An overview of the circumbinary population with *Kepler* & *TESS*

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Credits

Thanks to:

- Donald Short, William F. Welsh, Erika Dunning (SDSU)
- Veselin Kostov (SETI Institute, NASA Goddard)
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- John Hood, Jr. ($$$)

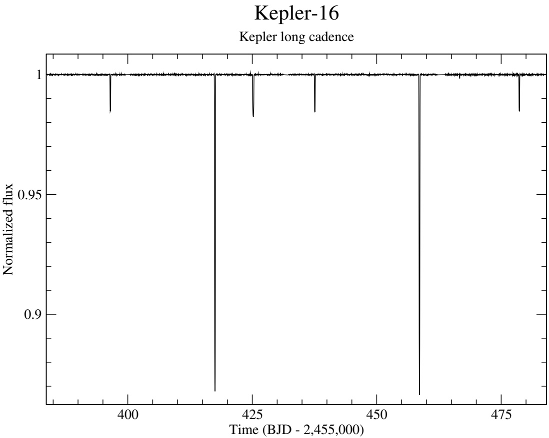
Overview

1. The Introduction: Three Ways to Find CBPs
2. The *Kepler* sample
3. The *TESS* sample
   - *TESS* observations of known *Kepler* targets
   - Confirmed and candidate *TESS* CBPs
4. Summary

Three ways to find CBPs

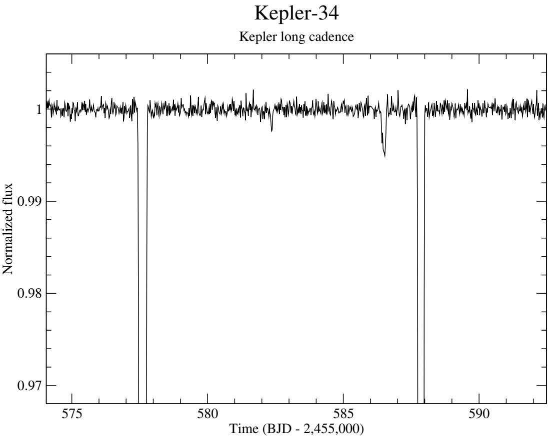
- We have three main ways to find circumbinary planet (CBP) candidates:
    1. Find eclipsing binaries (EBs) in the data, look at plots of the light curves for transits.

Looking for transits



- Kepler-16 was the first transiting CBP found by *Kepler*.

Looking for transits



- Kepler-34 was the second transiting CBP found by *Kepler*.

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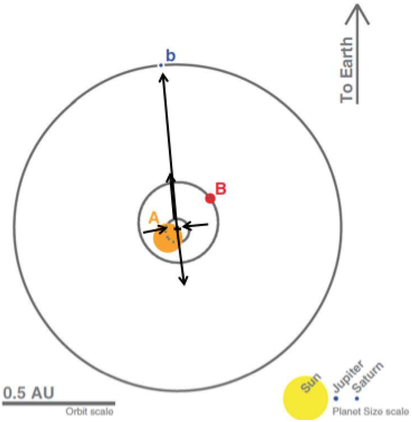
  2. Find EBs in the data, measure eclipse times, look for distinct eclipse timing variations (ETVs).

Using eclipse timing variations

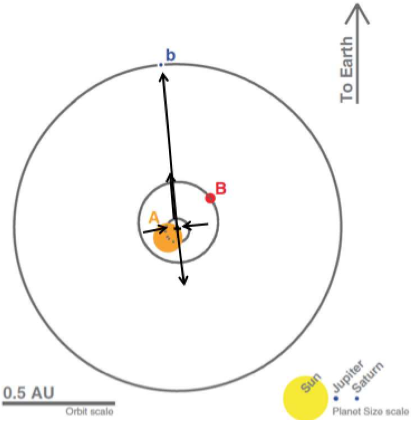
Image credit D. Fabrycky



- The big arrow is how the planet pulls on the COM of the binary; the small arrows are the tidal force the planet puts on the stars.

Using eclipse timing variations

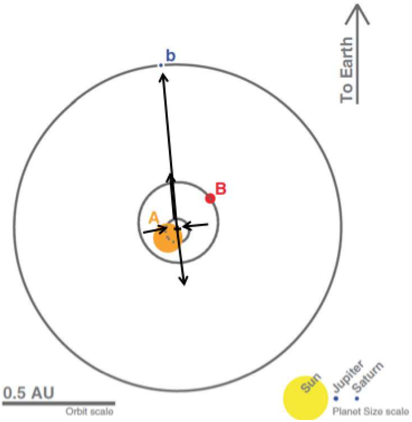
Image credit D. Fabrycky



- The $m = 2$ tidal pattern rotates at the planet's orbital period, and every half an orbit the stars have to climb up and down the tidal potential.

