing Binaries:**
- **CVs** (Cataclysmic Variables): HU Aqr, DP Leo, UZ For, ....
- **PCEBs** (Post-Common Envelope Binary Stars): NN Ser, V470 Cam, NY Vir, ....
- Other Binaries (W UMa type, etc.)

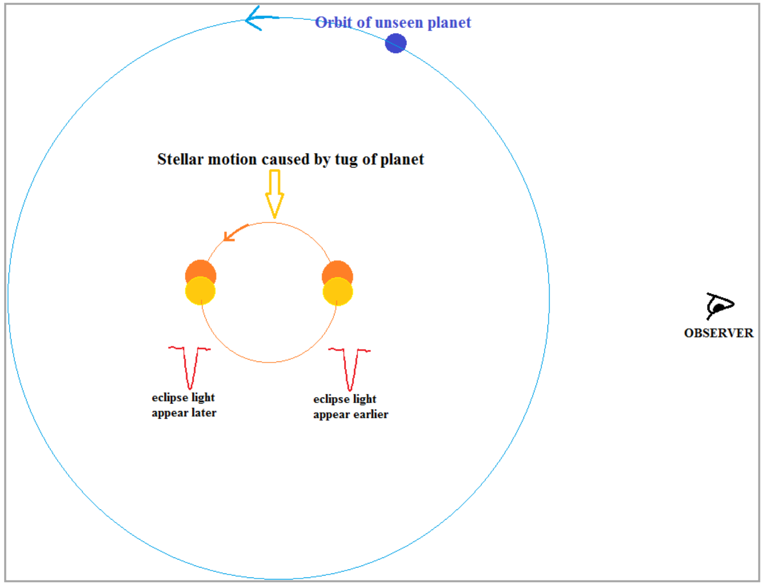
(Potter et al. 2011, Beuermann et al. 2011, Goździewski et al. 2015)

# Timing

## Linear Ephemeris:

- differences between Observed and Calculated **(O-C)** of timing eclipse

  - ➢ Eclipse timings are examined by fitting with a linear ephemeris
  - ➢ The residuals can show cyclic variations.




## Cyclic variations of the (O-C):

- can results from the gravitational tug due to orbiting companions (planets),
- which leads to swinging of the eclipsing binary,
- causing the eclipse light appears earlier or later

  - ➢ the LTT effect can be measured with a high accuracy
  - ➢ used to infer the presence of planetary-mass companions

(Irwin 1952; Goździewski et al. 2012, 2015; Horner et al. 2012).

# Timing

## “Timing” Method:

- Sensitive to massive companions in long period orbits (due to $K \sim M_3$ ve $K \sim P_3^{3/2}$)
- The amplitude of the LTT effect increases for low mass binaries

(Ribas 2005; Pribulla et al. 2012)

***Other effects can produce periodic variations in (O-C)***

## - Applegate mechanism:

- magnetic activity → triggers solar cycles → changes the internal structure of the star.
- oscillations of the orbital period
- can be discarded if a companion star does not provide enough energy to drive changes

(Applegate 1992, Lanza et al. 1998)

## -A combination of a few effects with the third body.

- magnetic braking, angular momentum loses, mass transfer...)

## -Criteria for determination of a circumbinary system

- the period variation must be recurring and periodic in time
- The system should be dynamically stable

(Horner et al. 2013, Hinse et al. 2014)

# Sources, Observatories, Observational Data

- **TUG-T100 (**TUBİTAK National Observatory) SI 1100 CCD (4096x4096, readout ~ 45 s (1x1), 13 s (2x2))
- **ADYU60** (Adıyaman University Observatory ) Andor Ikon-M 934 CCD (1024x1024, readout ~ 1-2 s (1x1))
- Some other telescopes : **- OPTICON** (Optical Infr. Coordination Network for Astronomy),
  - 60 cm at **Suhora** and 60 cm at **Krakow Obs.** (Poland)

