Circumbinary Planets With Transit Missions

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Credits

Thanks to:

- Donald Short, William F. Welsh, Erika Dunning (SDSU)
- Veselin Kostov (SETI Institute, NASA Goddard)
- Nader Haghighipour (PSI)
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- NASA grant #22-XRP22_2-0190 (P.I. N. Haghighipour)
- John Hood, Jr. ($$$)

Overview

1. The Probabilities and Efficiencies
2. The Difficulties of the Transit Method for CBPs
3. The Advantages of the Transit Method for CBPs
4. The Characterization of the System
5. The Summary
6. A Brief Update, if Time is Left

The Probabilities

- For a transit to occur, the orbit needs to be roughly edge-on as seen from Earth.
- The probability of having a transit drops as the orbital period gets longer.
  - To be stable, the outer orbit needs to be $\gtrsim 4$ to 5 times longer than the inner orbit.
  - Consequently circumbinary planets will have longer periods than planets around single stars, thus the transits will be less likely and less frequent.
- Before Hot Jupiters were discovered, many early papers suggested searching for transits in eclipsing binaries, with the assumption that the planet orbits would be coplanar with with the binary and would hence be seen roughly edge-on (e.g. Schneider & Doyle 1995).

The Efficiencies

- If your goal is to simply find *planets* generally via the transit method, then you will find far more around single stars:
  - The *Kepler* mission found on the order of 2,600 confirmed planets around single stars via transits.
  - The *Kepler* mission found on the order of 10 confirmed circumbinary planets via transits.

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  - The *Kepler* mission found on the order of 2,600 confirmed planets around single stars via transits.
  - The *Kepler* mission found on the order of 10 confirmed circumbinary planets via transits.
- I will assume our goal here is to find circumbinary planets (CBPs) specifically via the transit method...

The Difficulties

- There are (at least) three types of difficulties in finding transiting CBPs:
  - "Dilution" of the transit by the light from another star.
  - Light curves that are not "flat" owing to star spots and other types of variability associated with close binaries.
  - Stellar eclipses can overwhelm the transit signal.

The Difficulties

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  - "Dilution" of the transit by the light from another star.
    - For a single star with flux F_a and radius R_A, being transited by a body with a radius R_T, the light lost and the fractional depth are

$$\begin{aligned} \Delta &= k^2 F_A \\ \delta_{\rm ss} &= \frac{\Delta}{F_A} = k^2 \end{aligned}$$

      where $k = R_T/R_A$

    - For a binary with stars A and B with fluxes F_a and F_B where the transiting body transits star A, the light lost and the fractional depth are

$$\begin{aligned} \Delta &= k^2 F_A \\ \delta_{\rm EB} &= \frac{\Delta}{F_A + F_B} < \delta_{\rm SS} \end{aligned}$$

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$$\begin{aligned} \Delta &= k^2 F_A \\ \delta_{\rm EB} &= \frac{\Delta}{F_A + F_B} < \delta_{\rm SS} \end{aligned}$$

    - When $F_A = F_B$ and $k = 0.1$, $\delta_{\rm SS} = 0.01$ and $\delta_{\rm EB} = 0.005$.
    - Thus it can be harder to detect smaller planets, depending on the flux ratio of the binary.

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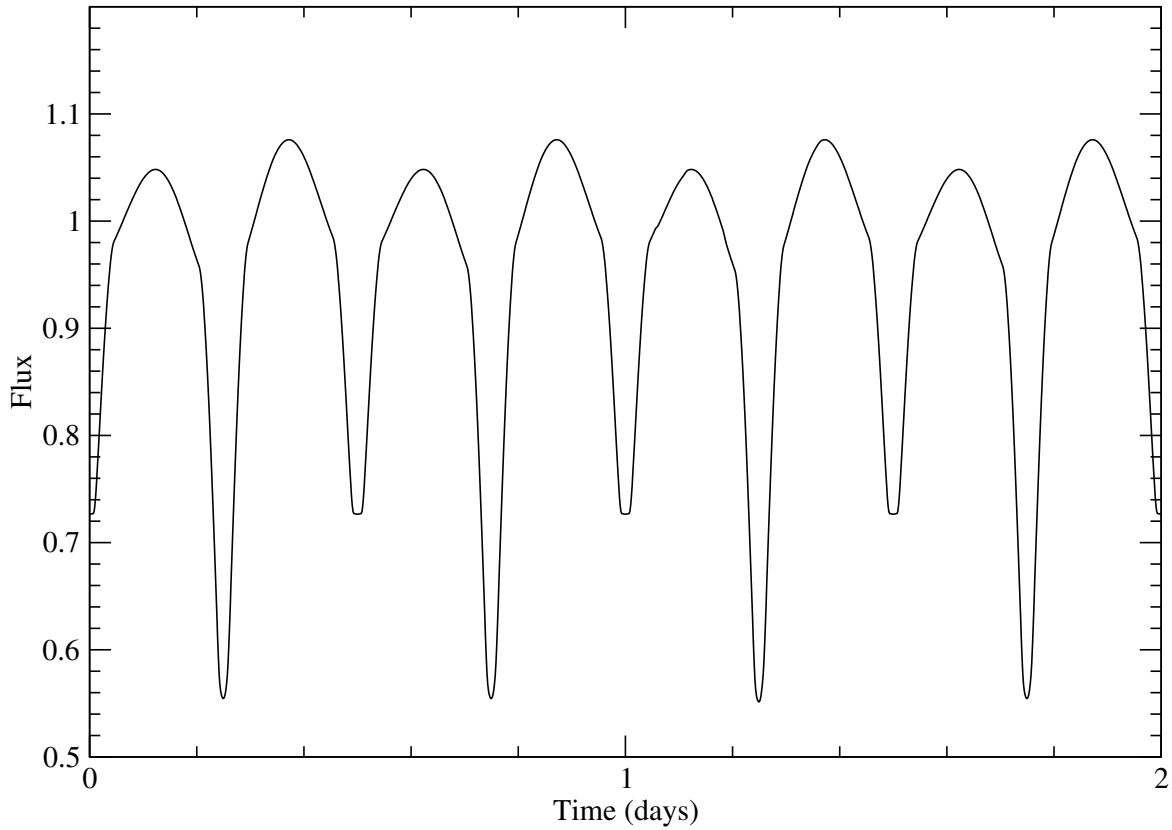
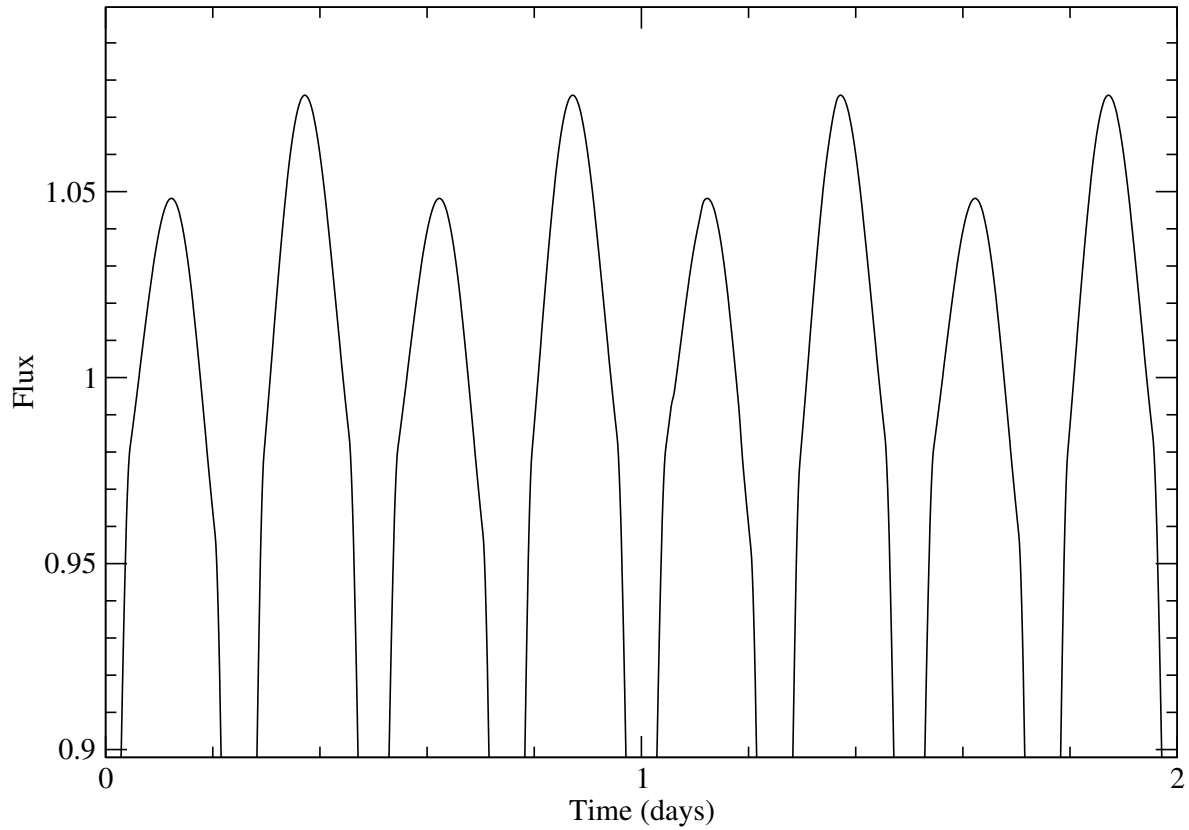
    - The stars will be rapidly rotating in close binaries (the timescale for tidal locking is usually short), therefore they tend to be more spotted.
    - In close binaries the stars are tidally distorted, giving rise to "ellipsoidal" variations.
    - Either star can heat the part of the other star facing it, thereby altering the local temperatures.
    - All of these effects can add substantial variation in the out-of-eclipse parts of the light curve, making it harder to spot comparatively weak transits.

