Formation, Detection, and Characterization of Extrasolar Habitable Planets
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Recent Kepler Results On Circumbinary Planets

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Abstract. Ranked near the top of the long list of exciting discoveries made with NASA's *Kepler* photometer is the detection of transiting circumbinary planets. In just over a year the number of such planets went from zero to seven, including a multi-planet system with one of the planets in the habitable zone (Kepler-47). We are quickly learning to better detect and characterize these planets, including the recognition of their transit timing and duration variation "smoking gun" signature. Even with only a handful of such planets, some exciting trends are emerging.

Keywords. Exoplanets, Eclipsing Binary Stars, *Kepler*

1. Introduction

The first transiting circumbinary planet, Kepler-16b, was announced in September of 2011 (Doyle *et al.* 2011). The fact that *transits* are present is crucial, in that they unambiguously establish the presence of the circumbinary body. In addition to being a key to circumbinary planet detection, the transits further provide the information necessary to obtain very precise stellar and planetary masses and radii, via the exact geometrical configuration necessary to produce the detailed shape, duration, and timing of the transits. The primary star's mass in Kepler-16 is known to better than 0.5%, and its radius to better than 0.2%. Similarly, the secondary star (an M star with mass of only 0.20 $M_\odot$) has uncertainties in its mass and radius of less than 0.33% and 0.26%. The planet's mass and radius are likewise known to remarkable precision, 4.8% and 0.34%, respectively. Also, the primary star's rotation axis has been measured to be aligned with the binary's orbital axis to within 2.4 degrees (Winn *et al.* 2011). The circumbinary configuration provides a boon to stellar and exoplanet astrophysics.

But despite these impressive results, many questions remained unanswered: e.g. What kinds of planetary orbits are possible (what periods and eccentricities)? What kinds of stellar orbits are possible? Is there a preferred stellar mass ratio? What planetary radii, masses, and temperatures are possible? And perhaps most importantly, was Kepler-16 just a lucky accidental quirk, or are circumbinary planets common?

In the short time since Kepler-16 was discovered, five† additional transiting circumbinary planet systems have been confirmed, including the Kepler-47 system (Orosz, *et al.* 2012b) discussed below. Moreover, several candidate systems are under investigation.

† The sixth system (seventh planet) was discovered and announced by the Planet Hunters after the IAU Symposium by Schwamb, *et al.* (2012), and was also independently discovered by Kostov, *et al.* (2013).

These discoveries establish that Kepler-16 was not a rare oddity and that the circumbinary planets are indeed a new class of planet (Welsh, *et al.* 2012). These discoveries are spurring on investigations of circumbinary planet formation and stability (e.g. Meschiari (2012), Paardekooper, *et al.* (2012), Youdin, *et al.* (2012), Rafikov (2013)). In the following section we discuss the multi-planet Kepler-47 system and the rapidly developing picture of the nature of circumbinary planets.

2. The Circumbinary Planet “Smoking Gun”

Transits† in a circumbinary system are harder to detect than transits in a single-star system for a variety of reasons. The eclipses are usually very much stronger than the transits, and their presence tends to swamp out or mask the transit signal. But the more challenging issue is that the transits are neither periodic nor of equal duration. A single planet orbiting a single star will exhibit strictly periodic transits. Searches based on a periodic signal can be highly efficient at detecting the planet. If there are other planets in the system that strongly gravitationally interact with the transiting planet, the times of transits are no longer periodic, but can vary by a few tens of minutes to a few hours, typically, e.g. Kepler-9 b and c (Holman *et al.* 2010). These are the well-known transit timing variations (TTVs) that can be used for planet confirmation and mass determination. In contrast, for a circumbinary planet, the transit period is very far from being strictly periodic. For example, in Kepler-16, the third transit across the primary star occurs 8.8 *days* (days, not hours) early compared to the expected time based on the first two transits (Doyle *et al.* 2011). The reason for the changing period is that the primary star is not stationary with respect to the planet: it orbits the barycenter of the binary star system. Sometimes the transits occur when the star is before stellar conjunction, and sometime transits occur after conjunction. If $M_{\rm planet} \ll M_2 \ll M_1$, the geometrical configuration-induced TTVs will be $\sim$ zero since the primary is always near the system barycenter. Equal mass stars will result in the largest TTVs, and in a configuration with the planet and stars coplanar and on circular orbits, the deviation of the primary transit times from a linear ephemeris is a minimum of $\pm \sim 0.11$ times the orbital period of the binary stars. For more general orbital orientations and eccentricities the TTVs can be even larger; and transits of the secondary star will have yet larger TTVs, e.g., $\pm \sim 12$ days for Kepler-16b secondary transits. Obviously the TTVs will limit the success of planet searches based on a periodic signal.