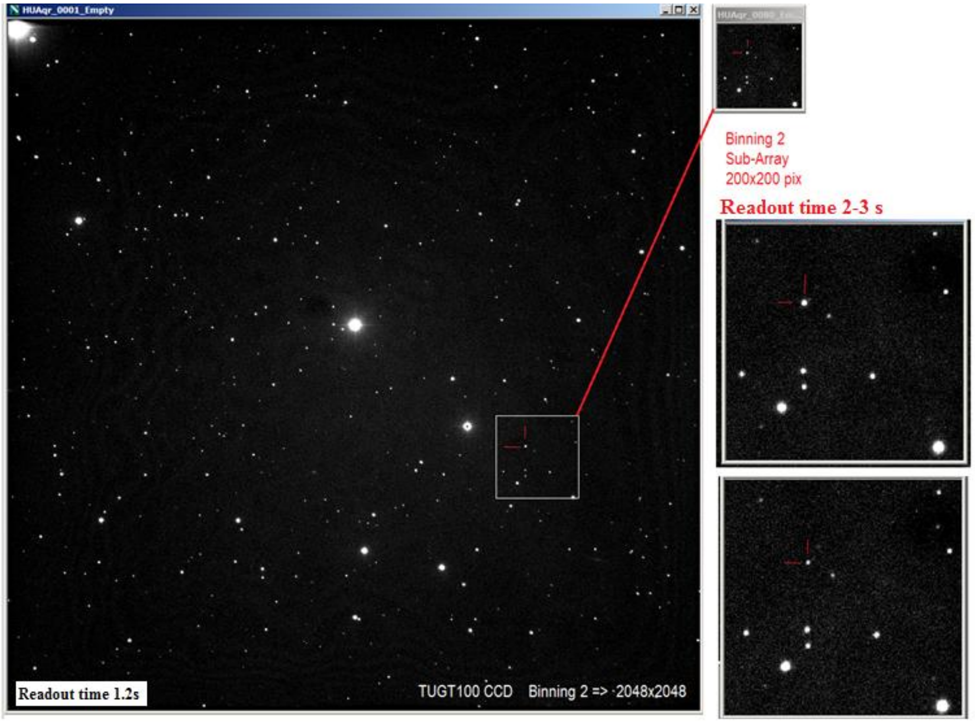
## Sources:

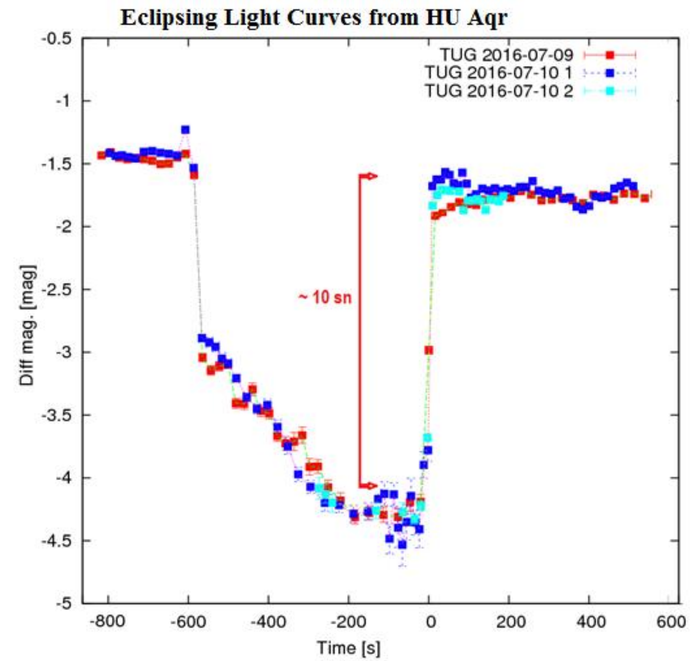
- short orbital periods (**1.77–10 hrs)**
- brightness (8-18 mag)
- period changes detected in 15 systems

| Object | Period (h) | Magnitude | Total Eclipse | Total Eclipse |
|---|---|---|---|---|
| | | | TUGT100 | ADYU60 |
| V470 Cam | 2,295 | 14,70 | 20 | 37 |
| HS 2231+2441 | 2,654 | 14,00 | 21 | 35 |
| NSVS14256825 | 2,649 | 13,20 | 23 | 36 |
| NSVS05629361 | 3,018 | 12,70 | 13 | 31 |
| NSVS 07826147 | 3,822 | 13,00 | 10 | 20 |
| NSVS 06507557 | 12,360 | 13,40 | 4 | 6 |
| NY Vir | 2,424 | 13,30 | 10 | 24 |
| HW Vir | 2,801 | 10,50 | 7 | 28 |
| QS Vir | 3,618 | 14,80 | 5 | 16 |
| XY Leo | 6,818 | 9,70 | 1 | 15 |
| EP And | 9,698 | 11,40 | 3 | 12 |
| U Gem | 4,170 | 8,00 | 6 | 11 |
| EX Dra | 5,030 | 13-15 | 9 | 28 |
| HU Aqr | 2,083 | 15-18 | 18 | 1 |
| DQ Her | 4,650 | 14-16 | 7 | 13 |
| DP Leo | 1,497 | 17,50 | 5 | |
| NN Ser | 3,122 | 16,60 | 3 | |
| | | Total | 165 | 313 |