The Difficulties



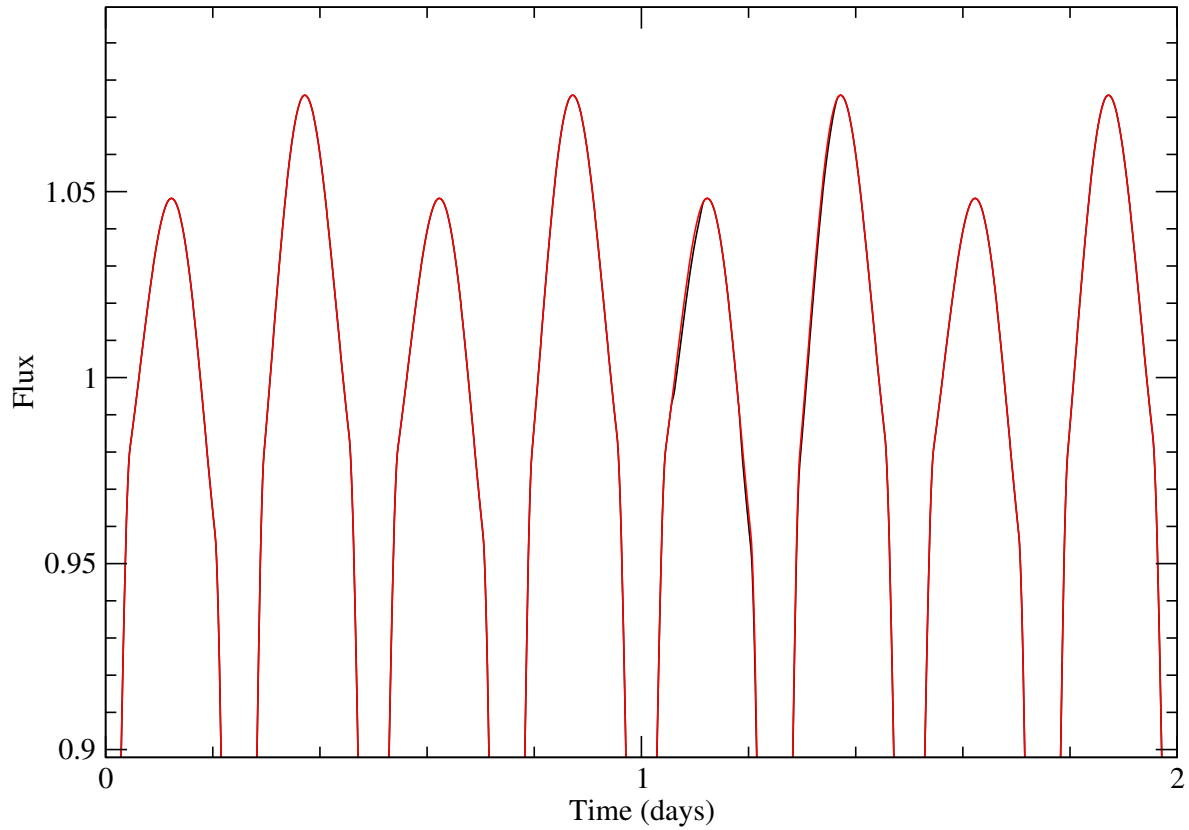
- Here is the light curve of a binary with $P_{\rm bin} = 0.5$ days, $M_1 = 1.0\,M_\odot$, and $M_2 = 0.7\,M_\odot$. There is a Saturn-sized planet with a period of 9.71 days and $i = 90°$.

The Difficulties



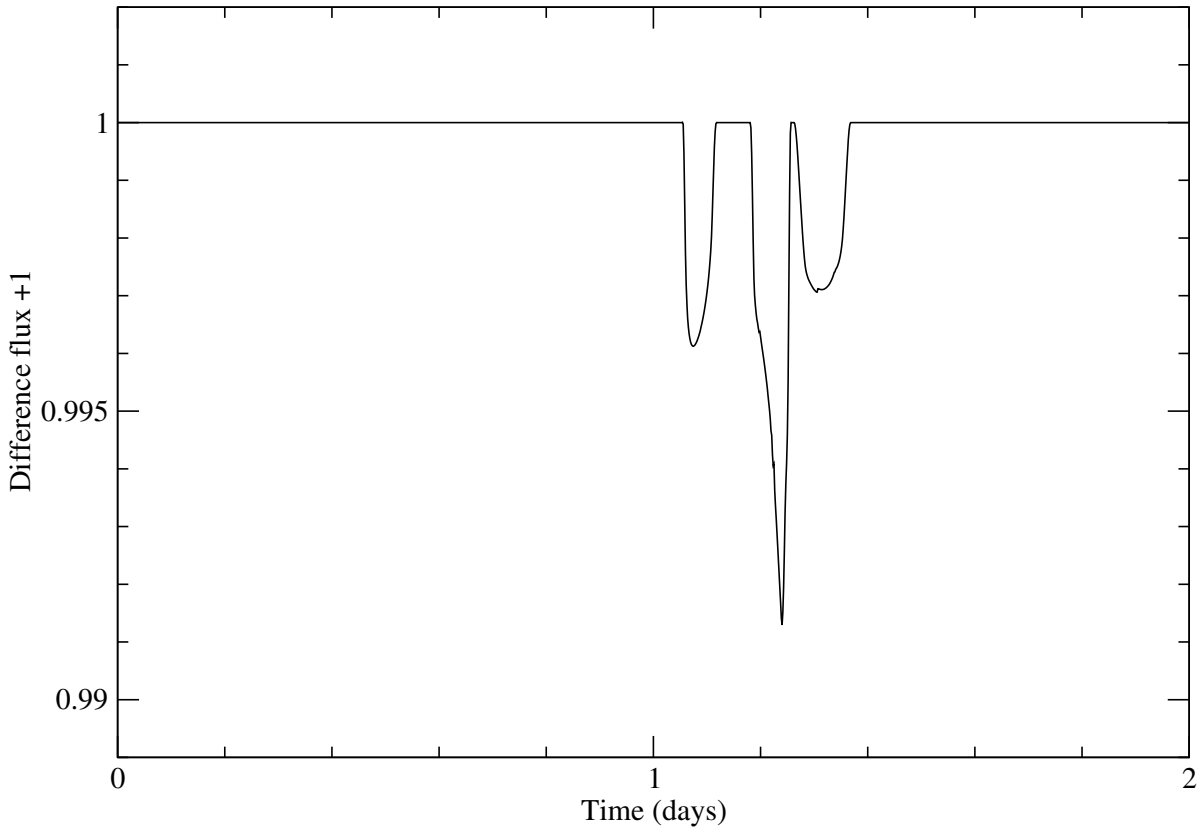
- Let's zoom in on the y-axis.

The Difficulties



- Let's overplot the light curve of the binary with no planet in red.

The Difficulties



- Let's plot the difference curve +1.

The Difficulties

- There are (at least) three types of difficulties in finding transiting CBPs:
  - Light curves that are not "flat" owing to star spots and other types of variability associated with close binaries.
    - The median orbital period in the Villanova EB catalog from the *Kepler* light curves is around 2.5 days, so you will be throwing away at least half of your sample in order to get EBs with relatively "flat" light curves out-of-eclipse (e.g. the EBs with longer periods).

The Difficulties

- There are (at least) three types of difficulties in finding transiting CBPs:
  - Light curves that are not "flat" owing to star spots and other types of variability associated with close binaries.
    - For the shorter-period EBs that have transiting planets, we don't know what the light curve of an otherwise similar binary but with no planet looks like.
    - Spots are time-variable, so phase-folding long stretches of the light curve to get the planet-free light curve does not work well enough.
    - Margo Thorton for her SDSU Master's thesis examined a sample of 73 EBs with *Kepler* short cadence data and attempted to use "local templates" to construct difference curves, and no convincing candidates were found.

The Advantages

- There are (at least) two advantages of the transit method for finding CBPs:
  - If three or more transits are found, the light curve can be self-validating.
  - For certain situations, it is possible to have a validated candidate in a light curve with a comparatively short time span.

