GROUND-BASED PHOTOMETRIC DETECTION OF EXTRASOLAR PLANETS

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Abstract

The discovery of terrestrial-sized extrasolar planets around main-sequences stars is currently possible from the ground for several sub-solar, small-radii eclipsing binary systems. Terrestrial planets in these systems should form in the binary orbital plane, and are likely to have periods significantly smaller than those of the terrestrial planets in the Solar System, and hence, should be more easily detectable. Our observations of the CM Draconis system indicate that such detections are indeed possible, especially when the photometric data (differential light curve) can be correlated with possible planetary orbital models of the quasi-periodic signal expected (i.e. a matched-filter implementation). The importance of the discovery of the first habitable planets, and follow-up observations for the detection of exobiology are outlined. In addition, non-transiting jovian-mass planets in such systems can also be detected by precisely timing the binary eclipse minima. Our preliminary observations of ten such systems have demonstrated the feasibility of this detection method. Over two hundred such systems could be surveyed for jovian-mass planets, providing a statistically meaningful sample for understanding the formation of giant planets around close double stars, thus complimenting our main objective: the detection of habitable-sized planets.

1. Detection of Terrestrial-Sized Planets

The detection of habitable-sized (i.e. terrestrial-like) planets is presently considered to be decades in the future, according to the recent scientific literature. Yet detection from the ground of planets closer in size to Earth than to Neptune has been shown to be presently possible for a special class of stars – small eclipsing binary systems [1], [2], [3].

Various extrasolar planetary detection methods are being pursued [4], but — aside from the gravitational lens method, which cannot follow up on any detections — the only method presently capable of detecting terrestrial-sized planets around habitable (i.e. main sequence) stars is the photometric method [5], [6]. The method has typically, however, been statistically limited in that it relies on the (1% random) probability of a planetary orbit lying along the observer's line-of-sight, so that a photometric drop in the star's brightness may be detected due to a planetary transit. Two approaches have recently been suggested to mitigate these statistical limitations. The first is to observe hundreds of thousands of stars, of which 1% should show transits (the *Kepler Mission*)

[7]. However, this will require a space-based telescope as the required photometric precision will be about two parts in 10^5 for detection of an Earth-sized planet in transit across a solar-sized single star.

A second approach presented in this paper to mitigate the effects of the statistical unlikelihood of planetary transits is to preselect systems that are already known to be edge-on, namely eclipsing binary systems [8]. Can planets be expected to form in the binary orbital plane? Preliminary observational evidence indicates that this is the case [9]. In addition, close double stars will cause a precession of externally orbiting material such that the varying precession rates of protoplanetary material with orbital distance should add a further damping effect to the formation of planets in the plane of the binary orbit [10]. This is in addition to the usual conservation of angular momentum process that can be expected to form a protoplanetary disc [3]. Thus, eclipsing binaries should be good starting candidates for such photometric planet searches. Addressing the question as to whether planets might form in double star systems (of significant importance since likely half the stars in the Galaxy are binaries), orbital simulations suggest that stable orbits should exist if the axis ratio of the planet's orbit is at least four times the binary separation [11]. The recent detection of a giant planet around a single member of the binary pair 16 Cygni is indicative, although the planet has a very high eccentricity [12]. But of more importance for consideration here is the discovery of a β Pictoris-type disc surrounding the close binary pair BD +31°643 [13].

The next question concerns the photometric precision required to detect terrestrial-sized extrasolar planets. We will assume an arbitrary definition of a terrestrial-sized planet here as one closer in disc area to Earth than to Neptune, i.e. less than about 2.8 Earth-radii. As stated, the photometric precision required is about two parts in 10^5 for a one-Earth-radius planet to be detected transiting a star with the disc area of the Sun. The limit to typical ground-based photometry seems to be about one part in 10^3 [14], although this photometric limit (imposed by atmospheric scintillation) can apparently be pushed to 0.67 parts in 10^4 with larger telescopes [15]. The clearest way to detect smaller planets, then, is to observe smaller stars,— the smaller their disc areas, the larger the differential attenuation due to a transiting planet will be.

2. The CM Draconis System

The smallest known eclipsing binary is CM Draconis which consists of two M4 main-sequence stars [16]. We shall base our discussion here primarily on this star upon which most of our observing has been performed to date. Other candidates, however, for the general application of this method are, for example, the recently characterized star BW3 V38 (an eclipsing binary composed of two M3 main-sequence stars [17]), YY Geminorum (an eclipsing pair of M0 stars), and RW Doradus (an M1 and K2 eclipsing pair), among others [18], [3]. The two stellar disc areas of CM Draconis together are only 12% the disc area of the Sun, immediately allowing detection of planets with disk areas an order of magnitude smaller than for a single solar-sized star. A single transit of a 2.8-Earth-radii planet across the CM Draconis disc would therefore cause an 0.6% drop in the stellar brightness, easily detectable with usual aperture photometry [1]. But how can we detect planets with transit signatures smaller than the precision of the photometry? To examine this we first should look at transit occurrences.

