Modelling the circumbinary candidate KOI-1741

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1. What is a circumbinary planet?

Since the launch of the *Kepler* mission[1] in 2009, the number of exoplanets detected via the transit method has significantly increased. The combination of a wide field of view and exquisite photometric precision has led to an improvement in both the quantity and quality of data available. Consequently, astronomers are now faced with an unprecedented abundance of unusual and exciting astronomical systems.

A large number of confirmed exoplanets exist within binary systems. There are two categories:

- S-type, where the planetary body orbits around just one component of its host binary.
- P-type, where the planet orbits both components of its host binary. This is also known as a *circumbinary*.

Kepler-16b[2] was the first circumbinary discovered using the transit method; a further 9 circumbinaries have since been confirmed using similar techniques.

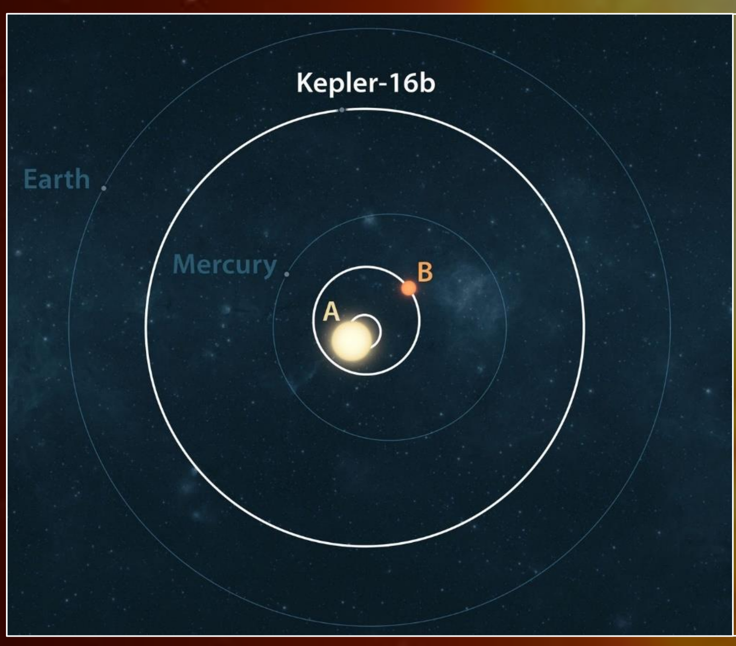

Fig. 1
The orbit of *Kepler*-16b. Star A is 0.6897 $M_{\odot}$, star B is 0.2026 $M_{\odot}$ and the planet itself is 0.333 M_{Jup}. The binary stars complete their orbital cycle once every 41.08 d, whilst the planet takes 228.78 d to orbit the two stars. The planet orbits at a distance of roughly 0.7 AU from the binary, closer than Earth is to the Sun.

2. Markov Chain Monte Carlo (MCMC) methods

Light curves for KOI-1741 were extracted from the Mikulski Archive for Space Telescopes. In total, 14 quarter-years of data were available; these were used in conjunction with radial velocity measurements for one of the stellar components of the binary.

MCMC methods are frequently used in the field of astronomy to establish the optimal set of parameters for a given system.

Consider a set of time series data, $D(t_i)$. Suppose that we also have a proposed model, $y(t_i|\theta)$, where θ are a set of free parameters that change the function in some way. The first step is to define an error function of the form

$$\chi^2 = \sum_i \frac{(D(t_i) - y(t_i|\theta))^2}{2\sigma^2},$$

where σ is some estimate of the error in the data.

It is then necessary to construct a likelihood function; this needs to be maximal when the error is minimal. A Gaussian is often chosen, of the form

$$P(D|\theta) = exp(-\chi^2).$$

An existing Python implementation of the MCMC method, emcee[3], was used to optimise the parameters of the KOI-1741 binary (see Fig. 2).