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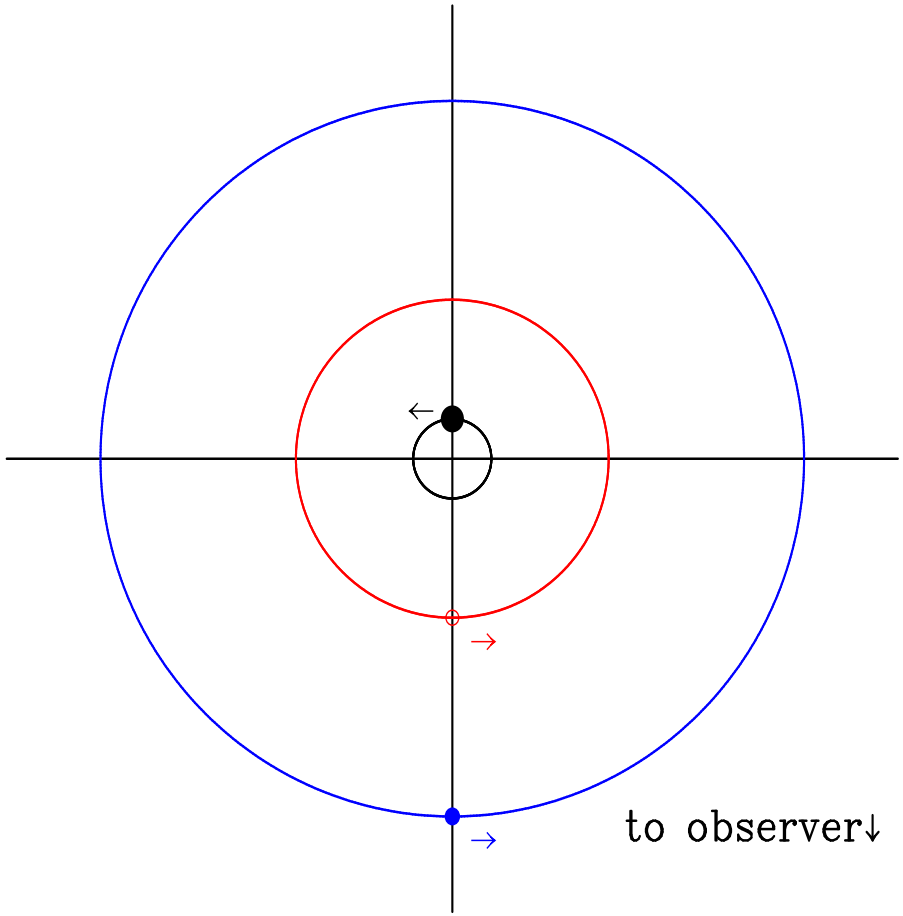
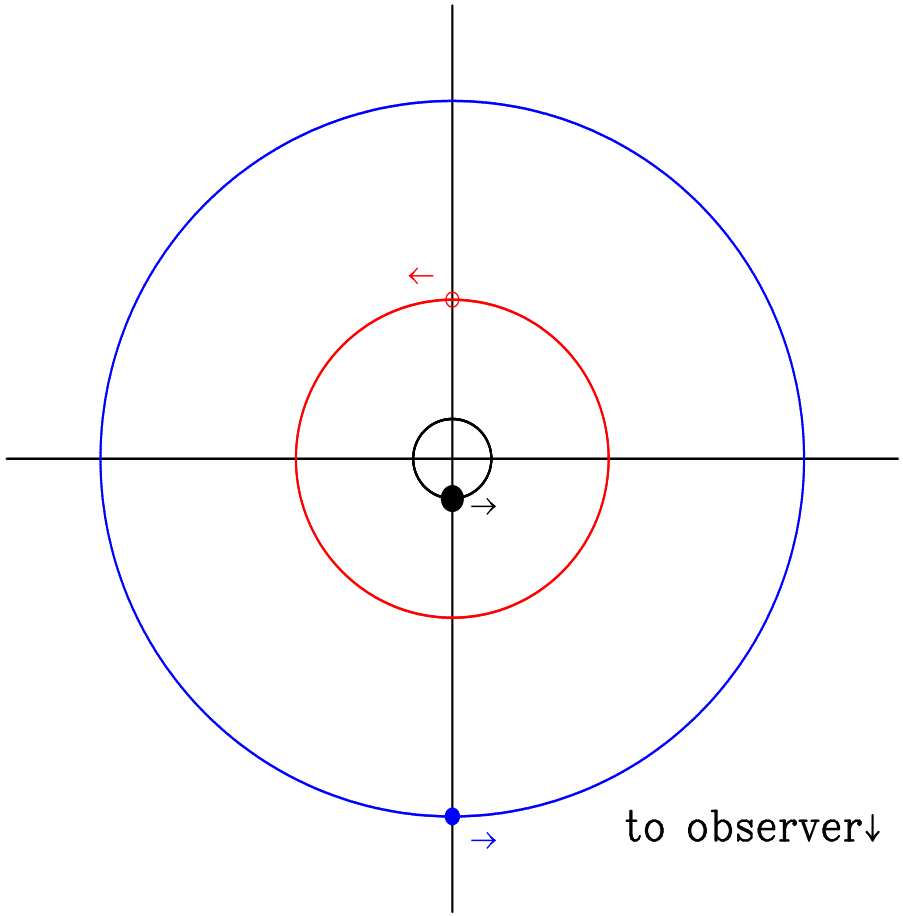
    - On the other hand, either star won't necessarily be crossing the system barycenter during a transit, leading to substantial eclipse timing variations (ETVs).

The Advantages



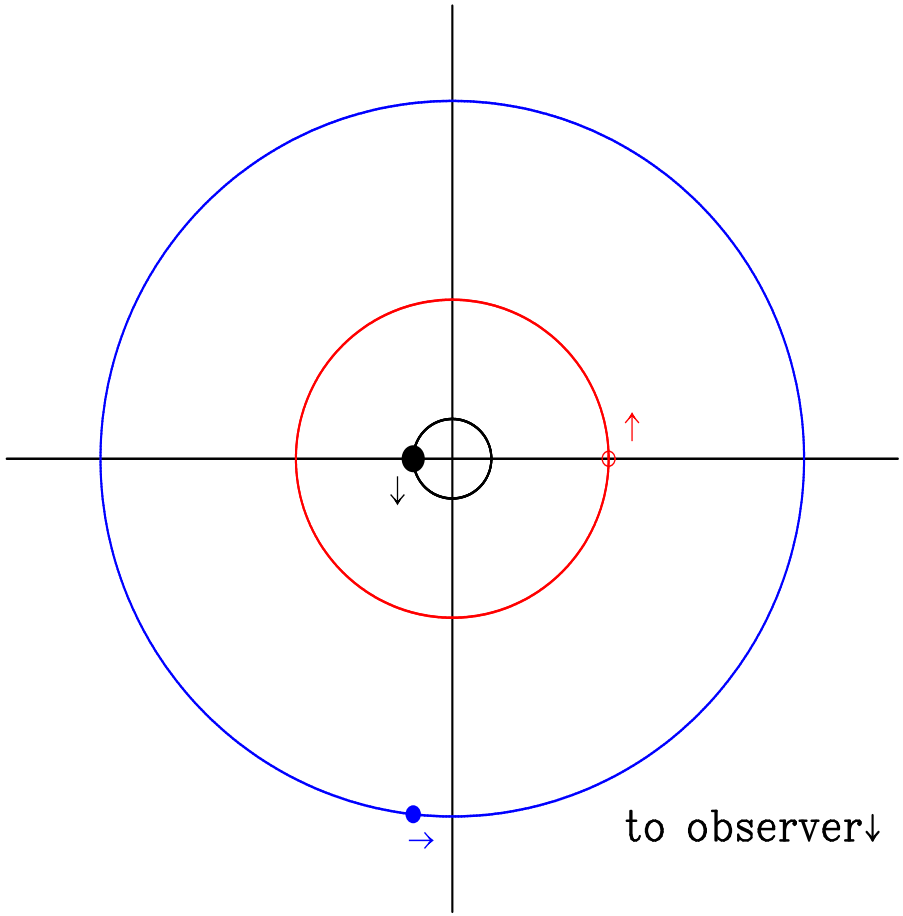
- Here is a transit of the primary during the primary eclipse. The primary is crossing the barycenter at this time, hence the transit occurs at the same time as the planet's barycenter crossing.

The Advantages



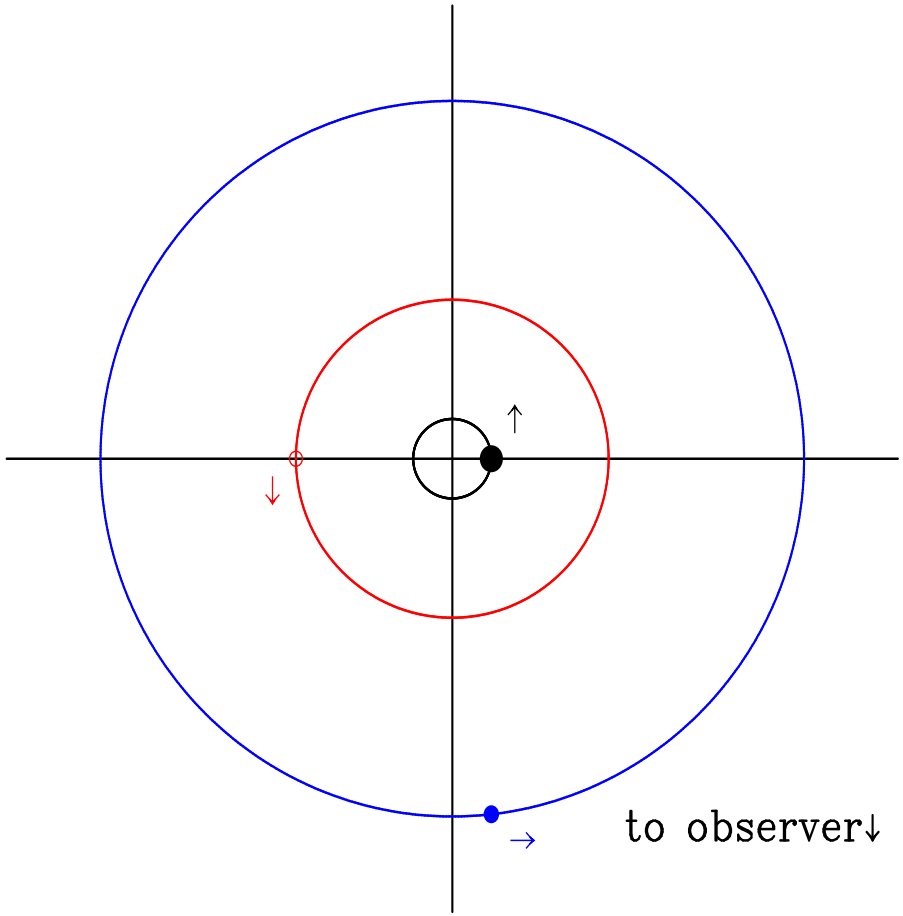
- The situation is the same for the transit of the primary that occurs at the same time as the secondary eclipse

The Advantages



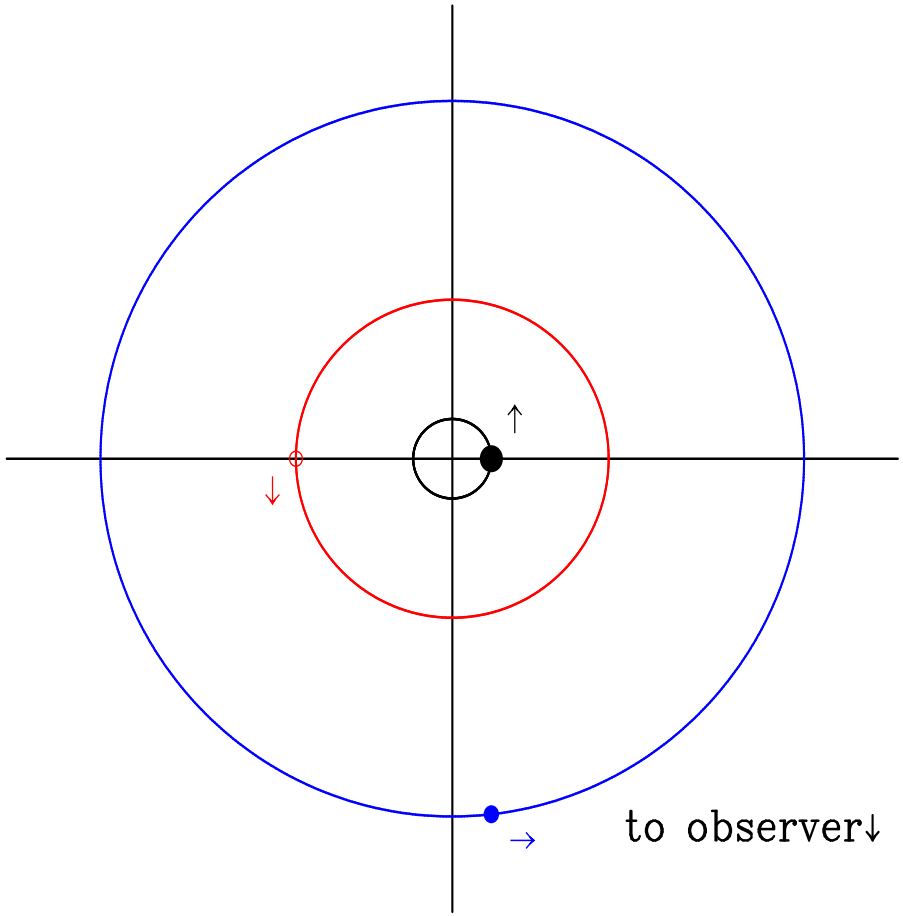
- When the transit of the primary occurs between the primary eclipse and secondary eclipses, the transit time is earlier than the planet's barycenter crossing time.