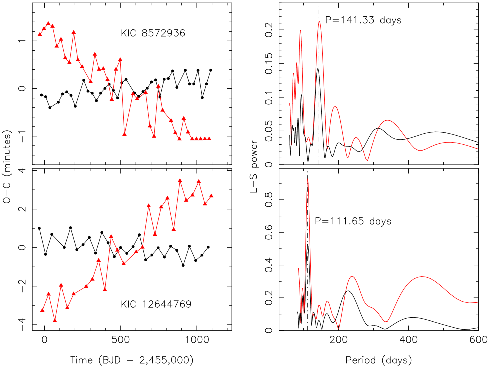
Using eclipse timing variations

Image credit D. Fabrycky



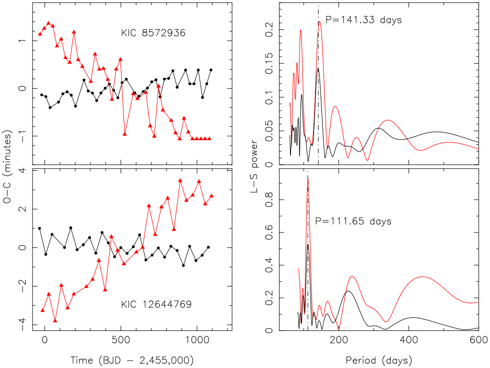
- Their phases are successively delayed and advanced every period of the planet, so the observed effect is twice the planet's frequency.

Using eclipse timing variations



- Common-Period Observed minus Computed (CPOC) diagrams for Kepler-34 (top left) and Kepler-16 (bottom left) show diverging signals for the primary (black) and secondary eclipses (red) caused by forced precession of the binary by the planet.

Using eclipse timing variations



- We also see the "chopping" in each signal with a periods ≈ 1/2 of the known planet periods.

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Three ways to find CBPs

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  1. Find eclipsing binaries (EBs) in the data, look at plots of the light curves for transits.
  2. Find EBs in the data, measure eclipse times, look for distinct eclipse timing variations (ETVs).
  3. Use very precise radial velocity measurements to find deviations from Keplerian orbits.

Using radial velocities

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Article | Published: 12 June 2023

Radial-velocity discovery of a second planet in the TOI-1338/BEBOP-1 circumbinary system

Matthew R. Standing ✉, Lalitha Sairam, David V. Martin, Amaury H. M. J. Triaud, Alexandre C. M. Correia, Gavin A. L. Coleman, Thomas A. Baycroft, Vedad Kunovac, Isabelle Boisse, Andrew Collier Cameron, Georgina Dransfield, João P. Faria, Michaël Gillon, Nathan C. Hara, Coel Hellier, Jonathan Howard, Ellie Lane, Rosemary Mardling, Pierre F. L. Maxted, Nicola J. Miller, Richard P. Nelson, Jerome A. Orosz, Franscesco Pepe, Alexandre Santerne, Daniel Sebastian, Stéphane Udry & William F. Welsh — Show fewer authors

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- The second planet in the TOI-1331 system was the first CBP to be discovered using radial velocities.
- Kepler-16 (Triaud et al. 2022) and TIC 172900988 (Sairam et al. 2023) have also been detected using radial velocities.

The *Kepler* sample

- The *Kepler* mission has found 13 transiting CBPs in 11 binary systems:
    - Kepler-16 (Doyle et al. 2011)
    - Kepler-34, Kepler-35 (Welsh et al. 2012)
    - Kepler-38 (Orosz et al. 2012a)
    - Kepler-47 (three planets, Orosz et al. 2012b; Orosz et al. 2019)
    - Kepler-64 (Schwamb et al. 2013)
    - Kepler-413 (Kostov et al. 2014)
    - Kepler-453 (Welsh et al. 2015)
    - Kepler-1647 (Kostov et al. 2016)
    - KIC 10753734 (Orosz et al. 2016 [conference poster])
    - Kepler-1661 (Socia et al. 2020)

The *Kepler* sample

- The *Kepler* mission has found 4 nontransiting CBPs in 4 binary systems:
  - Kepler-1660 (Borkovits et al. 2016; Getley et al. 2017; Goldberg et al. 2023)
  - KIC 7821010 (Borkovits et al. 2016; Welsh et al. 2012)
  - KIC 8610283 (Welsh et al. 2012, 2013)
  - KIC 3938073 (Welsh et al. 2012, 2013)

The *Kepler* sample

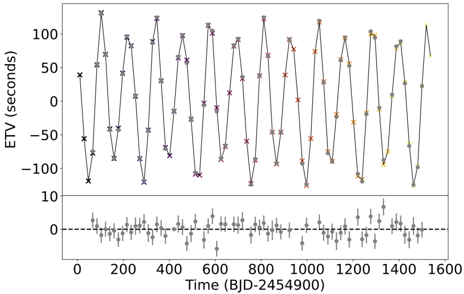


Figure 3. The Observed–Calculated primary eclipse times. Eclipse mid-times from the *N*-body model are the coloured crosses, times from the light-curve fit are the grey circles.