The other effect that is important is that the widths of the transits can vary by very substantial amounts, yielding transit duration variations (TDVs). The varying transit widths are often readily detectable by eye in the light curves. This is again due to the “moving target” effect. Assuming the planet orbits in the same sense and in nearly the same plane as the binary, the transit duration is set by the size of the star (and planet) and the relative velocity of the star and planet (i.e. their transverse velocity). Near binary phase zero (defined by the primary eclipse), the star and planet are moving in the opposite direction, and the transits are short in duration. Near secondary eclipse, the star and planet are moving in the same direction and the transits can be very long. Near the quadrature points of the binary orbit, the transits are “normal” duration. The effect is strong: *eclipse durations can vary by factors of several,* in some cases varying from a few hours to a few days. This TDV phenomenon for planets orbiting binary stars was

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† For clarity, we use the terminology “primary” and “secondary” eclipse for the stars, “primary transit” when the planet transits the primary star, “secondary transit” when the planet transits the secondary star, “primary occultation” when the planet is occulted by the primary star, etc.

noted as early as 1996 (Jenkins *et al.* 1996, and in particular see their figures 5 and 6), several years before the first transiting planet was discovered.

Because the transit widths vary so much, search algorithms that simply fold transits on a linear ephemeris are not optimal for circumbinary planet detection. Fortunately, sophisticated methods to cope with the TTV and TDVs do exist, notably the "TDA matched filter method" (Jenkins *et al.* 1996), the "CB-BLS algorithm" (Ofir 2008), and most recently the "QATS" algorithm in EB mode (Carter & Agol 2013). As the search for transiting circumbinary planets pushes to super-Earth-size planets and smaller (so that individual transits can not be detected visually), such automated search methods will be of great value.

While these TTVs and TDVs make circumbinary planet hunting difficult, they do have a very important positive consequence. When a candidate transiting circumbinary planet is found, it is very easy to confirm or refute it is a physically bound body. The binary star phase-specific TTV and TDVs provide a 'smoking gun'; no other known astrophysical phenomenon, such as a background eclipsing binary, can mimic such variations.

If the planet is massive enough to measurably alter the stars' orbits, stellar eclipse timing variations (ETVs) will be apparent. Because eclipses are generally much deeper than transits, eclipse times can usually be measured with much higher precision than transit times, allowing for detection of timing deviations as small as a few seconds. The most readily measurable effect of a planet on the binary stars is the precession of the stellar orbits that results in a difference between the orbital period as defined by the primary eclipses versus the orbital period as defined by the secondary eclipses. The observed-minus-computed times of the primary eclipses and secondary eclipses then show a diverging trend with time, e.g., see Welsh, *et al.* (2012). In addition to this dynamical perturbation, a light-travel time effect (LITE) can also be present and help constrain the mass of the planet relative to the binary. Thus the moving target aspect of circumbinary planet host stars allows for a rock-solid confirmation of the planets based on the presence of: 1) transits; 2) very large TTVs; 3) very large TDVs. Also very helpful for a full solution of the system parameters are 4) ETVs and 5) LITE.

