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Fortnightly residence schedules for Kepler-34 b and Kepler-35 b

Iona E. Veyranel

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Residential calendars record the nights spent with each of two hosts. We construct such calendars for Kepler-34 b and Kepler-35 b from three-body integrations initialized with the discovery solutions. Each planet is assigned to the nearer star or, in a separate calculation, to the star supplying most of the incident Kepler-band light. By proximity the secondaries receive 53.14% and 50.33% of the term, respectively. For Kepler-34 B the light criterion gives 39.60%. We test whether its share can be taken as a regular two-day stay every fortnight. A fixed pair of dates can be honored in at most 39 of 104 fortnights. Letting the dates vary admits a stay in 72 to 79 fortnights, depending on the clock offset. Kepler-35 B achieves a flux majority only during eclipses. Its 59 intervals of residence include 7 to 15 registered overnights and no complete day. The distinction between nightly credit and an uninterrupted stay persists over the reported uncertainty in the relative node.

I. INTRODUCTION

Residential calendars for two households can have the same number of nights at each address and quite different intervals between exchanges. In the survey of [1], the lengths of stays and the number of transitions were recorded separately. One common summary is a binary classification. If each host accounts for at least 40% of the nights, the residence is classed as shared [2]. That statistic gives little information about the feasibility of a recurring weekend.

We use the calendar to describe residence in a circumbinary system. A night's entry is the identity of one star. We consider two kinds of evidence for an entry. From the three-dimensional orbit one can establish which star was closer to the planet. Given the stellar light ratio, the same orbit yields the identity of the star that provided most of the incident light. Unlike the distance ordering, this assignment can change within a stellar eclipse. The relevant eclipse geometry is the one seen from the planet.

Kepler-34 b and Kepler-35 b were characterized in the same discovery study [3]. In both systems the stellar masses are similar. The components of Kepler-34 also have comparable surface temperatures and radii, whereas Kepler-35 B supplies only 39% as much Kepler-band light as A at equal distance. We calculate the overnight share in each system and then try to place a recurring 48 h stay at the secondary within the measured intervals. In a system with residence concentrated near conjunction, the latter requirement can constrain the schedule even when the overnight share is large.

II. ORBITS AND ALLOCATION RULES

We start each system at its own reference epoch, BJD 2454969.20 for Kepler-34 and 2454965.85 for Kepler-35. The integrations use the central entries in Supplementary Tables 1 and 2 of [3]. Selected inputs are in Table I. We take the argument of periapse from the tabulated sine and cosine components of the eccentricity vector and its magnitude from the eccentricity entry. For each orbit the initial mean anomaly is the tabulated mean longitude less the argument of periapse. The inner displacement runs from A to B. The outer displacement runs from their center of mass to the planet.

TABLE I. Adopted binary and planetary parameters. The two semimajor axes are Jacobi elements. The light ratio is for unobscured stars at equal distance.

Quantity	Kepler-34	Kepler-35
Mass of A ($M_\odot$)	1.0479	0.8877
Mass of B ($M_\odot$)	1.0208	0.8094
Radius of A ($R_\odot$)	1.1618	1.0284
Radius of B ($R_\odot$)	1.0927	0.7861
Inner semimajor axis (au)	0.22882	0.17617
Outer semimajor axis (au)	1.0896	0.60347
Inner eccentricity	0.52087	0.1421
Outer eccentricity	0.182	0.042
Kepler light ratio, q	0.8475	0.3941

We convert the initial Jacobi elements to Cartesian positions and velocities and advance the three Newtonian point masses by fourth-order Runge–Kutta steps for 1,460 days. We retain the published relative nodes and inclinations. A pair of fixed ellipses would miss forced oscillations of the planetary orbit [4]. The term is long enough to contain about 47 and 59 synodic cycles respectively. It is a calculation from rounded elements, with no refit to the transit times.

Let d_A and d_B denote distances from the planet. The proximity rule assigns B the interval when $d_B < d_A$. In clear view the ratio of incident fluxes is

$$Q = q(d_A/d_B)^2. \tag{1}$$

A clear-view assignment to B requires $d_A/d_B > q^{-1/2}$, or 1.086 in Kepler-34 and 1.593 in Kepler-35. We use the integrated light ratio in the Kepler band throughout. Applying a bolometric correction would define a different residence criterion.

During an eclipse we multiply each star's flux by its visible fraction. At the planet we place two circles of angular radii $\arcsin(R_i/d_i)$ at the angular separation of the stellar centers. The nearer disk remains visible. For the farther disk we subtract the area of the common lens from its apparent area, using a flat tangent plane and uniform surface brightness [5]. This prescription also covers an annular eclipse. For the limb-darkening check we divide the rear disk into 64 annuli and weight each occulted area by the intensity at the annulus midpoint, with the coefficients from [3]. The detector is at the center of the planet and responds to either star anywhere on the sky.