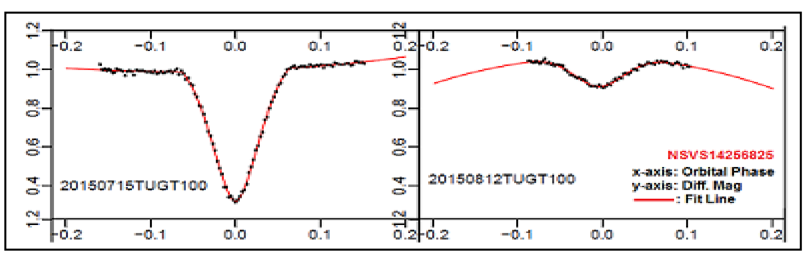
# Sources, Observatories, Observational Data

**TUG-T100** **SI 1100 CCD**




Binning – 2 and sub-windowing




Binning-2 of full frame

Data reduction

Python, IRAF, *Sextractor*

# Derivation of the Minimum Times

Fitting with truncated inverted **Gaussian** $G(t)$ multiplied by **a polynomial** $P(\tau)$

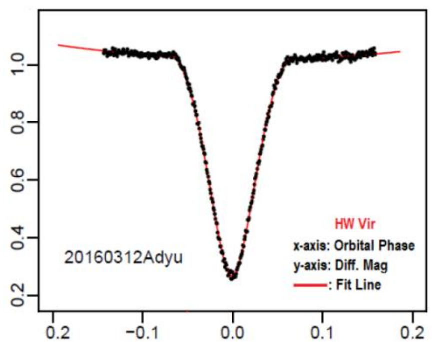
$\tau = t - p_1$ ve $p_i$, i=1...8 fit parameters

$$F(t) = P(\tau)\min(1, G(\tau))$$

$$G(\tau) = p_2 - p_3 \exp\left[-\frac{1}{2}\left(\frac{|\tau|}{p_4}\right)^{p_5}\right]$$

$$P(\tau) = p_6 + p_7\,\tau + p_8\,\tau^2$$

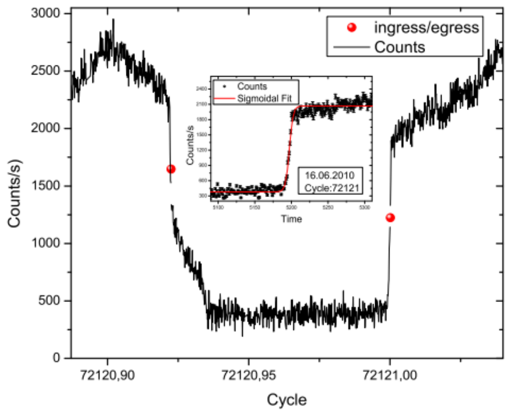
(Beuerman et al., 2012)




Fitting with **sigmoidal** function

$a_1$, initial value, $a_2$ final value, $\Delta t$ time constant
$t_0$ center (middle of the Egress)

$$I(t) = a_1 + \frac{(a_2 - a_1)}{(1.0 + \exp([t_0 - t]/\Delta t))}$$



# Expressing the LTT signal

The model for the presence of planetary companions is given by equations

**The LTT signal for circumbinary companions,**

$$\tau(t) = -\frac{\zeta_i}{c},$$

where $c$ is the speed of light and $\zeta_i$ is given as

$$\zeta_i(t) = K_i \left[ \sin\omega_i \left(\cos E_i(t) - e_i\right) + \cos\omega_i \sqrt{1 - e_i^2} \sin E_i(t) \right]$$

**The semi-amplitude of the LTT signals,**

$$K_1 = \left(\frac{1}{c}\right) \frac{m_1}{m_1 + m_*} a_1 \sin i_1$$

$$K_2 = \left(\frac{1}{c}\right) \frac{m_2}{m_1 + m_2 + m_*} a_2 \sin i_2$$

*i = 1, 2*; number of companions
*e*, orbital eccentricity
$w_i$, argument of pericentre of companion
$P_i$, orbital