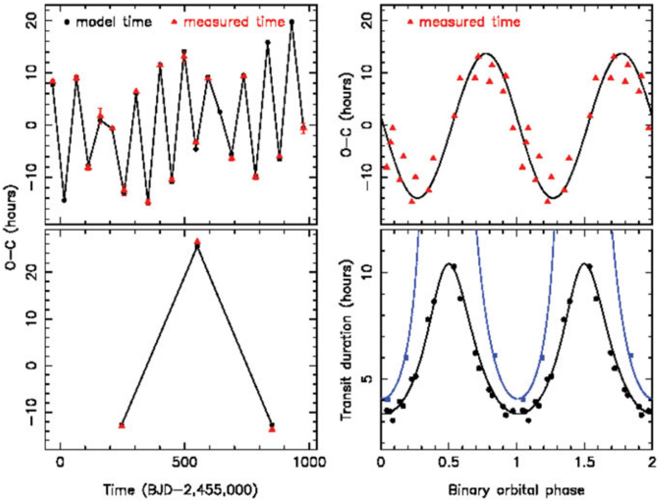

Figure 1. *left:* Transit timing variations and transit duration variations for Kepler-47 b (top) and c (bottom). *right:* TTVs for planet b and TDVs for both planets phase-folded onto the binary star's 7.4 day orbital period.

3. Kepler-47

Visual inspection of the light curve of the eclipsing binary KIC 10020423 (KOI-3154) revealed transits of two candidate circumbinary planets. The outer candidate, "c", has a transit depth of ~0.2% and was readily detectable, but the inner candidate "b" was harder to find because of its shallower ~0.1% transit depth. The system is faint, with Kp=15.2 mag, and thus noisier than other *Kepler* circumbinary systems. In addition, variations of amplitude 2-4% in the light curve due to starspots made detection considerably more difficult. Three transits of candidate c were discovered, and using a preliminary model of the system as a guide, 18 transits of candidate b were eventually found. A modified version of the photometric-dynamical code developed for the previous *Kepler* circumbinary planets was used to model the light curve and radial velocities. The code assumes spherical bodies moving under the influence of Newtonian gravity. Since the planets are not sufficiently massive to noticeably perturb the binary stars nor each other, they were treated as massless bodies to greatly reduce the computation time. Details of the photometric-dynamical code are provided in the Supplementary Material of Orosz, *et al.* (2012b). While the planets do not induce measurable dynamical effects, the "moving target effect" causes planet b to exhibit peak-to-peak TTVs of ~28 hrs and TDVs of ~7.2 hrs. Planet c has observed peak-to-peak TTVs of 39.7 hr and TDVs of 2.4 hrs. The best-fit photometric-dynamical model gives an excellent match to the data, confirming these as circumbinary planets.

The primary eclipses are ~15% deep while the (total) secondary eclipses are only ~0.6% deep. Combining the *Kepler* photometry with radial velocities obtained at the McDonald Observatory allowed a partial solution of the binary star parameters. A full solution was not possible because only the primary star's radial velocities were detected in the spectra. However, tight constraints on the primary star's location and motion in its orbit are placed by the planetary transits. This provided the mass ratio of the system, and thus the full set of binary star system parameters. The primary star is quite Sun-like, with a mass of 1.04 ± 0.06 $M_\odot$, radius 0.96 ± 0.02 $R_\odot$, and temperature of 5636 ± 100 K. The secondary is a diminutive star of mass 0.36 $M_\odot$ and radius 0.351 ± 0.006 $R_\odot$, and emitting only 0.57% the flux of the primary in the *Kepler* bandpass. With the stellar radii known, the planetary radii can then be determined. Planet b has a radius of 3.0 $R_{\rm Earth}$, making it the smallest transiting circumbinary planet yet discovered. Planet c has a radius of 4.6 $R_{\rm Earth}$, or ~1.2 $R_{\rm Neptune}$. While the masses are currently below our detection threshold, 3-σ upper limits of < 2 $M_{\rm Jup}$ and < 28 $M_{\rm Jup}$ can be placed, based on the lack of measurable ETVs and the lack of LITE of the binary. Because of their small radii, the masses are likely to be very much smaller than these upper limits.