A. The overnight ledger

We record the assignment every 7.5 min, including the initial instant and excluding the far endpoint. A visit is a contiguous run of assignments to B. We omit a visit cut by either end of the integration when reporting durations. For the night count we keep both ends of every night's 24 h accounting interval within the term and sample at a fixed offset ϕ from its start. If I_B is one when B holds the planet and zero otherwise, its credited nights are

$$N_B(\phi) = \sum_{j=0}^{1459} I_B(jD + \phi), \qquad D = 1\ \mathrm{d}. \tag{2}$$

The day in Eq. (2) is an Earth day. No rotation period or surface longitude enters the ledger. Each of the 192 possible clock offsets on the calculation grid uses precisely the same orbit. Averaging their counts recovers the integrated time in days, since every time sample occurs in exactly one ledger. We also count visits in which B retains the planet for at least one full day. This last count concerns the length of a stay and does not depend on the registration of midnight.

B. Fortnightly schedule

We divide the first 1,456 days after a clock offset into 104 fortnights. The remaining time at the ends is discarded. A two-day stay must cover all 384 samples of a 48 h interval. Both dates must belong to the same fortnight. For a standing arrangement we choose one of the 13 eligible start dates and use it in all 104 blocks. For an arrangement made one fortnight at a time, any eligible start date is admissible. A third tally requires that each star can accommodate a two-day stay within the same block. The two stays necessarily occupy disjoint intervals. We repeat all three counts at the 192 clock offsets used for the nightly ledger.

III. RESULTS

By distance both systems fall inside the shared-residence interval (Table II). Kepler-35 B is the closer star for 734.8 days, of which 723.7 are assigned to A by flux. The maximum clear-view ratio is $Q = 0.770$. At that distance ratio B needs at least 23% of the light from A to be occulted before the assignment can reverse. Fig. 1 shows the first reversal. B supplies 40.5% of the unobscured flux near the center of this event.

TABLE II. Allocation to star B during 1,460 days. Night ranges run over the 192 clock offsets. Visit statistics use visible flux and count complete visits only.

Assignment to B	Kepler-34	Kepler-35
Nearer, % of time	53.14	50.33
Brighter, clear view, %	39.60	0.00
Brighter, eclipses included, %	39.60	0.76
Nights by proximity	771–783	728–741
Nights by visible flux	574–582	7–15
Completed visits	47	59
Median duration (h)	325	4.0
Visits lasting at least 24 h	47	0

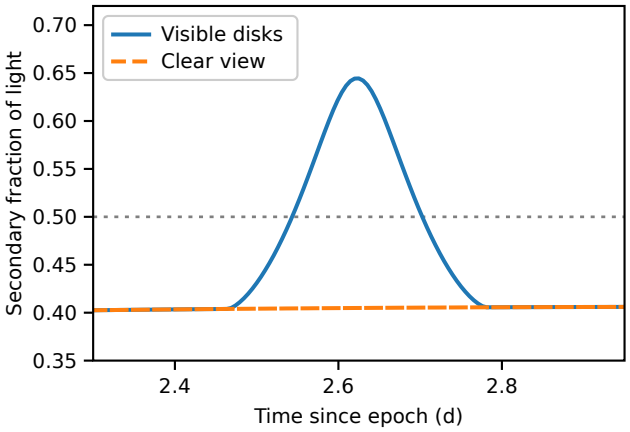


FIG. 1. Kepler-35 B's fraction of the light incident on the planet during its first visit. The dashed curve restores the portion of A hidden by B. Time is measured from BJD 2454965.85. The ledger changes hands at a fraction of 0.5.

For Kepler-34 the clear-view ratio reaches 1.585. Of its 47 complete visits the shortest lasts 2.49 days and the longest 20.81 days. Allowing for the overlap of stellar disks changes none of the sampled assignments. In

this system the handovers can be reconstructed from the two distances and the unobscured light ratio.

The 59 visits of Kepler-35 B sum to 11.11 days. Individual stays range from 3.1 to 7.1 h. Depending on the clock origin, seven to fifteen of these cross midnight (Fig. 2). The other visits occur entirely within a calendar date. None qualifies as a full day. The upper count of fifteen occurs for only one of the 192 clock settings.

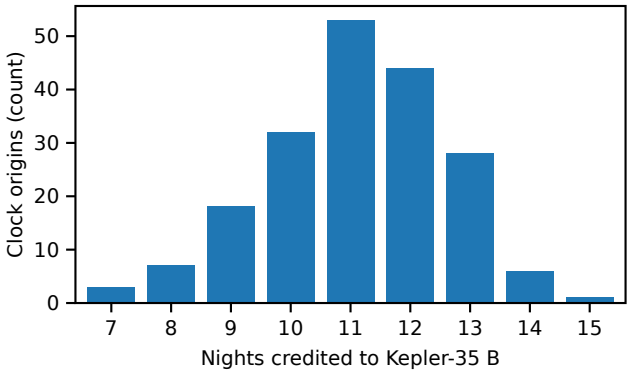


FIG. 2. Number of clock origins yielding each overnight count for Kepler-35 B. The 192 origins uniformly divide one Earth day. The mean count is 11.11.