$a_i$, semi major axis
$i_i$, inclination of the orbit relative to the sky plane
*m**, mass of the combined binary
$m_i$, companions

**(Gozdziewski et al. 2012)**.

# Results

## Post-common envelope binary NSVS14256825

- Orbital Period : 2.65 hrs
- cyclic behaviour of the (O-C)
  - one or two Jovian-type planets

(Beuermann et al. 2012, Almeida et al. 2013)

- 2-planet system unstable (Wittenmyer et al. (2013)
- Time span of data is not long enough (Hinse et al. (2014)

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### Observatories

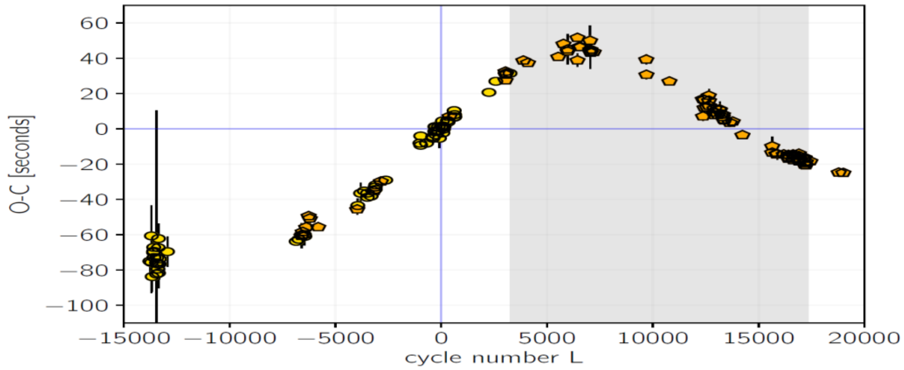
- TUG-T100, ADYU60 (Turkey)
- Skinakas-130 (Crete),
- Suhora-60, Krakow-60 (Poland)

- 87 new min times
- extended the time span of previous (O-C) by 3 yrs.
- The (O-C) diagram shows quasi-periodic variations
- a brown-dwarf (15 Jup), period ~ 10 years (*e ~ 0.175)*

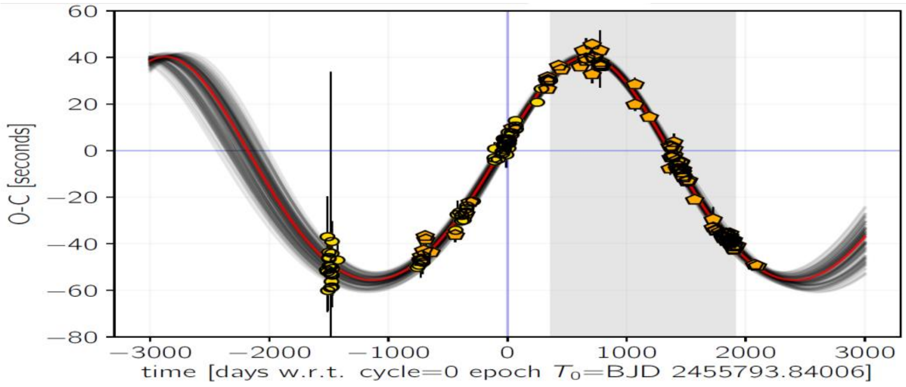
**(Nasiroglu , Gozdziewski & Slowikowska et al 2017)**

- New data fit the earlier third body (April-May 2017)

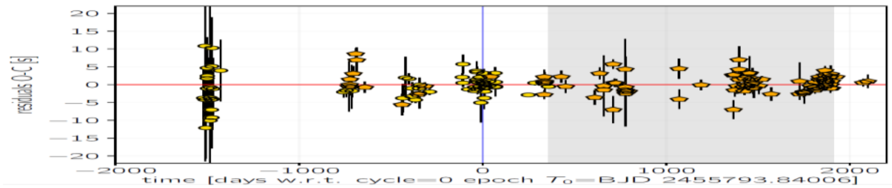
shaded region represent the new data




(O–C) diagram w.r.t. the linear ephemeris for all data




The synthetic curve of the best-fitting model (**red curve**) to all data




Residuals to the best-fitting model

# Preliminary Results

**HU Aqr (Magnetic CV, Polar)**

• Orbital Period : 125 min.