- The O-C diagram for the primary eclipses in Kepler-1660 (there are no secondary eclipses owing to the eccentric orbit, Goldberg et al. 2023).

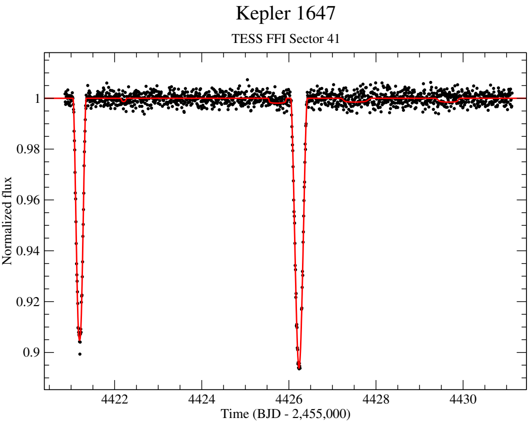
TESS Observations of the *Kepler* sample

- *TESS* has visited the *Kepler* field 5 times so far (Year 2, twice in Year 4, and twice in Year 6).
- The number of sectors available for a given target depends a bit on the exact location within the field.
- Two activities come to mind regarding new light curves for known *Kepler* targets:
  - Look for additional transit events.
  - Collect additional eclipse time measurements.

TESS Observations of the *Kepler* sample

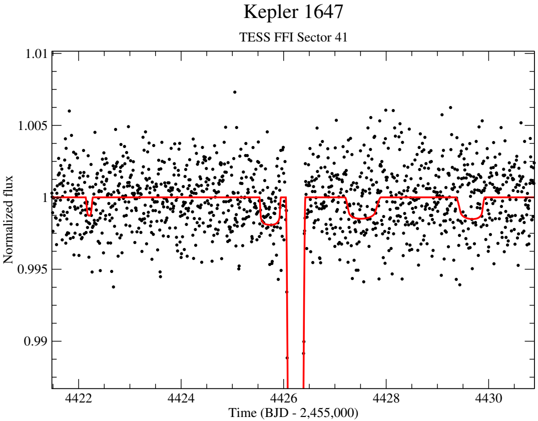
- Regarding looking for transits in the *TESS* data, the S/N of the *TESS* light curves is not as good as *Kepler*.

TESS Observations of the *Kepler* sample



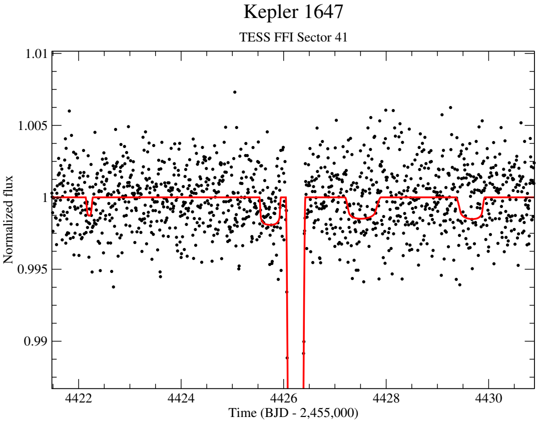
- This is Sector 41 data (10 minute cadence) of Kepler-1647. Four transits were predicted to occur...

TESS Observations of the *Kepler* sample



- This is Sector 41 data (10 minute cadence) of Kepler. Four transits were predicted to occur...none are evident.

TESS Observations of the *Kepler* sample

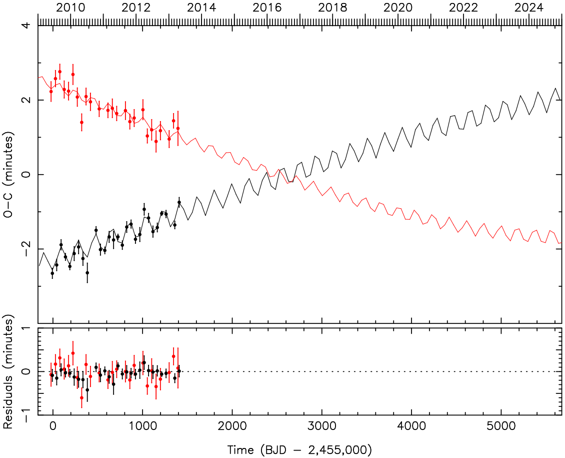


- Kepler-1647 and Kepler-47 the only known Kepler CBP systems that had expected transits in the observed *TESS* sectors.