The Advantages



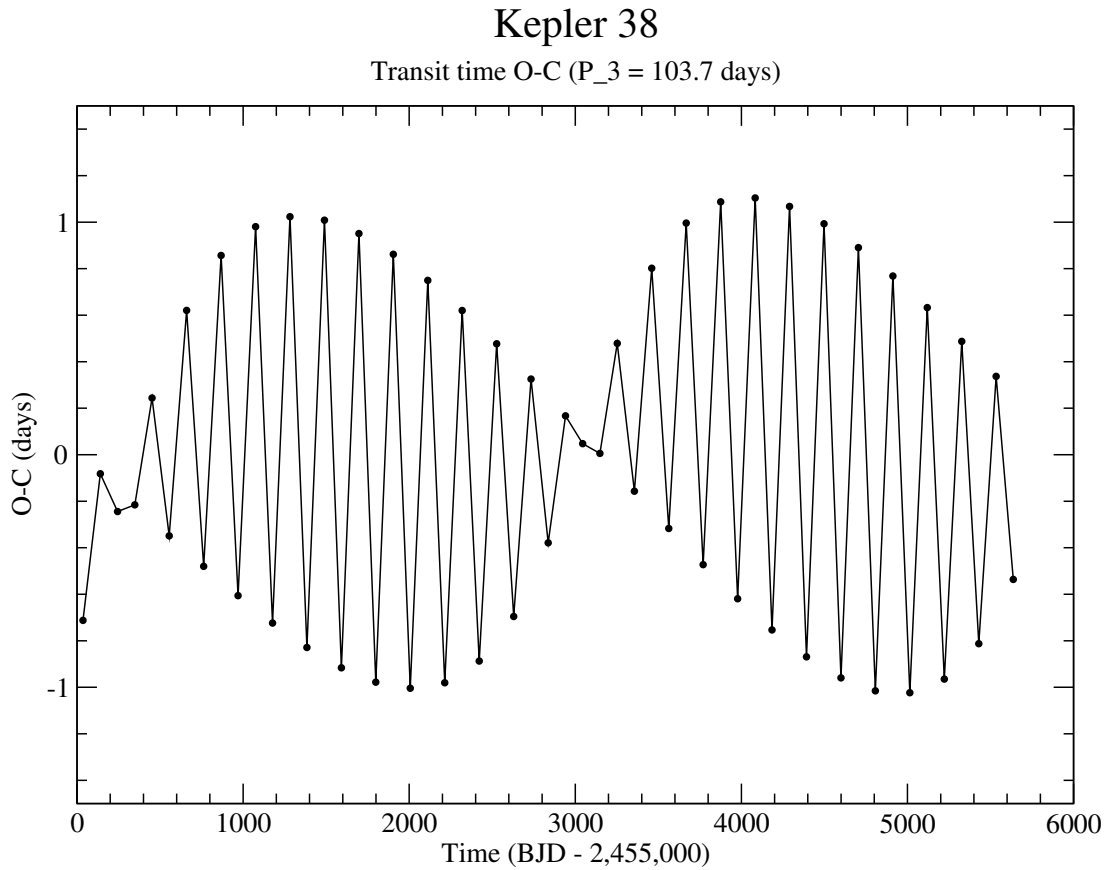
- When the transit of the primary occurs between the secondary eclipse and primary eclipses, the transit time is later than the planet's barycenter crossing time.

The Advantages



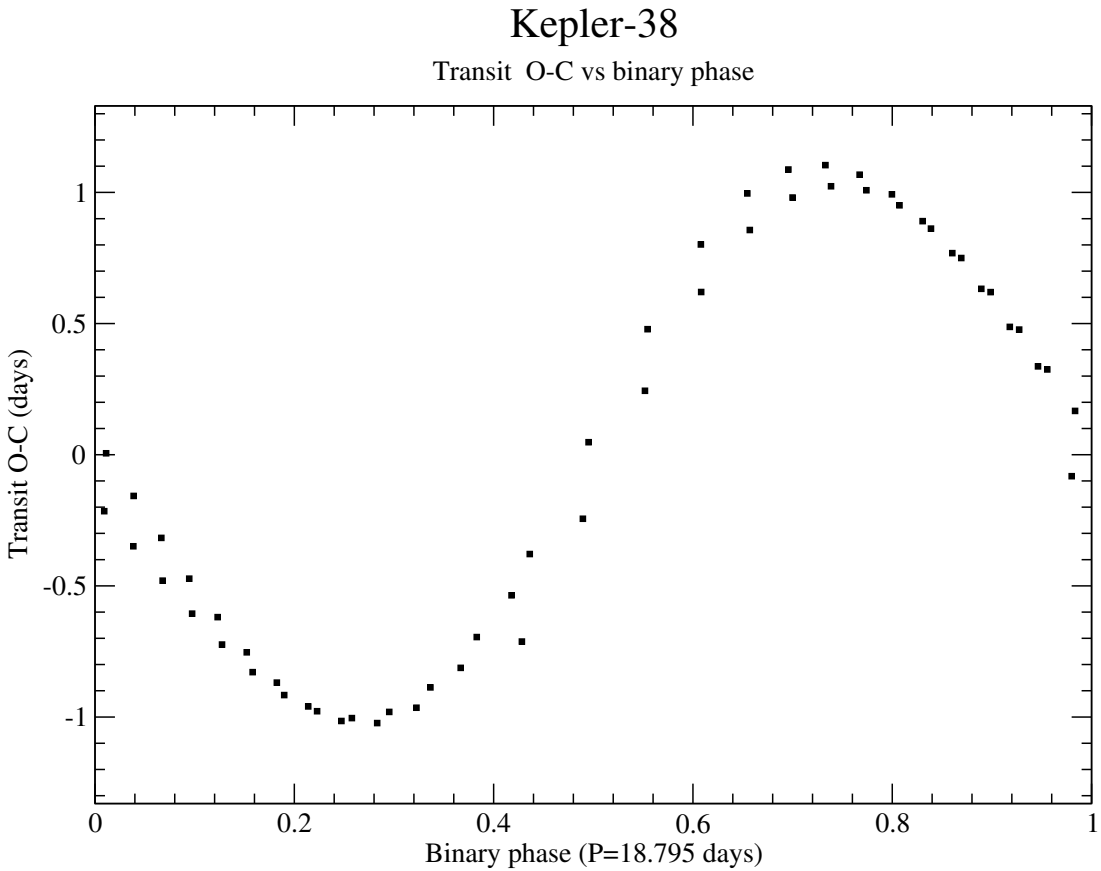
- Since the time delay depends on the primary's x-coordinate on the sky plane, the timing variations of the transits should be sinusoidal (for small eccentricities at least).

The Advantages



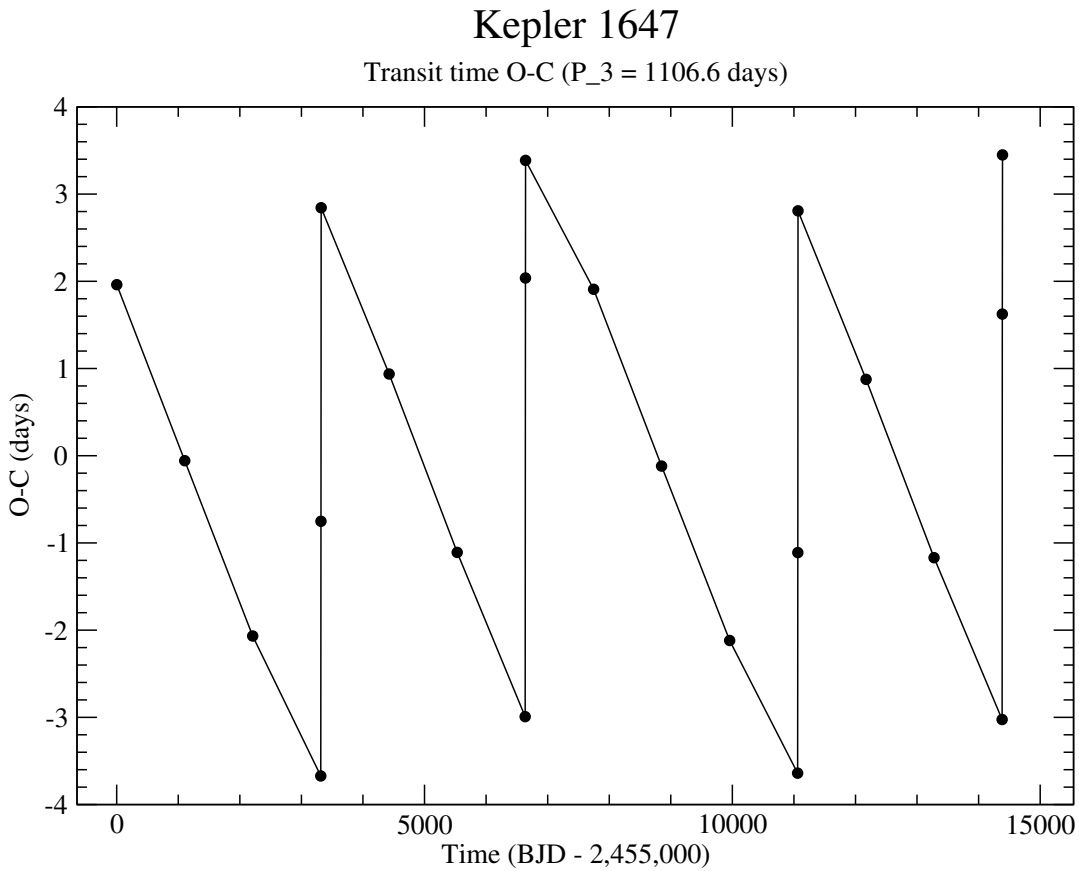
- Here are the timing variations of the (model) Kepler-38 transits relative to a linear ephemeris.