The orbit of the binary has a very mild eccentricity ($e = 0.023$) and a period of 7.45 days. The orbital periods of the planets are 49.5 d and 303.1 d, respectively (Kepler-47c is currently the longest period confirmed transiting planet). The eccentricity of planet b is low ($e < 0.035$). For planet c, only 3 transits are measured so the eccentricity is harder to constrain; a 95% upper limit of $e < 0.41$ is found, with $e \sim 0.1$ preferred. The period of planet b is 6.6 times the binary period, 77% larger than the critical period below which interaction with the binary stars could lead to a dynamical instability (Holman & Wiegert 1999). While planet b is well interior to the habitable zone (HZ), planet c lies completely within the HZ for $e < 0.2$, and even with $e = 0.4$ the mean insolation is 96% of the Sun-Earth insolation. It is the mean insolation that is relevant for habitability (Williams & Pollard 2002).

In addition to the transits caused by planets b and c, there is an unexplained single transit-like event of depth 0.2%. The signal is six cadences wide and is not an obvious

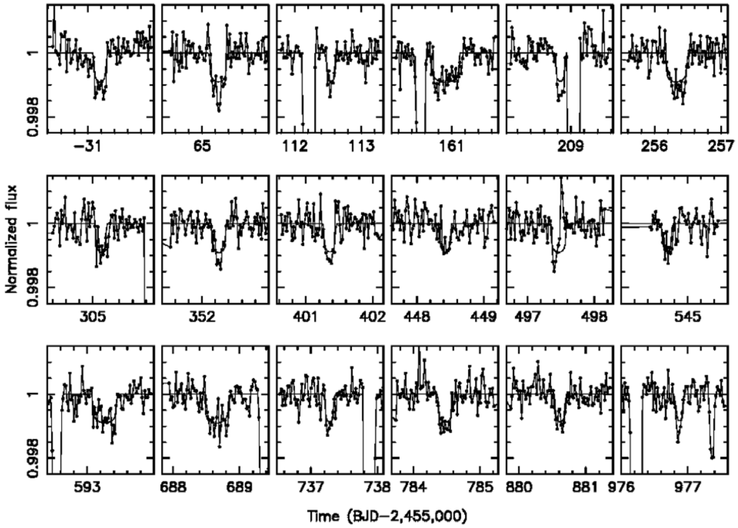

Figure 2. Each of the eighteen Kepler-47 b transits and the photometric-dynamical model fits. The occasional large downward excursions are due to eclipses.

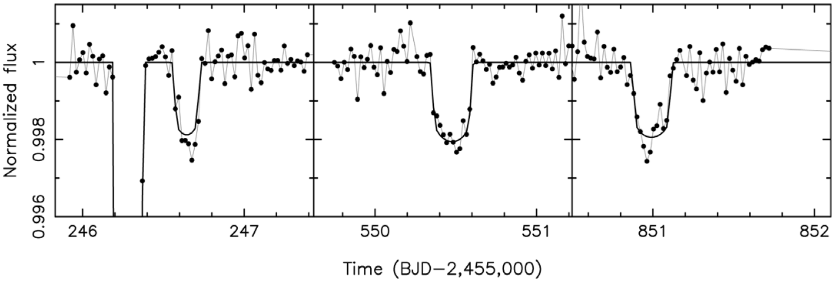

Figure 3. The three observed Kepler-47 c transits with model fits. The large excursion in the first panel is a primary eclipse.

instrumental artifact. It is tempting to suspect an additional planet as the source of this "orphan" transit, but with only one event measured, the parameter space is too unconstrained to place confidence in the planet hypothesis – though we note that dynamically there is plenty of room between planets b and c for a third planet.