TESS Observations of the *Kepler* sample

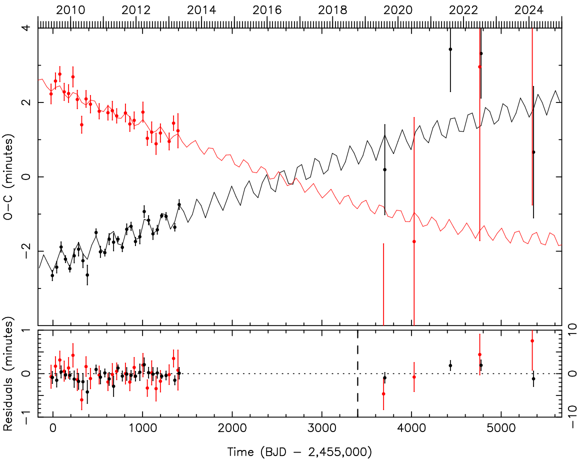
- Regarding measuring eclipse times in the *TESS* data, the S/N of the *TESS* light curves is not as good as *Kepler*.

TESS Observations of the *Kepler* sample



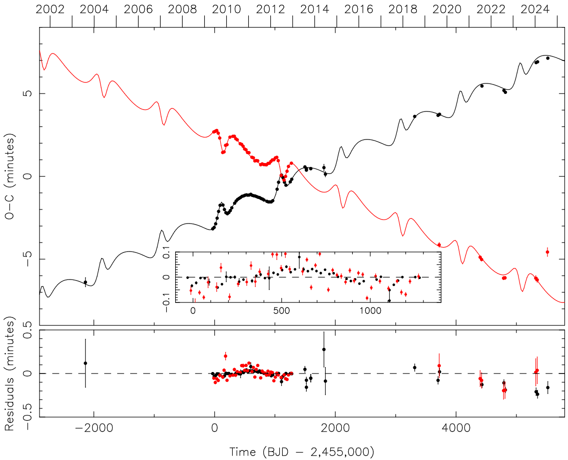
- Here is the Common Period O-C diagram for KIC 8610483 using the *Kepler* eclipse times.

TESS Observations of the *Kepler* sample



- Here is the Common Period O-C diagram for KIC 8610483 using the *Kepler* eclipse times and *TESS* eclipse times.

TESS Observations of the *Kepler* sample



- Here is the Common Period O-C diagram for KIC 7821010 using the *Kepler* eclipse times and *TESS* eclipse times.

TESS Observations of the *Kepler* sample

- Regarding measuring eclipse times in the *TESS* data, the S/N of the *TESS* light curves is not as good as *Kepler* (the S/N is around 10 to 15 times worse).

Confirmed *TESS* CBPs

- Confirmed CBPs found in the *TESS* data:

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  - TOI-1338 (Kostov et al. 2020; Orosz et al. 2024; Wang & Liu 2023).

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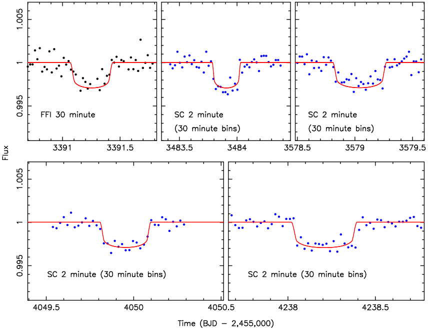
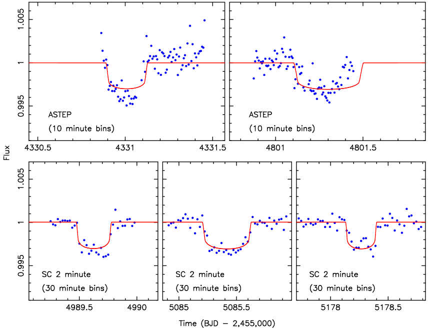
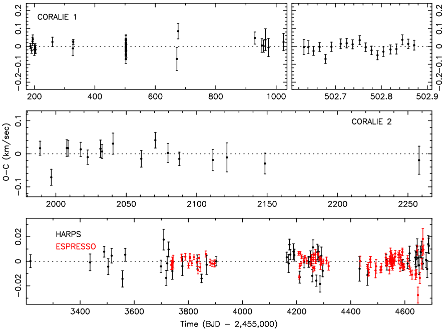
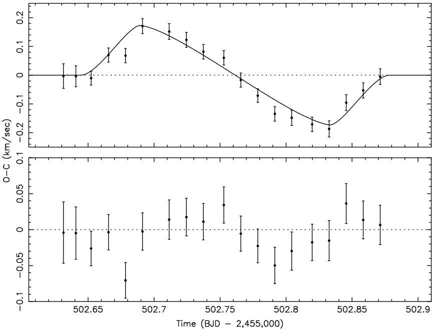




- We have 8 transits observed by *TESS* and two transits observed by ASTEP.