The Advantages



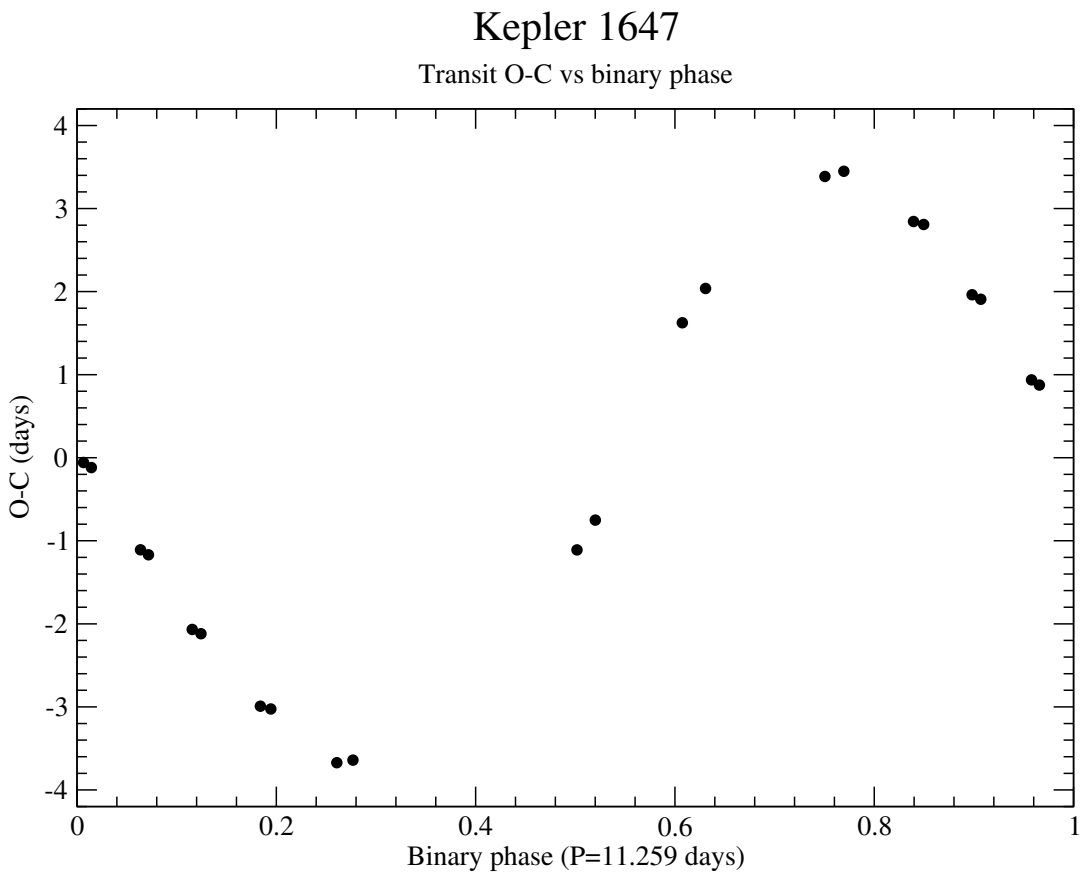
- Here they are plotted as a function of the binary orbital phase.

The Advantages



- Here are the timing variations of the (model) Kepler-1647 transits relative to a linear ephemeris. The $O - C$ values are ± 4 days!

The Advantages



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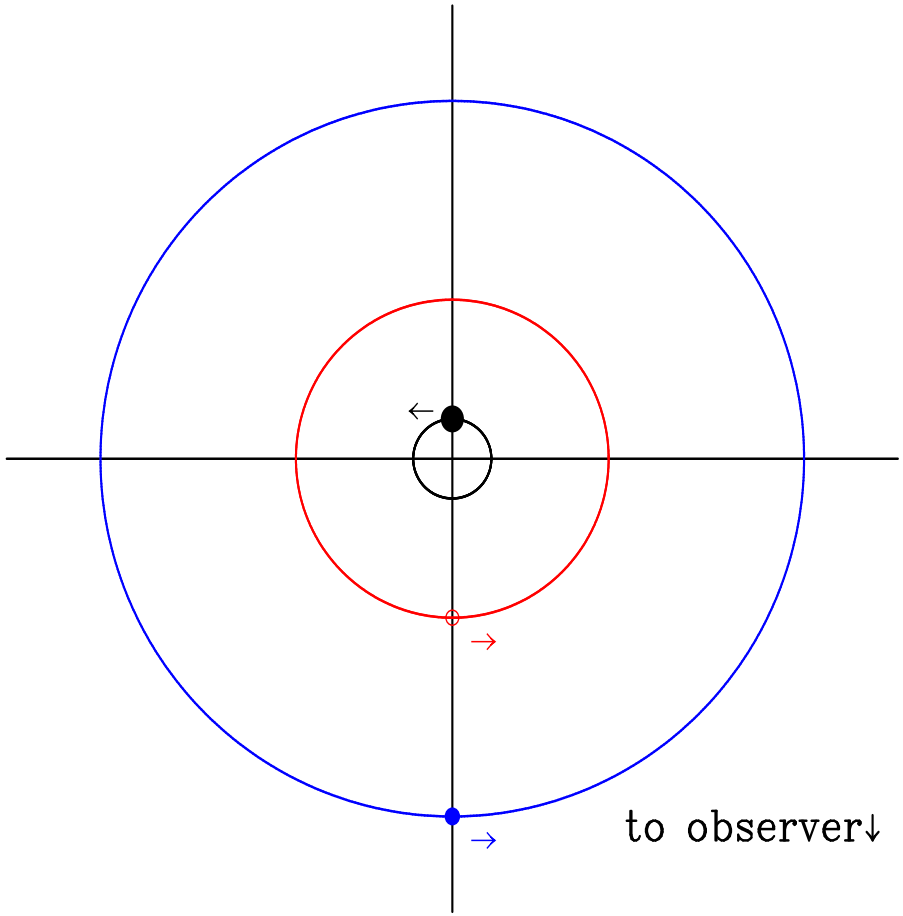
    - Also, since the relative speed of the star being transited and the planet on the sky plane depends on the binary phase, the transit durations will likewise depend on the binary phase.

The Advantages



- Here is a transit of the primary during the primary eclipse. In this case, the speed of the planet relative to the primary is larger, hence the transit duration at this time will be shorter.

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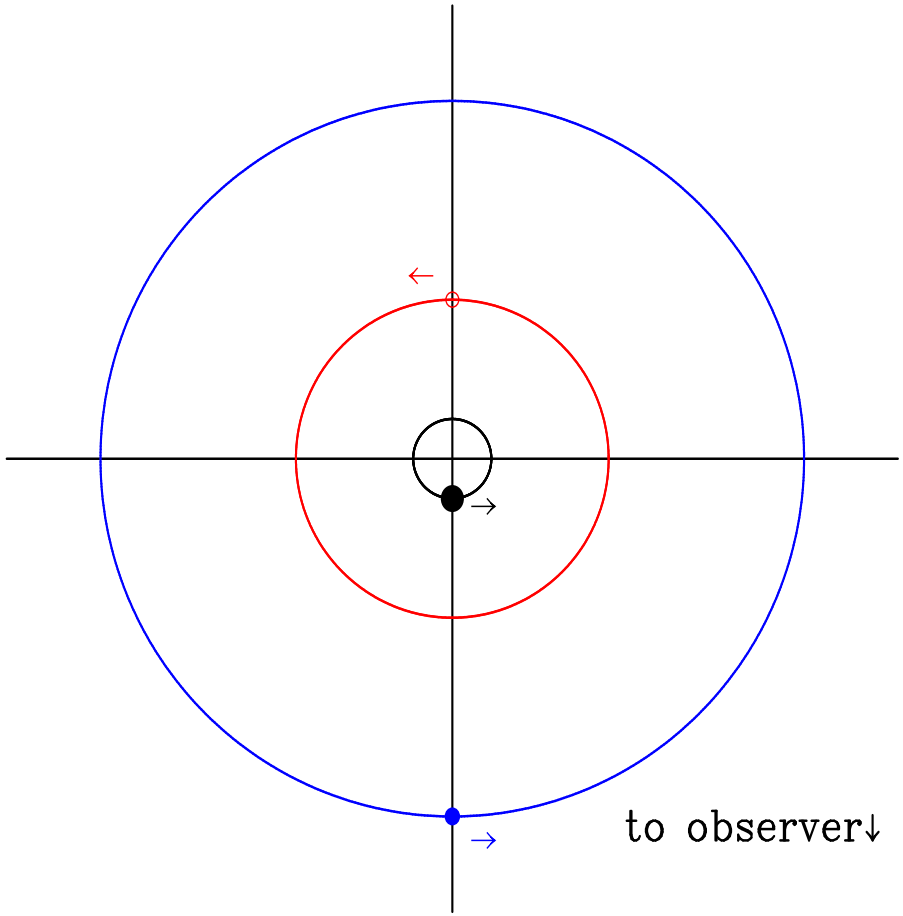
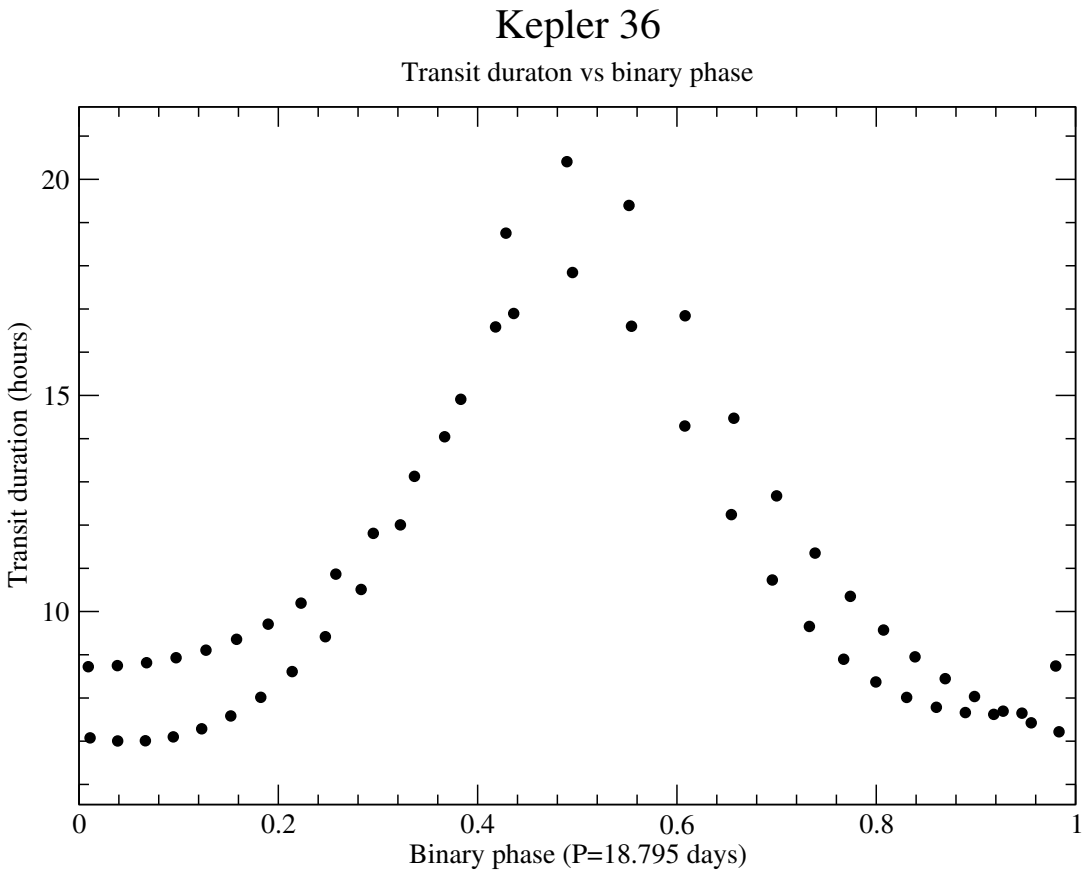