Kepler-47 is significant because it establishes that planetary *systems* (not just single planets) can form *and persist* in the chaotic environment close to a binary star. The binary stars tend to augment planet-planet interactions (Youdin *et al.* 2012), so planetary orbits that lie close to the binary are highly susceptible to dynamical instability. And Kepler-47c shows that circumbinary planets can exist in the habitable zones around their host stars, opening up new habitats for life to potentially exist.

4. The Developing Circumbinary Planet Picture

The stars in Kepler-16 have an eccentricity of 0.159 and star A is 3.4 times the mass of star B. This sizable mass ratio means star A orbits relatively close to the barycenter of the binary. When only Kepler-16 was known, one might have speculated that these stars are in a particularly benign configuration for planet formation and migration. But Kepler-34 and 35 quickly refuted that notion because the stars are close to equal mass

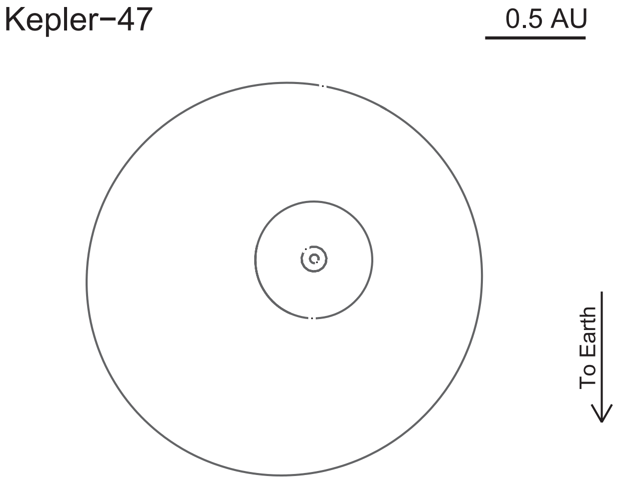

Figure 4. Bird's eye view of the binary and planetary orbits for Kepler-47. The small gaps in the orbit curves show the location of the bodies at this particular epoch.

(ratio A/B is 1.03 and 1.10 respectively), and so both stars orbit the barycenter nearly equally. Furthermore, Kepler-34 A and B have highly eccentric orbits (e=0.521) and their interaction with the planet is strong enough to produce a noticeable deviation from a Keplerian solution even after just one period. It is now clear that there is a wide range of stellar configurations for which circumbinary planets can exist. Primary star masses range from 0.69 to 1.53 $M_\odot$ (Kepler-16 A & PH1 Aa), mass ratios from 1.03 to 3.76 (Kepler-34 & PH1), and eccentricity from 0.023 to 0.521 (Kepler-47 & Kepler-34). Likewise, the planetary orbits have a sizeable spread in eccentricities, ranging from nearly circular e=0.007 to a significant e=0.182 (Kepler-16 & Kepler-34). There is no tendency for orbital resonances with the binary. It is clear that no special geometry is favored, with two notable exceptions: co-planarity and close-in orbits.

All seven *Kepler* circumbinary planets orbit their stars very close to the plane of the binary (in a prograde direction). And in cases where the stellar spin axis has been measured (Kepler 16 and 47; and possibly PH1 based on the match between the observed and expected $V_{rot} \sin i$), the spin axes are closely aligned with the binary axis. While tidal forces act to align the spin axes with the orbital axis (e.g. see Winn, *et al.* 2011), the planet and stellar orbital co-planarity suggests that a single-disk formation and migration scenario is likely.