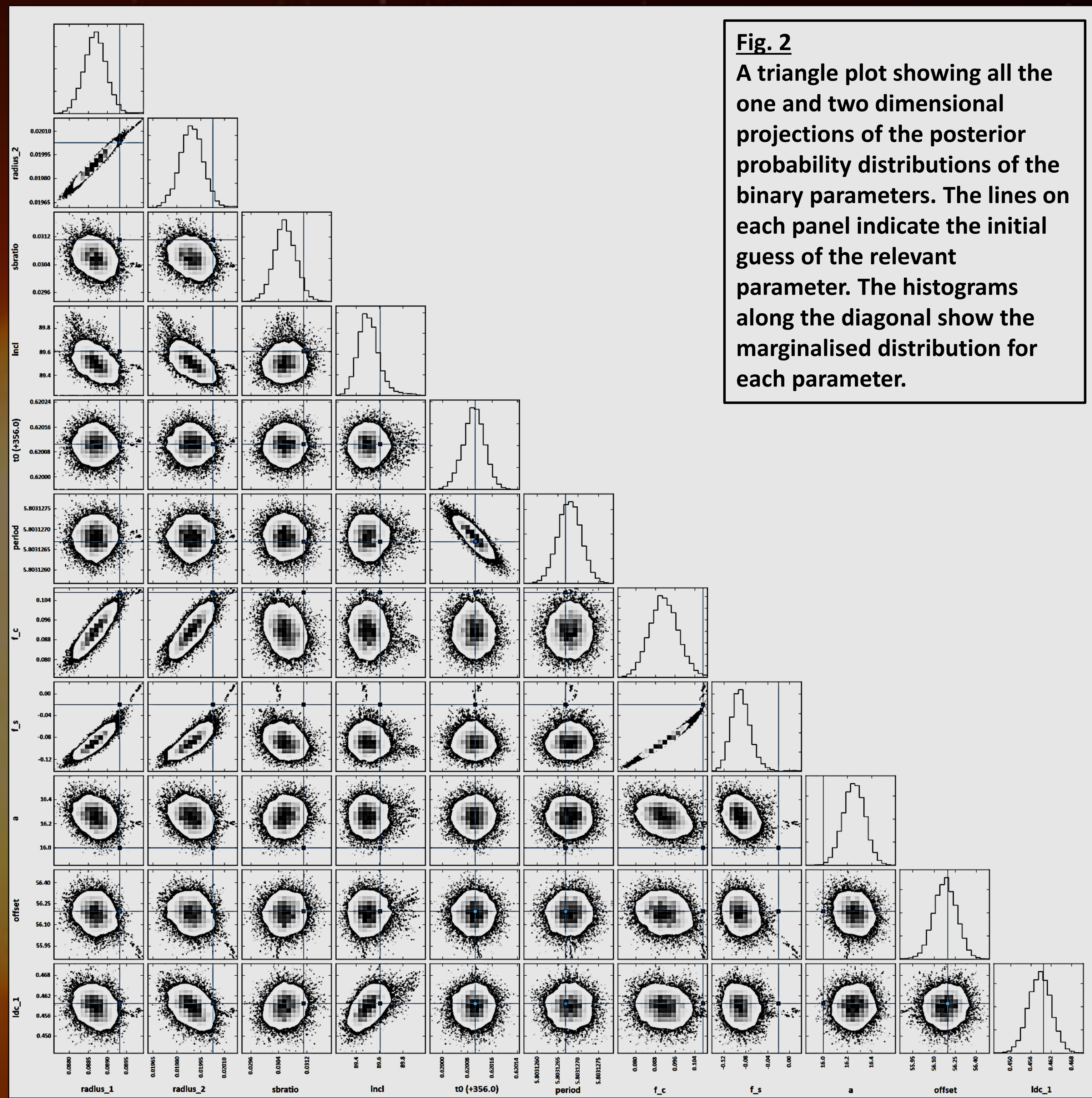

Fig. 2
A triangle plot showing all the one and two dimensional projections of the posterior probability distributions of the binary parameters. The lines on each panel indicate the initial guess of the relevant parameter. The histograms along the diagonal show the marginalised distribution for each parameter.

3. Output parameters

Two separate MCMC runs were performed using the data available for KOI-1741. The first combined the light curve and radial velocity data, allowing the parameters of the binary to be optimised. In addition to these, it was possible to manually determine planetary transit times and durations for the system by scanning through the light curve. This new information enabled the planetary parameters to be optimised in a second run. The overall set of parameters are shown in Table 1.