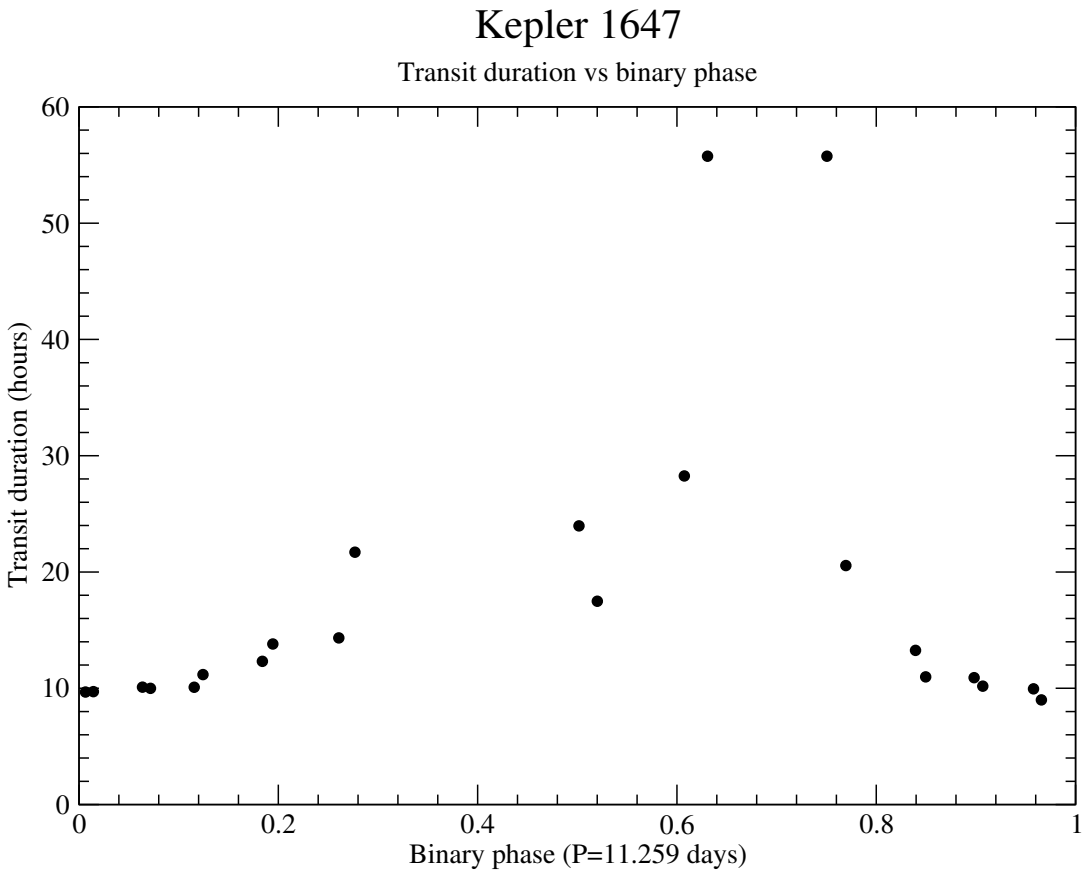
- Here is a transit of the primary during the secondary eclipse. In this case, the speed of the planet relative to the primary is smaller, hence the transit duration at this time will be longer.

The Advantages



- Here are the (model) transit durations of Kepler-38 plotted as a function of the binary phase. The range is ≈ 15 hours.

The Advantages



- Here is the same plot for Kepler-1647. When $P_3 \gg P_{\rm bin}$ the situation can be more complicated.

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    - Also, since the relative speed of the star being transited and the planet on the sky plane depends on the binary phase, the transit durations will likewise depend on the binary phase.
    - These timing and depth variations of the transits cannot be mimicked by the common false-positive scenarios that plague planet transits in single stars, hence the light curve is self-validating.

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    - The planet may transit both stars during its conjunction, and if the flux ratio of the stars is not too extreme, two transits can potentially be seen.

The Advantages

The Astronomical Journal, 160:174 (9pp), 2020 October https://doi.org/10.3847/1538-3881/abad40
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Multiple Transits during a Single Conjunction: Identifying Transiting Circumbinary Planetary Candidates from TESS

Veselin B. Kostov[1,2], William F. Welsh[3], Nader Haghighipour[4], Billy Quarles[5], Eric Agol[6], Laurance Doyle[2], Daniel C. Fabrycky[7], Gongjie Li[5], David V. Martin[7,10], Sean Mills[8], Tsevi Mazeh[9], Jerome A. Orosz[3], and Brian P. Powell[1]

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- Here is a paper that discusses the "1-2 punch" scenario.