Confirmed *TESS* CBPs





- We have a growing number of high precision RV measurements from Espresso.
  - *Left*: The residuals of the RV measurements from CORALIE, HARPS, and Espresso.
  - *Right*: A close-up of the fit to the Rossiter effect observed with CORALIE.

Confirmed *TESS* CBPs

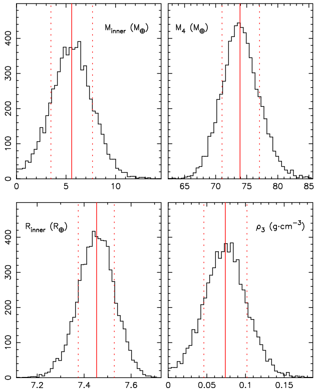


Table 1: Masses and Radii for TOI-1338

	primary	secondary	inner planet	outer planet
mass ($M_\odot$ or $M_\oplus$)	1.099 ± 0.007	0.308 ± 0.001	5.6 ± 2.1	73.9 ± 3.1
radius ($R_\odot$ or $R_\oplus$)	1.314 ± 0.003	0.3084 ± 0.0007	7.45 ± 0.08	...
density (g cm^{-3})	0.683 ± 0.003	14.80 ± 0.07	0.07 ± 0.03	...

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  - KIC 172900988 (Kostov et al. 2021; Sairam et al. 2024).

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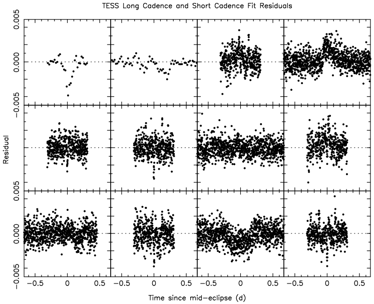

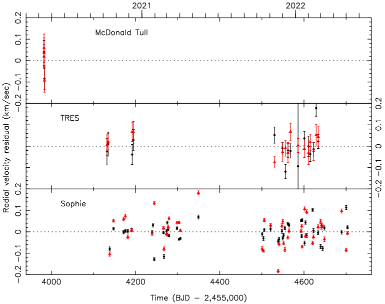

- We have 4 more sectors of *TESS* short cadence data, as well as more TRES spectra and Sophie spectra.
- $P_3 = 165.18 \pm 0.18$ d, $M_3 = 560.3 \pm 3.4\, M_\oplus$, $R_3 = 11.57 \pm 0.17\, R_\oplus$, $\rho_3 = 1.990 \pm 0.093$ g/cc.

New candidate *TESS* CBPs

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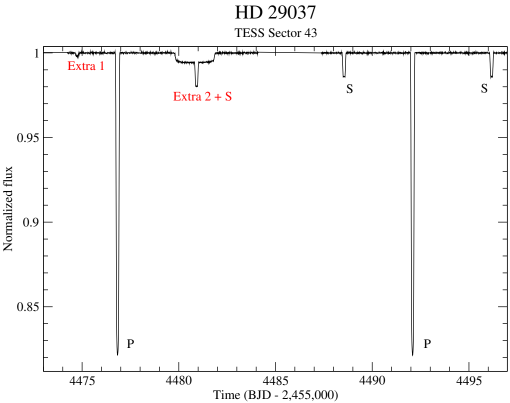
- New candidate CBPs found in the *TESS* data:
  - TIC 408342294 (HD 29037)
    - $\alpha = 04\ 35\ 35.4484905696$, $\delta = +32\ 34\ 47.241496488$, $\varpi = 11.8356 \pm 0.0308$ mas ($d = 84.5$ pc), $V = 8.46$.
    - TESS observed HD 29037 in Sectors 19 (30 minute cadence), 43, 44, 59 (10 minute cadence), 70, 71, 86 (200 second cadence).
    - We have spectroscopy from Sophie, TRES, and two citizen scientists with their own spectrographs.

New candidate *TESS* CBPs



- The binary period is 7.63 days, and the secondary eclipse is weak and total. The binary eccentricity is $e = 0.067$.
- There were 5 extra transit events seen.

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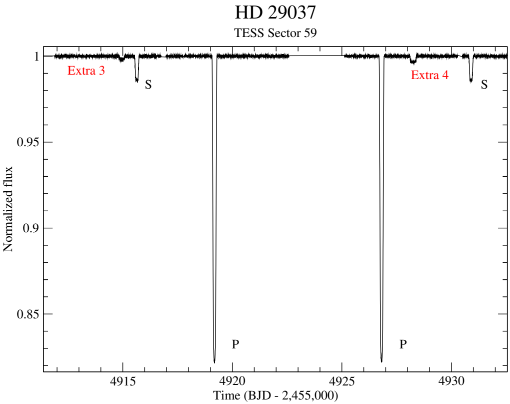