Parameter, variable*	Value ± 1σ
[1]Binary orbital period, period	5.80312679 ± 0.00000028 [d]
Time of primary eclipse, t0	356.6201025 ± 0.0000343 [d**]
[1]Scaled radius of star 1, radius_1	0.08868776 ± 0.00029431 (R_1/a)
[1]Scaled radius of star 2, radius_2	0.01989460 ± 0.00007315 (R_2/a)
[2]Radius of star 1, R_A	1.74392809 ± 0.16761791 [$R_{\odot}$]
[2]Radius of star 2, R_B	0.39182605 ± 0.03766505 [$R_{\odot}$]
[2]Mass of star 1, m_A	2.72041386 ± 0.81588419 [$M_{\odot}$]
[2]Mass of star 2, m_B	0.31628891 ± 0.22706164 [$M_{\odot}$]
[1]Binary inclination, incl	89.5047903 ± 0.0937815 [deg]
[2]Nodal longitude, Omega_bin	0 (by convention) [deg]
[1]$\sqrt{e}\cos(\omega_{bin})$ for binary, f_c	0.09147862 ± 0.00566778
[1]$\sqrt{e}\sin(\omega_{bin})$ for binary, f_s	-0.08949381 ± 0.01849108
[1]Star 1 to centre of mass, a	16.25564577 ± 0.08764087 [AU]
[1]Surface brightness ratio, sbratio	0.03058223 ± 0.00031085 (S_2/S_1)
[1]Linear limb darkening coefficient (star 1), ldc_1	0.45868778 ± 0.00335364
[1]Instrumental offset γ (rv), offset	56.1805224 ± 0.0815674 [kms^{-1}]
[2]Planetary orbital period, P_p	279.28486175 ± 0.22503047 [d]
Time of planetary conjunction, t0	1142.1782707 ± 0.0156342 [d**]
[2]Inclination, inc_p	90.29990683 ± 0.06650652 [deg]
[2]Eccentricity, e_p	0.18403582 ± 0.01083898
[2]Nodal longitude, Omega_p	-0.35757423 ± 2.69364168 [deg]
[2]Argument of periapsis, omega_p	30.07995779 ± 4.95970786 [deg]

Table 1
[1]Output of the MCMC chain combining the light curve and radial velocity data. A reference epoch t0 of 2455189.620 [BJD] was used for this run.
[2]Output of the MCMC chain combining the planetary transit times and durations. A reference epoch t0 of 2455975.178 [BJD] was used.
*Name given to each parameter in the source code for the program.
**Values quoted are in units of [BJD-2454833].

4. Light curve and radial velocity curve models

In order to model the light curve and radial velocity data, the ellc model[4] was used. This takes in the binary parameters and returns light curves and radial velocities, accounting for *Kepler*'s exposure time in the process.