The Advantages

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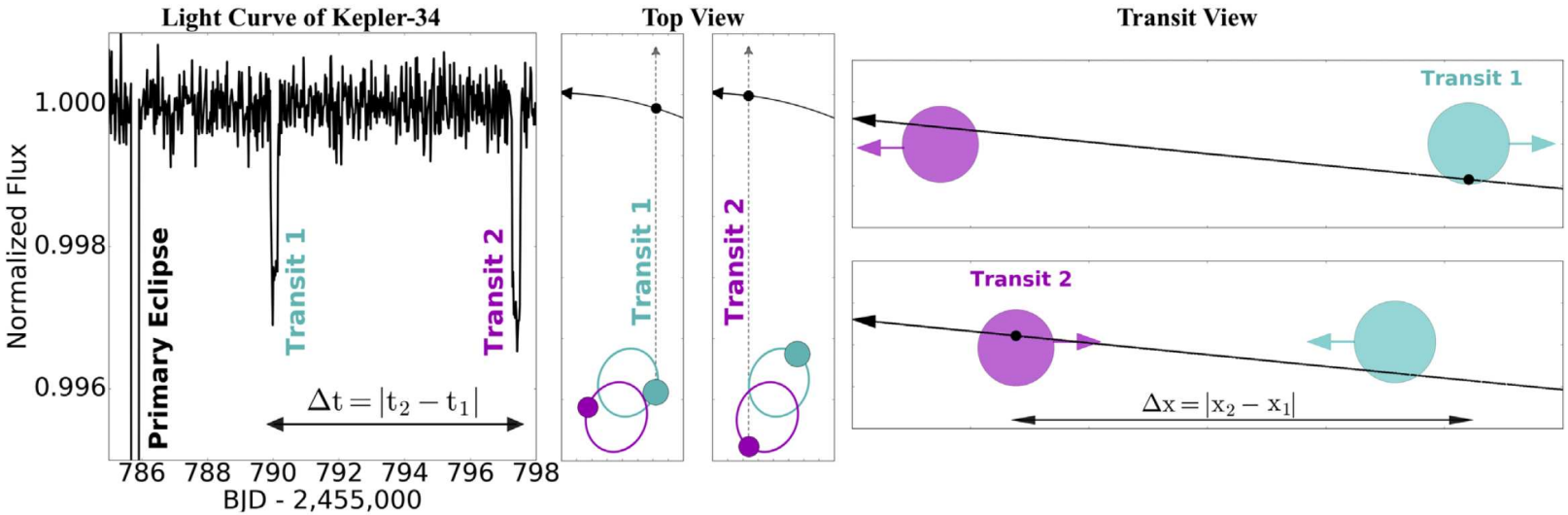
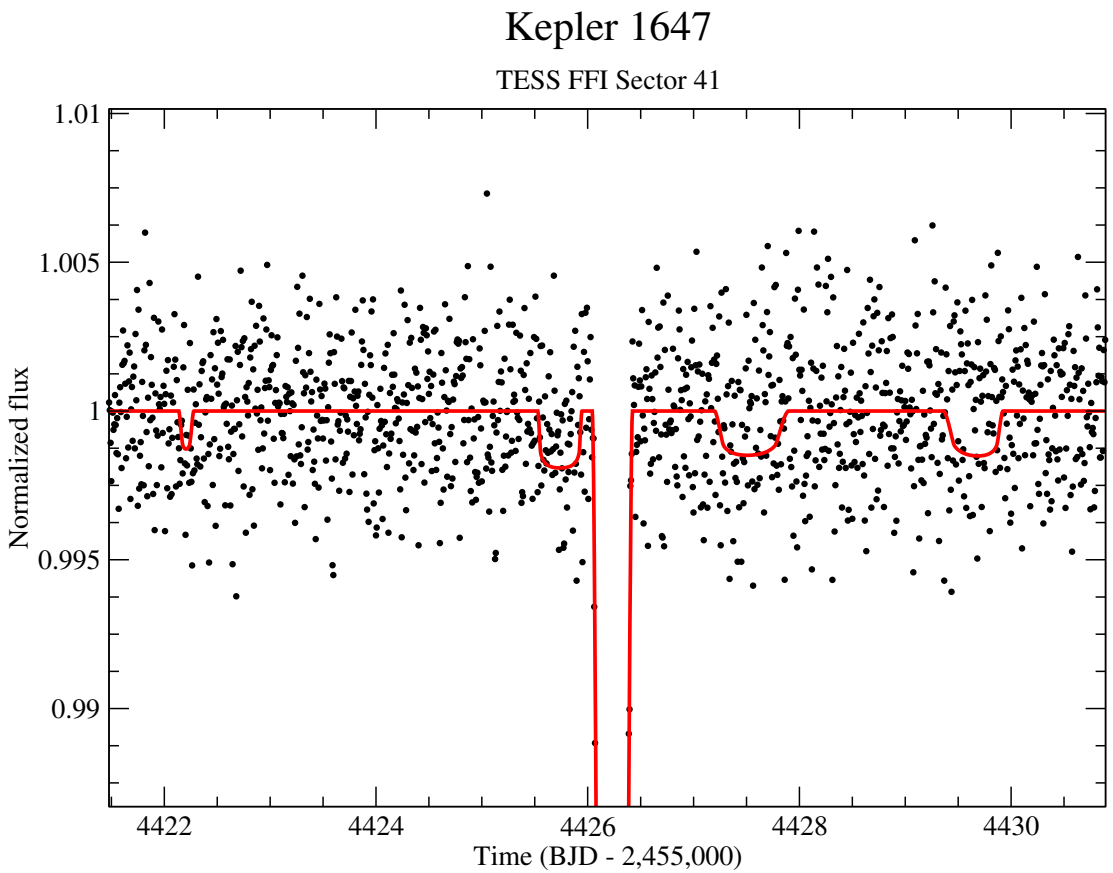


Figure 1. Left: a short segment of the Kepler light curve of Kepler-34 showing two transits of the CBP during one conjunction. Middle and right: schematic orbital configuration of the system during the two transits. The dashed arrow in the middle panels indicates the direction to the observer. The right panels show the orbital configuration of the system as seen from the Kepler telescope. The size of the CBP (black circle) has been exaggerated.

- Kepler-34 has a 1-2 punch (a transit of the secondary followed by a transit of the primary) where the transit depths and durations were slightly different from each other.

The Advantages



- Kepler-16 had an undetected quadruple transit event during TESS Sector 41.

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  - For certain situations, it is possible to have a validated candidate in a light curve with a comparatively short time span.
    - The planet may transit both stars during its conjunction, and if the flux ratio of the stars is not too extreme, two transits can potentially be seen.
    - The 1-2 punch scenario cannot be easily mimicked by the common false-positive situations that plague transits around single stars, hence the light curve is (somewhat) self-validating.
    - If radial velocity curves are available for both stars, the planet's orbital period can be estimated to within $\approx 10\%$ of its true value using a light curve that spans $\approx 5\%$ of the planet's period.

The Characterization

- To fully characterize a CBP system:
  - Radial velocity measurements of at least one star are needed.
    - Since the transit timing and depth variations depend on the binary mass ratio, a single-lined EB can be fully characterized if the transits sample enough of the binary phase.
  - A full "photodynamical" modeling code is needed since the orbits are not Keplerian (see Orosz et al. 2019 and Orosz 2023).
    - The parameter space can be large since there is an extra body and orbit.
    - Finding solutions can be difficult.
    - However, once a solution is found, the masses and radii of the stars and the planet(s) can be determined quite precisely.

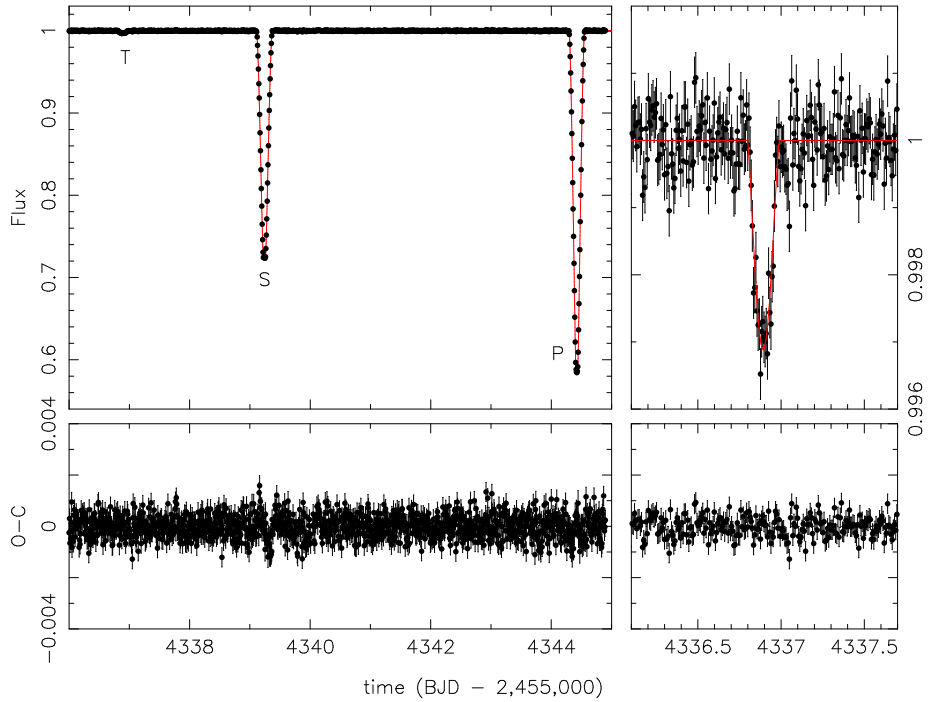
The Summary

- We have some challenges:
  - Difficulties with short-period binaries with intrinsic variability out-of-eclipse.
  - Generally lower transit probabilities, so getting large sample sizes similar to the one for single-star hosts.
  - The full characterization can be difficult owing to the large number of free parameters.
- We have some rewards:
  - It can be easy to rule out many of the common false-positive scenarios that plague transits around single stars (e.g. background EBs).
  - Since the transit timing and depth variations depend on the binary mass ratio, a single-lined EB can be fully characterized if the transits sample enough of the binary phase.
  - A full "photodynamical" solution can yield very precise stellar and planetary parameters.

The Future

- Some random thoughts:
  - Can we push the detections to planets with radii $\lesssim 2\,R_\oplus$. We need higher signal-to-noise and better search techniques.
  - Are there close-in planets around very short-period binaries (say $P_{\rm bin} = 0.7$ days and $P_3 = 8$ days)? We need larger samples, and good signal-to-noise wouldn't hurt either.
  - Which technique has the potential for the most *discoveries* (all are needed for full characterization): transits, eclipse timing variations, or radial velocity measurements?
    - RVs and ETVs can detect nontransiting planets, but both need fairly massive planets.
    - Owing to precession of the planetary orbit, the probability of transits in a fixed time interval can be quite low.
    - Note: owing to precession, transits are almost guaranteed if the orbits are no coplanar and the entire precession cycle can be observed (this can be decades to centuries).

New candidate *TESS* CBP: TIC 241449505



- This was observed in Sectors 11, 38, 64, and 65. There is a transit-like event in Sector 38 that is on-target.
- No ETVs are seen down to a few seconds.
- 15 HARPS good spectra were obtained starting ≈ 750 days after the end of Sector 65 by Amaury Triaud and Aleyna Adamson.