• Studied since 1993.  more than 200 min. times collected

• First quasi- periodic  variation of the (O-C)

(Schwope et al. 2001)

• one or two Jovian-type planets

(Schwartz et al 2009,  Qian et al 2011, **Gozdziewski et al 2012, 2015**)

• 2-planet system unstable (Wittenmyer et al. (2012).

**2011-2014**

• examples of 3-planets configuration

• middle planet in retrograde orbit

**(Gozdziewski et al 2015)**

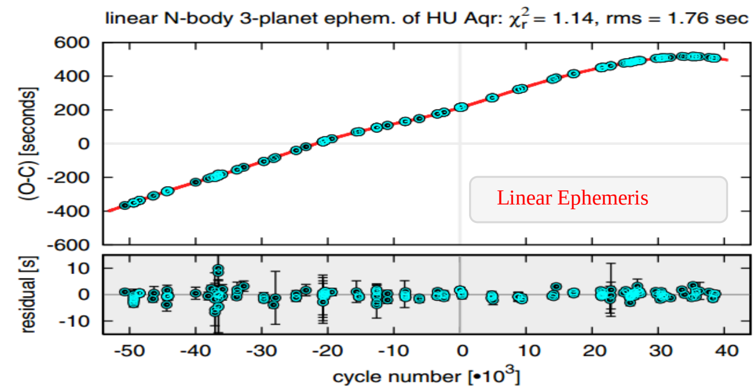
**2015-2016**

• TUGT100, ADYU60    (12 new minimum times)

• Significant mid-egress decay in the O-C diagram

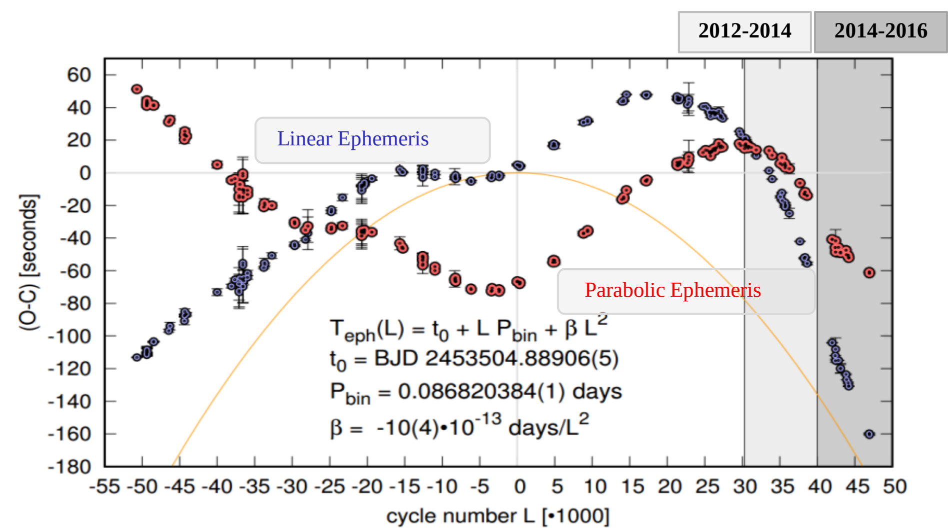
• other effects  may produce such decay

**•Need more observation to understand this kind O-C deviations**




2011-2014 .... Example of 3-planet  **Gozdziewski  et al. 2015**.

Darker  shaded  region is for the new data




**2015**....  the mid-egrees decay reached 180 s for the linear ephemeris, and more than 90 s for the parabolic ephemeris.

# Preliminary Results

**V470 Cam (PCEB)**

•Hot subdwarf with period of 2.3 hrs

(Drechsel et al. 2001)

•Studied since 2001

•cyclic behaviour of the (O-C)

•Brown dwarf orbiting the system

(Qian et al. 2009, Çamurdan et al. 2012, Beuermann et al. 2012)

•Possible third and fourth body

(Pulley et al. 2015)