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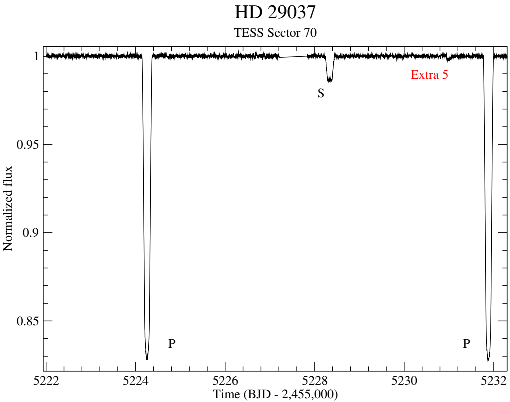

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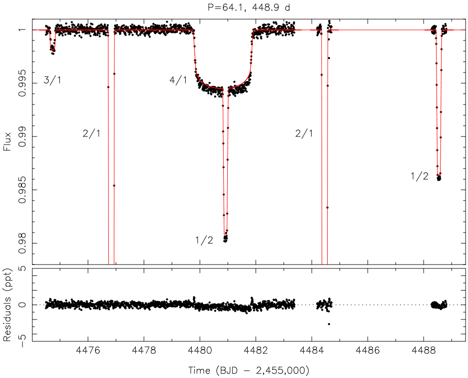

- Three of the extra events can be tied to one planet with a period ≈ 64 days. The other two events can be tied to a planet with a period of ≈ 450 d, ≈ 225 d, or ≈ 150 d, depending if 0, 1, or 2 transits were missed.

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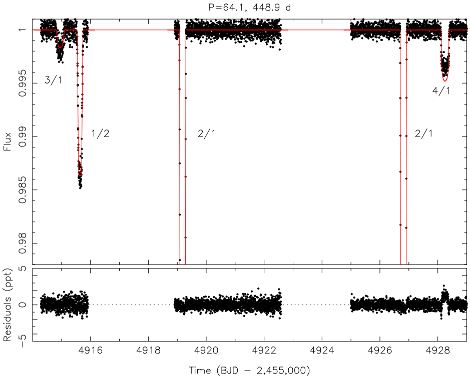

- Three of the extra events can be tied to one planet with a period $\approx$ 64 days. The other two events can be tied to a planet with a period of $\approx$ 450 d, $\approx$ 225 d, or $\approx$ 150 d, depending if 0, 1, or 2 transits were missed.

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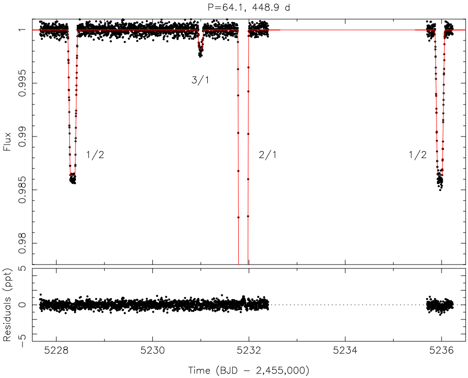

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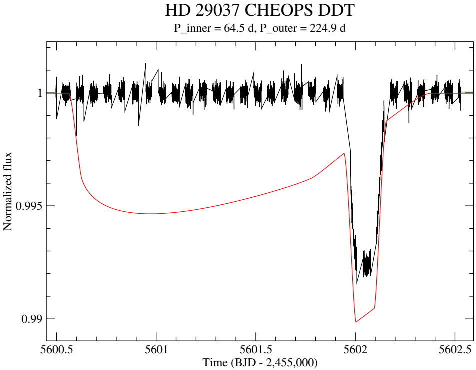
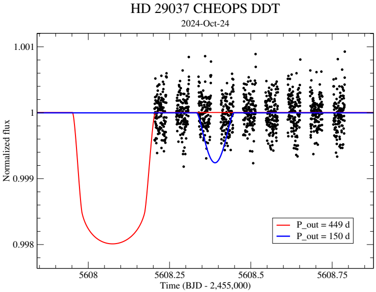
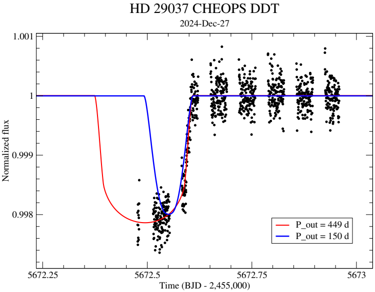


- There were 5 visits using a CHEOPS DDT. The outer period near 225 days is firmly ruled out (the ≈ 2 day transit that was predicted near 2024-Oct-17 did not occur).

New candidate *TESS* CBPs





- The model with an outer period near 450 days seems to be preferred.