The propensity of circumbinary planets to orbit close to their host stars has been noted since the discovery of Kepler-16. The (inner) planets orbit surprisingly close to the boundary where dynamical instabilities due to perturbations from the binary can be present (Holman & Wiegert 1999). The observed circumbinary planets have semi-major axes that lie between 1.09 and 1.46 times the critical radius. The reason for this is unclear. Migration might become inefficient near the critical radius, leaving planets just outside this radius. Or migration may operate normally but any planets within the critical radius are lost, leaving only those at larger radii. Or this is just an observational bias - the closer in the planet, the more likely it will transit the stars. Another interesting observation is that the circumbinary planets tend *not* to exist around the shorter period *Kepler* eclipsing binaries. The shortest period *Kepler* eclipsing binary hosting a planet is 7.44 d (Kepler-47; the longest is Kepler-16 with a binary period of 41 d). While a strong observational bias against detecting long period planets is present, the opposite is true for short period binaries (assuming the tendency for the planet to orbit near the critical radius continues to hold). And in addition to the geometrical factors, the shorter period binaries allow shorter period planets, so more transits should be present in the *Kepler* data allowing easier detection. The majority of *Kepler* eclipsing binaries have periods less than 1 day. Since these short-period binaries are unlikely to have formed in such a tight orbit, their lack of planets may be related to the mechanism that removed angular momentum and allowed the stars to orbit so closely. The apparent lack of circumbinary planets around short-period binaries is worthy of investigation.

An interesting characteristic of the circumbinary planets is that all eight have a size (mass and/or radius) smaller than Jupiter. Since a larger-size planet is more likely to be found than a smaller planet, this cannot be a selection effect. Pierens & Nelson (2008) predicted such a tendency, based on simulations of the orbital evolution of planets embedded in a circumbinary disk. This certainly deserves attention, especially if the trend continues as more circumbinary planets are discovered.

Finally, the tendency for the observed circumbinary planets to lie close to their critical radius has an interesting consequence for habitability. The stability criterion requires the planet to orbit outside roughly ∼2-4 times the binary semi-major axis, or periods ∼3-8 times the binary period. The known circumbinary planets have binaries with periods roughly around ∼10-40 days, so the planets will have periods a bit larger than ∼30-320 days. Since the *Kepler* targets are mostly G and K type stars, this orbital period is rather close to the habitable zone (HZ) around the binary. The first *Kepler* circumbinary planet discovered was just exterior to its HZ and thus too cold, while the second circumbinary planet discovered was slightly too hot. While extrapolating from two cases is inherently foolish, such sophistry did bear fruit with Kepler-47c – it is quite remarkable that it only took the discovery of five circumbinary systems to find a planet squarely in the HZ. Table 1 lists all the known transiting circumbinary planets as of 2012, with some of their characteristics related to the HZ. Of course none of the planets are terrestrial, but large moons of planets in the HZ would be very interesting. As the *Kepler* data are searched with better methods, smaller circumbinary planets will be teased from the data, and it will not be surprising to find an Earth-like circumbinary planet in the HZ. Because of the stellar binarity, the insolation received by the planet will likely be time-varying in an interesting way, quite unlike the steady insolation Earth receives from the Sun. The observational study of "tatooines" has just begun, and already we have found a system with at least two planets, a planet in the HZ, systems with rich dynamics, clues on planet and star formation/migration, and of course, abundant puzzles to nourish the human mind.

Table 1. Kepler Transiting Circumbinary Planets

Planet	$P_{\rm planet}$ (days)	$P/P_{\rm crit}$ for (in)stability	Insolation <S> (Sun-Earth)	$T_{\rm equilibrium}$[1]	Habitable Zone proximity
Kepler 16 b	229	1.14	0.3	180 K / -93 C	little too cold[2]
Kepler-34 b	289	1.21	2.4	312 K / 39 C	little too hot
Kepler-35 b	131	1.24	3.6	345 K / 72 C	too hot
Kepler-38 b	105	1.42	12.8	475 K / 202 C	way too hot
Kepler-47 b	49.5	1.77	9.6	442 K / 169 C	way too hot
Kepler-47 c	303	10.8	0.88	243 K / -30 C	Goldilocks!
PH1-b	138	1.29	10.6	454 K / 180 C	way too hot

[1] Assuming a Bond albedo of $A_B = 0.34$. [2] But it does lie in the *extended* HZ.

Acknowledgments

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