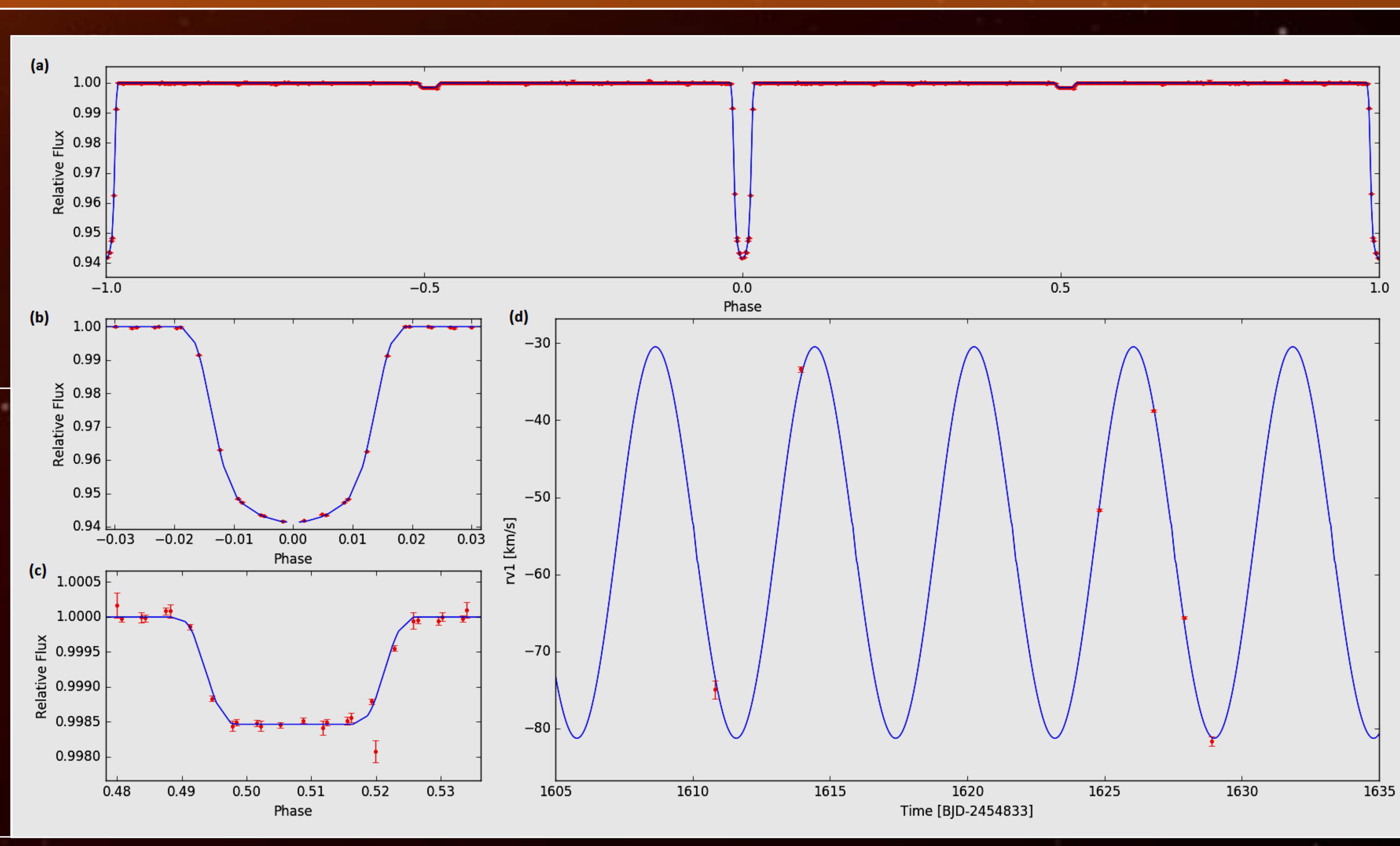

Fig. 3
The resulting ellc fits for the light curve and radial velocity curve after optimising the binary parameters using MCMC methods. (a) shows the phase curve for KOI-1741, whilst (b) and (c) display close-up versions of the primary and secondary eclipses. Finally, (d) shows the radial velocity curve. Note that the instrumental offset has not been accounted for in this plot, hence why the curve is offset from zero. For each plot, the raw data is shown in red, whilst the blue lines represent the relevant ellc model.

5. Planetary transit times and durations

It was possible to determine the transit times and durations by analysing the light curve of KOI-1741. An existing transit timing code, SSTT, was used in conjunction with this information to optimise the planetary parameters. In order to achieve this, the binary parameters involved were fixed as the output values from the previous MCMC chain. The overall set of optimised parameters could then be used to calculate the transit times (see Fig. 4).