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New candidate *TESS* CBPs

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  - TIC 408342294 (HD 29037)
    - $P_{\rm bin} = 7.6267$ d, $e = 0.0669$, $\omega = 325.7^\circ$
    - $P_{\rm inner} = 64.09$ d, $e = 0.0115$, $\omega = 13.4^\circ$
    - $P_{\rm outer} = 448.9$ d, $e = 0.2082$, $\omega = 161.9^\circ$
    - $I_{\rm inner} = 0.75^\circ$, $I_{\rm outer} = 15.9^\circ$
    - $a_{\rm inner} = 0.387$ AU, $a_{\rm outer} = 1.415$ AU

    - $M_1 = 1.33\,M_\odot$, $R_1 = 1.31\,R_\odot$
    - $M_2 = 0.54\,M_\odot$, $R_2 = 0.51\,R_\odot$
    - $40 \lesssim M_{\rm inner} \lesssim 70\,M_\oplus$, $6.45 \lesssim R_{\rm inner} \lesssim 6.60\,R_\oplus$
    - $0 \lesssim M_{\rm outer} \lesssim 30\,M_\oplus$, $9.85 \lesssim R_{\rm outer} \lesssim 9.95\,R_\oplus$
    - $0.6 \lesssim \rho_{\rm inner} \lesssim 1.4$ g/cc
    - $0.0 \lesssim \rho_{\rm inner} \lesssim 0.15$ g/cc

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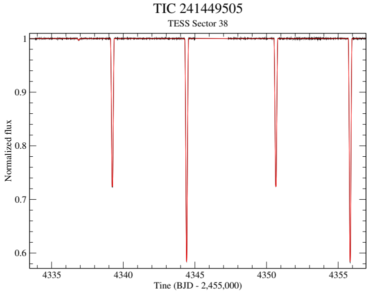
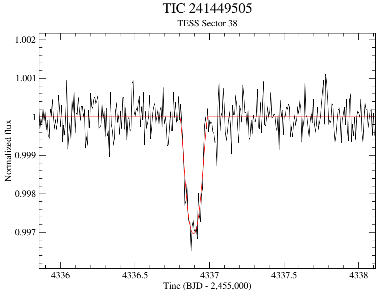
  - TIC 408342294 (HD 29037)
  - TIC 241449505 (part of Erika Dunning's thesis work)

New candidate *TESS* CBPs

- New candidate CBPs found in the *TESS* data:
  - TIC 241449505
    - Observed by TESS in Sectors 11, 38, 64, and 65
    - $P_{\rm bin} = 11.41$ d, $e = 0.072$
    - $\alpha = 13\ 42\ 32.5376287176$, $\delta = -49\ 25\ 45.591557988$, $V = 10.4$
    - $\varpi = 6.0027 \pm 0.0178$ mas ($d = 166.6$ pc)
    - It is in the *Gaia* catalog of double-lined systems

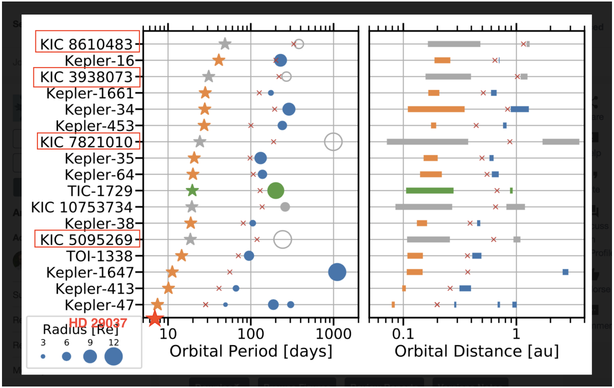
New candidate *TESS* CBPs





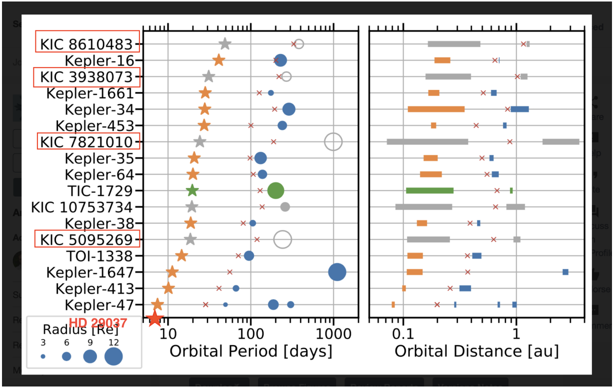
- There is a transit-like event in Sector 38 that is on-target.
- No ETVs are seen down to a few seconds. The model is for a planet mass of 100 d and a planet mass of 100 $M_\oplus$.
- $M_1 = 1.02\,M_\odot$, $R_1 = 1.09\,R_\odot$
- $M_2 = 0.94\,M_\odot$, $R_2 = 0.82\,R_\odot$

Summary



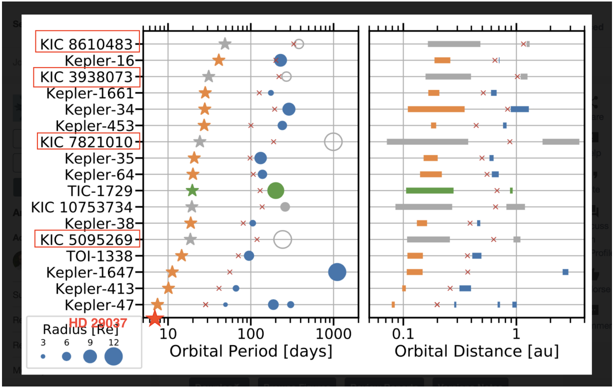
- We have 17 EBs with CBPs (13 systems where the CBP transits) with a total of 21 planets (e.g. 4 additional planets in 3 multi-planet systems). Graph from Kostov (2023).