A. Recurrence of two-day stays

In Kepler-34 the shortest complete interval at B is nearly two and a half days. This ensures time for a visit but does not fix its date. At zero clock offset, a standing reservation on days 1 and 2 can be used 37 times in 104 fortnights. Moving the reservation to days 5 and 6 reduces this to 30. The counts for all 13 choices are shown in Fig. 3. The synodic period is about 31 days, so the exchange times drift relative to the 14-day calendar. A recurring slot samples intervals at both stars over the term.

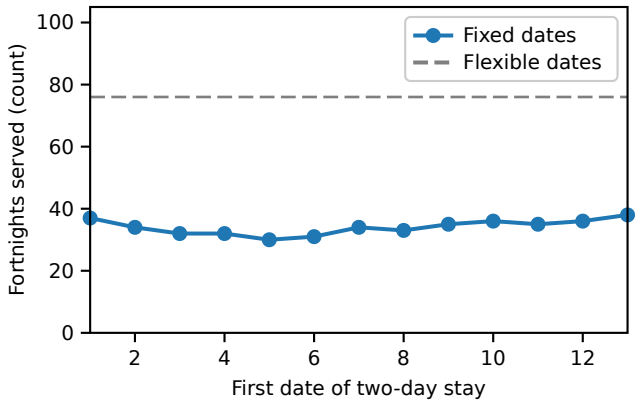


FIG. 3. Number of fulfilled two-day reservations at Kepler-34 B in 104 fortnights, at zero clock offset. The horizontal coordinate is the first of two consecutive dates. The dashed line gives the number of fortnights with a usable pair when dates can be chosen separately in each block.

Allowing a separate choice of dates in each fortnight gives B 76 usable blocks at zero offset. Only 61 of these can also accommodate two days at A. The remaining 15 have a two-day opening at B but lack a corresponding opening at A. Over clock offsets the number of flexible reservations at B ranges from 72 to 79. For a standing reservation the range over offsets and start dates is 30 to 39. Thus even the most favorable standing reservation leaves 65 fortnights to be rescheduled or forgone. For Kepler-35 the entries for either form of reservation are all zero.

IV. SENSITIVITY TO THE ORBITAL AND FLUX PARAMETERS

At the 40% threshold a host needs 584 of the 1,460 nights. Kepler-34 B is two short even on its best clock. This decision is sensitive to the light ratio. Changing q alone to its reported lower and upper limits (0.8399 and 0.8585) takes the time share from 38.78% to 40.75%. At the upper limit at least one clock must therefore credit the secondary with enough nights. The discovery photometry therefore does not resolve the shared-residence classification for this pair.

In Kepler-35 the orientation of the planetary orbit is the more material uncertainty. Moving its relative node from the nominal -1.24° to -1.57° or -1.00° changes the eclipse chords seen from the planet. The credited time becomes 0.63% or 0.82%, respectively. Neither endpoint produces a full-day visit. Moving only the light ratio between 0.3931 and 0.3952 gives 0.759% to 0.762%. At nominal geometry limb darkening gives 0.753%, compared with 0.761% for uniform disks. The secondary's own surface brightness does not change its integrated light during its visit. It is the brightness distribution across the primary, behind it, that matters.

These are one-parameter recalculations. Marginal medians need not constitute a single draw from the original fit, and the range from changing the node alone is not a joint credible interval. Repeating the nominal orbit integrations at 15 min changes the visible-flux time shares by less than 0.003 percentage points and recovers the same number of complete visits in each system. A longer integration would sample other orientations of the planetary apsides. The tally applies to the specified four-year term.

V. DISCUSSION

The schedule for Kepler-34 depends on two timescales. The relative angular motion sets the recurrence of a visit. The interval in which the secondary provides a majority of the light sets the permissible length of the visit. A change to the flux ratio can move the secondary across the threshold for shared residence. It cannot bring the synodic and fortnightly periods into register. The choice left to the calendar is whether to keep the exchange dates fixed or to preserve the number of stays.

For Kepler-35 the finite angular sizes of the stars determine whether there is any radiative residence at B at all. A calculation that masks eclipses, as one might do to study modulation with orbital phase, would give B zero nights. Including them gives a series of stays shorter than an Earth day. A residential calendar for this system needs separate fields for the number of nights credited and the longest continuous stay. A single date entered against the secondary cannot establish that it had the planet the following morning.

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[5] K. Mandel and E. Agol, Astrophysical Journal Letters **580**, L171 (2002).