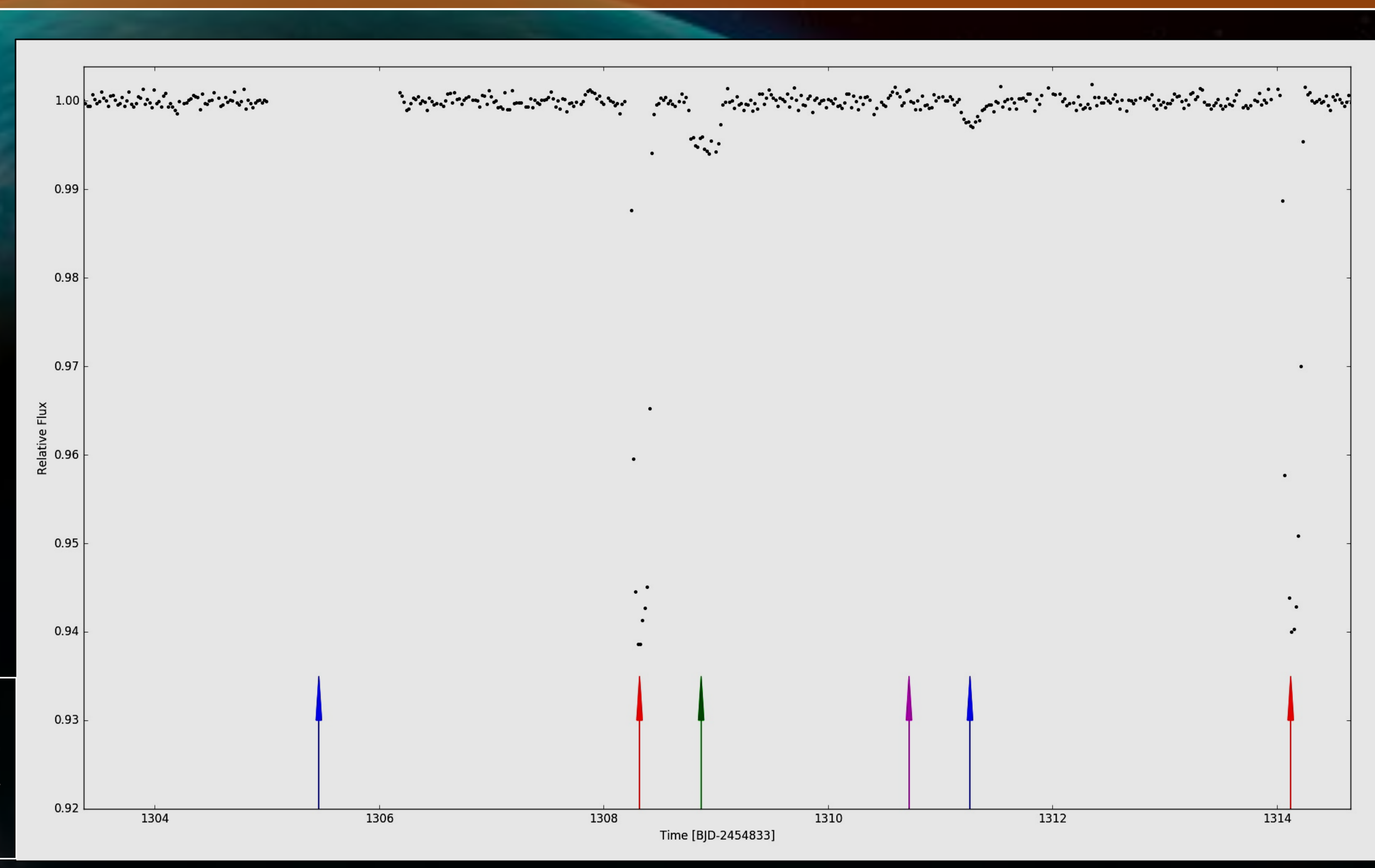

Fig. 4
A visual representation of the calculated times for the primary eclipses (red), secondary eclipses (blue), primary transits (green) and secondary transits (purple).

6. Further work

Improvements to the transit time MCMC code can still be made, since some of the durations fell short of what was expected by approximately 0.04 d. However, analysis performed thus far has given good estimates for several parameters. More complex modelling of the light curve can now proceed, going some way towards ultimately simulating the KOI-1741 system.

References and acknowledgements

[1] N. M. Batalha et al., ApJ **713**, L109 (2010)
[2] L. R. Doyle et al., Science **333**, 1602 (2011)
[3] D. Foreman-Mackey et al., Publ. Astron. Soc. Pac. **125**, 306 (2013)
[4] P. F. L. Maxted, arXiv:1603.08484v3 (2016)

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