Summary



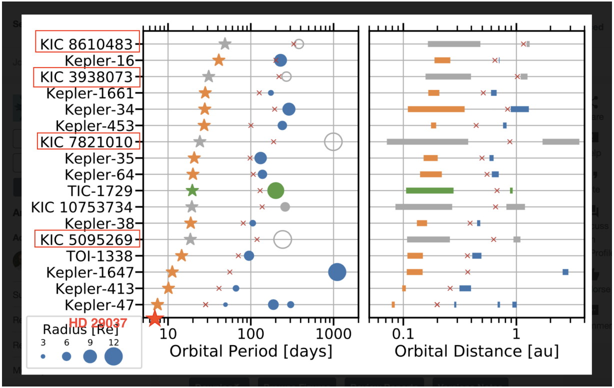
- The two longest planet periods are Kepler-1647 (1108 d) and KIC 7821010 (997 d).

Summary



- The two largest masses are KIC 7821010 ($804 \pm 3\, M_\oplus$) and TIC 172900988 ($M_3 = 560.3 \pm 3.4\, M_\oplus$).

Summary



- The two smallest masses are the outer planet in Kepler-47 ($2-5\,M_\oplus$) and the inner planet in TOI-1338 ($M = 5.6 \pm 2.1\,M_\oplus$).

Summary

- The density of the inner planet of KOI-1338 is $\rho = 0.07 \pm 0.03$ g/cc.
- Apart from TIC 172900988 (where $\rho = 1.990 \pm 0.093$ g/cc), the densities of the CBPs seem to generally be small.
- Some recent results for low-density planets in single-star systems:
  - TOI-1420b has $M = 25.1 \pm 3.8\, M_{\oplus}$, $R = 11.9 \pm 0.3\, R_{\oplus}$, and $\rho = 0.08 \pm 0.02$ g/cc (Yoshida et al. 2023).
  - HIP 67522b has $M = 13.8 \pm 1.0\, M_{\oplus}$, $R = 9.76 \pm 0.50\, R_{\oplus}$, and $\rho < 0.10$ g/cc (Thao et al. 2024).

Summary

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Multiple Transits during a Single Conjunction: Identifying Transiting Circumbinary Planetary Candidates from TESS

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Abstract

We present results of a study on identifying circumbinary planet candidates that produce multiple transits during one conjunction with eclipsing binary systems. The occurrence of these transits enables us to estimate the candidates' orbital periods, which is crucial as the periods of the currently known transiting circumbinary planets are significantly longer than the typical observational baseline of the Transiting Exoplanet Survey Satellite (TESS). Combined with the derived radii, it also provides valuable information needed for follow-up observations and subsequent confirmation of a large number of circumbinary planet candidates from TESS. Motivated by the discovery of the 1108 day circumbinary planet Kepler-1647, we show the application of this technique to four of Kepler's circumbinary planets that produce such transits. Our results indicate that in systems where the circumbinary planet is on a low-eccentricity orbit, the estimated planetary orbital period is within <10%–20% of the true value. This estimate is derived from photometric observations spanning less than 5% of the planet's period, demonstrating the strong capability of the technique. Capitalizing on the current and future eclipsing binaries monitored by NASA's TESS mission, we estimate that hundreds of circumbinary planet candidates producing multiple transits during one conjunction will be detected in the TESS data. Such a large sample will enable statistical understanding of the population of planets orbiting binary stars and shed new light on their formation and evolution.

Unified Astronomy Thesaurus concepts: Exoplanet detection methods (489); Exoplanets (498); Exoplanet astronomy (486)

- This estimate of the *TESS* CBP yield is perhaps 1 to 2 orders of magnitude too optimistic.

Summary

- The Kostov et al. (2020) estimate of the *TESS* CBP yield is perhaps 1 to 2 orders of magnitude too optimistic.
  - Sullivan et al. (2015) estimated *TESS* would find $\approx 476,000$ eclipsing binaries brighter than $K_s = 15$. The actual number is probably closer to 50,000.
  - The practical S/N of the *TESS* light curves is probably not as good as Kostov et al. (2020) assumed (the sensitivity to weak transits seems to be relatively poor).