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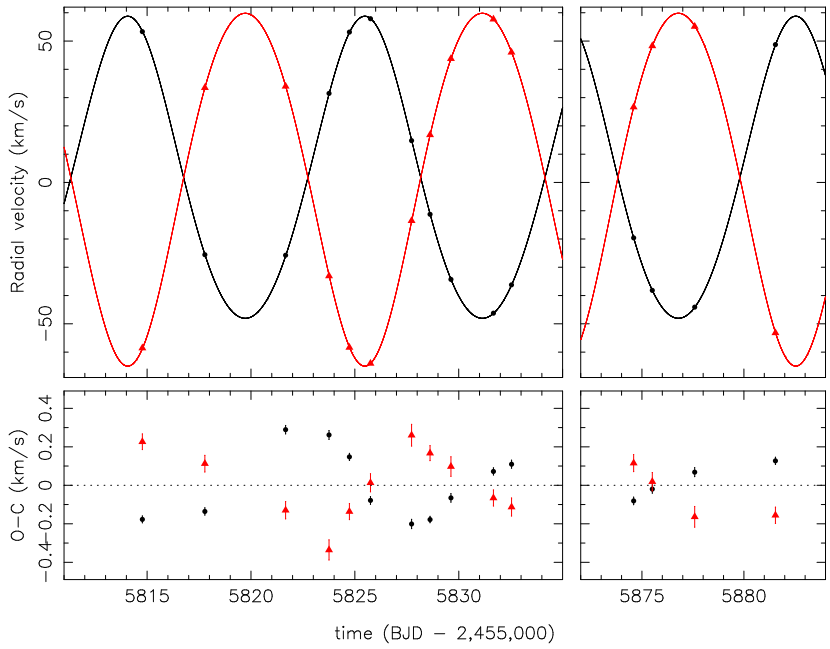

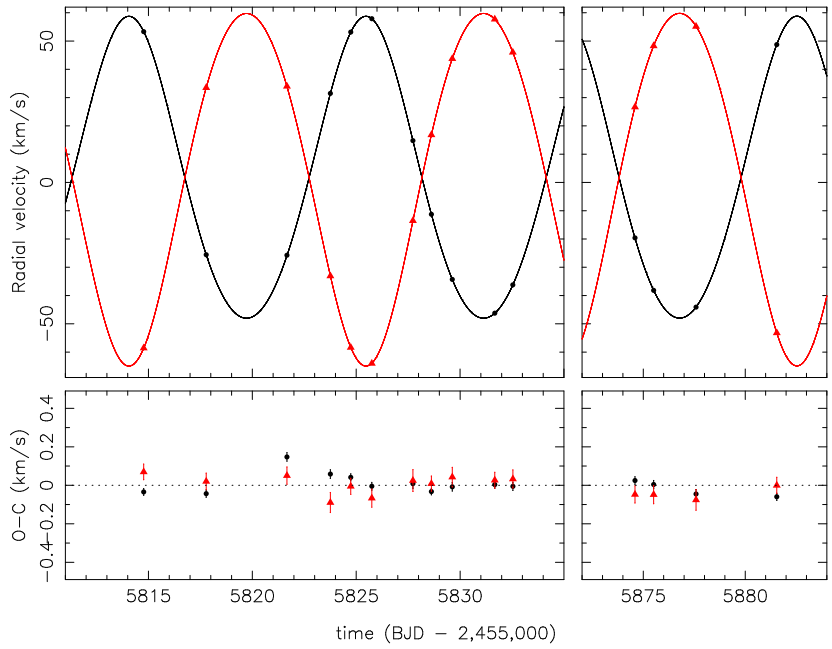

- Models without a planet have RV residuals due to unexplained apsidal motion (left). A planet with a mass of around 2.8 Jupiter masses gives a much better fit to the RVS (right).

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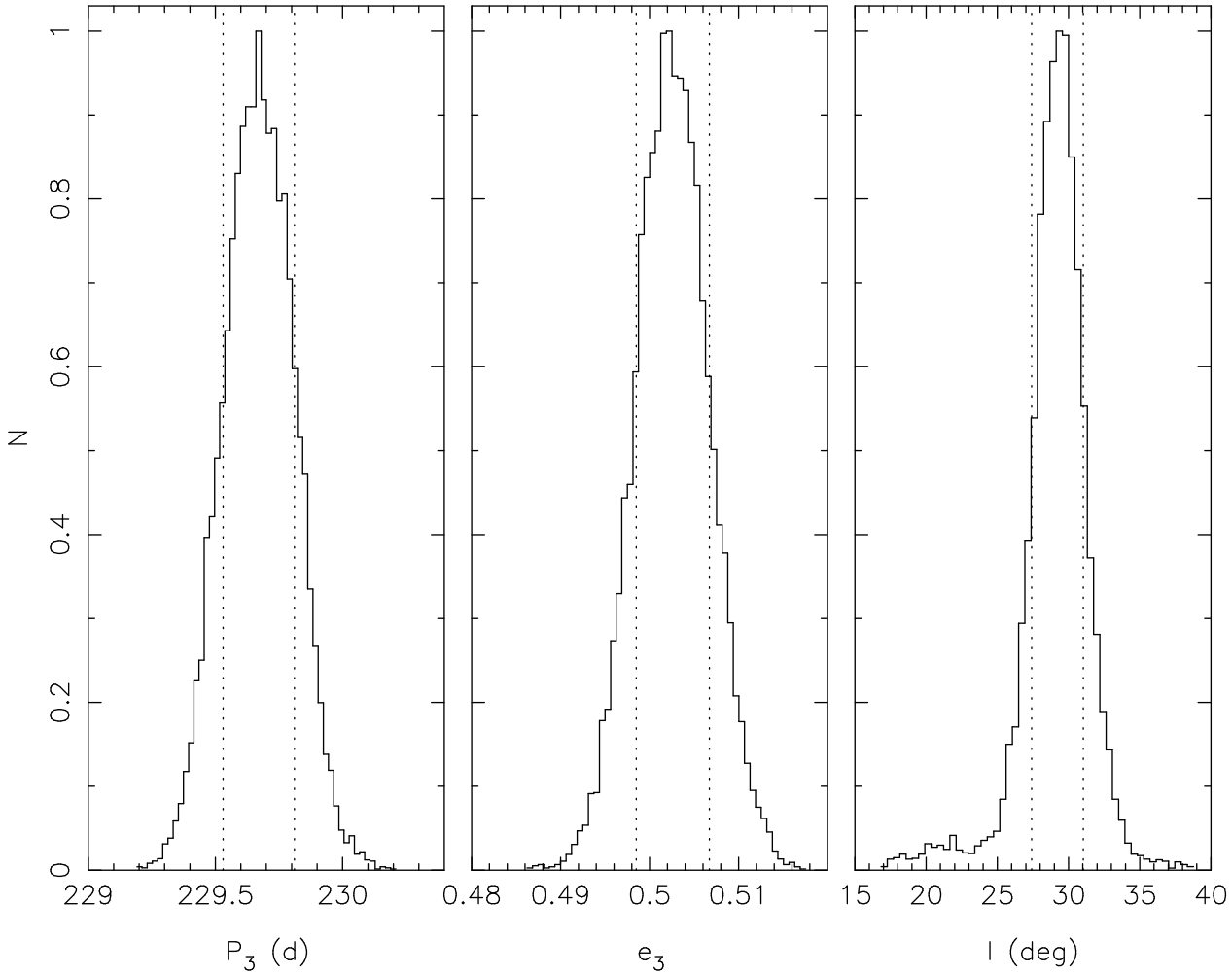

- $P_3 = 229.6 \pm 0.14$ days, $e_3 = 0.5025^{+0.0042}_{-0.0040}$, $I = 29.26^{+1.77}_{-1.85}$ degrees.

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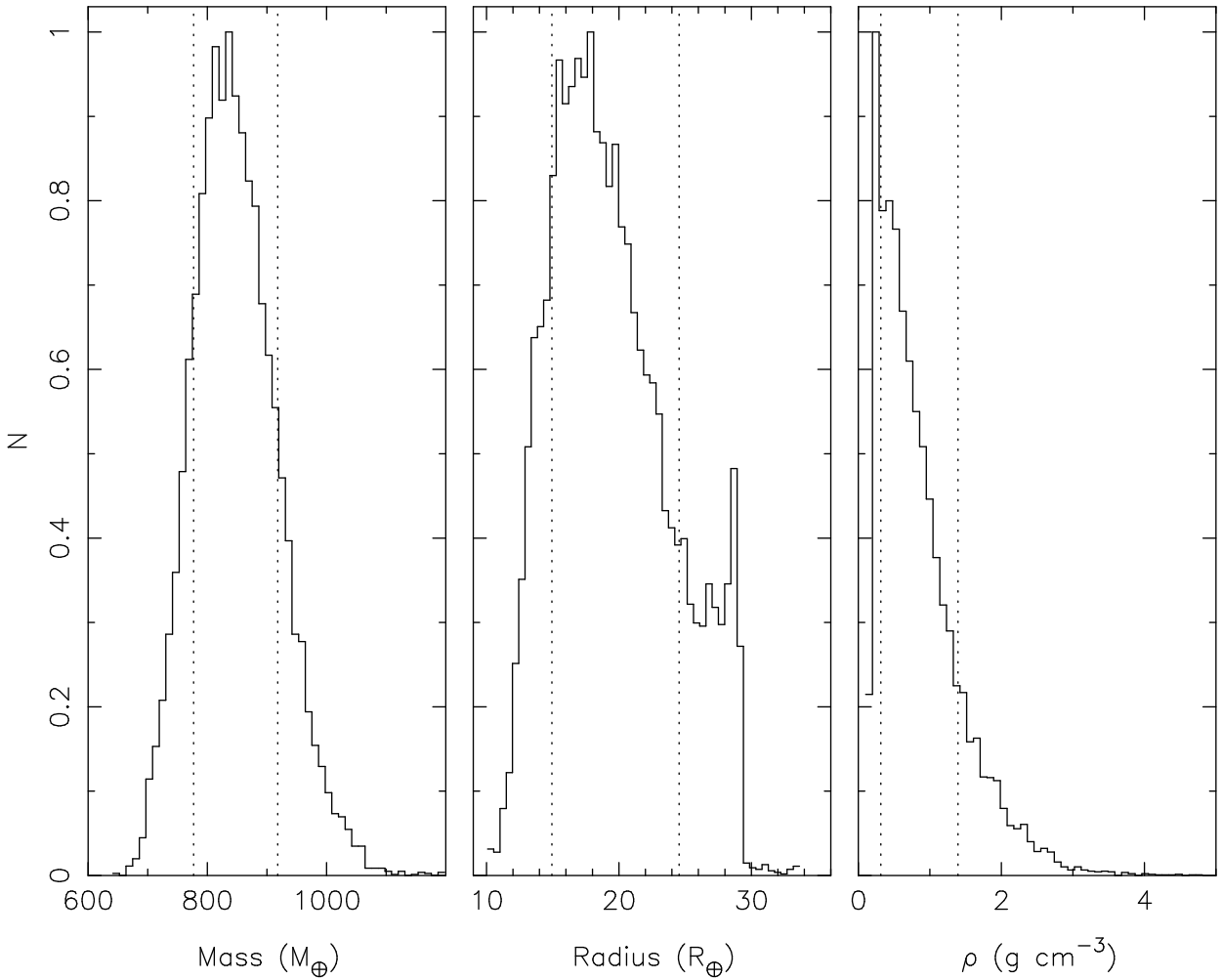

- $M_3 = 842^{+76}_{-65}\, M_\oplus$, $\rho_3 = 0.70^{+0.69}_{-0.39}$ g cm^3.