**Observations (2014-2017)**

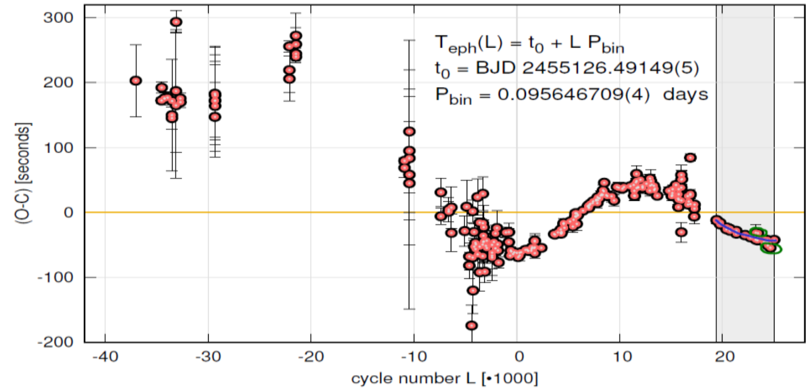
• TUG-T100, ADYU60 (Turkey)

• last 3 yrs, collected 57 new minimum

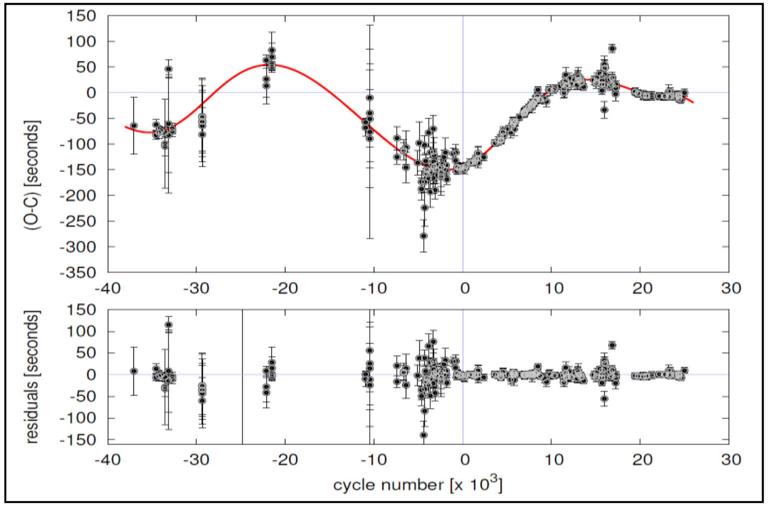
• two planet model

• need more observation to see effect of non-circumbinary mechanism.

shaded region represent the new data




(O–C) diagram w.r.t. the linear ephemeris for all data




The best-fitting model (**red curve**) to all data,
and Residuals (Bottom panel)

# Conclusion

- A few compact eclipsing binaries exhibit similar, quasi-periodic variations of the (O-C) attributed to low-mass companions,
- The GAIA mission has a great potential to confirm or dismiss the presence of such bodies.

Thanks to team of TUG for a partial support in using Telescopes (Project No: TUGT100-631), ADYU60 Observatory, and others.

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**Publication from the project**

Nasiroglu et al. 2017. **AJ**, 153, 137 (NSVS14256825)
Gozdziewski et al. 2015. **MNRAS**, 448, 1118 (HU Aqr)
Gozdziewski et al. 2012. **MNRAS**, 425, 930 (HU Aqr)

**References**

Almeida et al. 2013, ApJ, 766, 11
Applegate, J. H. 1992, ApJ, 385, 621
Beuermann et al. 2012, A&A, 540, A8
Beuermann et al. 2011, A&A, 526, A53
Camurdan et al., 2012, New Ast.17, 325
Drechsel et al., 2001, A&A 379, 893
Doyle, et al. 2011, Sci, 333, 1602
Goździewski et al. 2012, MNRAS, 425, 930
Goździewski et al. 2015, MNRAS,448, 1118
Hinse 2014, MNRAS, 438, 307
Horner et al 2012, MNRAS, 427, 2812
Horner et al. 2013, MNRAS, 435, 2033
Irwin, J. B. 1952, ApJ, 116, 211
Lee et al. 2009, AJ, 137, 3181
Potter et al. 2011, MNRAS, 416, 2202
Pribulla et al. 2012, AN, 333, 754
Pulley et al. BAA Journal 2015
Qian et al. 2009, AJ, 695 163
Qian et al. 2011, MNRAS, 414, L16
Ribas, I. 2005, in ASP Conf. Ser. 335, 55
Schwarz et al 2009, A&A, 496, 833
Schwope et al 2001, A&A, 375, 419
Wittenmyer et al. 2012, MNRAS, 419, 3258
Wittenmyer et al. 2013, MNRAS, 431,2150