In spite of initial model predictions [19], giant planets, at least, seem to be found at widely varying distances from their primary stars, including very close (the 51-Pegasi-type planets being the closest announced [20], [21]. Nevertheless, since our Solar System is the only system of planets presently known (with the exception of the pulsar planets [22]), we will take the Solar System as a typical working model. The CM Draconis system has a total luminosity only about one-hundredth that of the Sun. If planet formation locale is comparable to the thermal regime in which the Solar System formed [23], then any terrestrial-type planets would be expected to have formed around the CM Draconis system with periods of as little as one week (Venus insolation planet) to one month (Mars insolation planet). Modeling of possible planetary transits should perhaps, then, start with such short-period orbits.

Such inner planets should transit across the line of sight of the two components of the eclipsing binary, causing a drop in the brightness of the star dependent on the phase of the binary, i.e., its configuration at the time the planet passes across each component [24], [2]. We can see that such transits will consequently be not periodic but rather quasi-periodic. This implies that these transits might be modeled and separated from starspot noise, atmospheric scintillation, etc. by using a matched-filter approach, i.e., by generating all possible transit signature models and cross-correlating our light curve with these models. This has been done where white Gaussian noise was assumed, indicating that sub-noise signals can, indeed, be detected with a sufficient number of observations [2]. (We will see however, below, that our noise is not really white, but over the range of transit signatures of interest can nevertheless be separated from our observational noise.) Thus for these detections one is not so much limited by atmospheric scintillation as by the amount of "co-addable" transit events one has, i.e., the amount of photometric data.

In order to catch every transit possible (and to be able to rule out planets by non-detections) coauthor Doyle (along with Dr. J. Schneider of Observatoire de Meudon and coauthor Deeg) has set up and directs an international network of 1-meter-class telescopes, called the TEP (Transit of Extrasolar Planets) Network. We have had participants at observatories in California, Korea, Russia, Crete, France, Canary Islands, New York, New Mexico, and Arizona [25], [3]. To date we have collected a sufficient amount of photometric data from CM Draconis to begin to limit the periods of any sub-Neptune-sized planets that may exist there as well as to characterize the observational sources of error. Figure 1 shows a sample of the phase light curve of CM Draconis obtained at U.C. Lick Observatory on the Crossley 0.9-meter telescope. Our photometric precision has ranged from about 0.2% on the best nights to a bit better than 0.7% on more marginal nights, all of which are shown in Figure 1 (where flares and sunspots have not yet been removed). Our mean photometry for all the data to date is approximately 0.45% [1].

(Figure 1 Here)

Each point in Figure 1 is a CCD image of the CM Draconis star field in which nine comparison stars are used, with the sum of these fainter stars representing the "standard" star which is subtracted from CM Draconis to obtain the differential magnitude (after performing the usual photometric corrections of dark subtraction, flat fielding, aperture size definition, conversion of timeline to Heliocentric Julian Day, etc.). We have obtained more than a sufficient number of points to well characterize the binary system parameters, but the size of the sub-noise signals that can be detected is proportional to the amount of photometric data obtained, and its quality. Presently we can constrain the absence of any 3-Earth-Radii planets in the system with a period of 30 days or less, in the binary orbital plane.

3. Detectability of Transits in the CM Draconis System

Whether or not the transits of a terrestrial planet in the CM Draconis system can be detected in our data is a question of the quality of the photometry, and the data coverage. To maximize the chances for detecting small planets, we classified our data obtained to date into two categories: 1) those nights with photometric precision better than 0.4% and with no gaps longer than 1.5 hours, and 2) those nights failing to satisfy the criteria of 1). For the following analysis, we consider only the portion of data in the former category, which will be called "Class I" data. These data have a mean photometric precision of 0.3%, but comprise only 33% of the total data obtained over three years of observing, from 1994 through 1996.

(Figure 2 Here)

Figure 2 shows a power spectral density estimate (PSD) for the Class I data (i.e. Lomb periodogram for unevenly sampled data [26]). For comparison, the Lomb periodogram of a modeled 1.5-hr transit by a 2-R_e planet is shown by the stippled curve. (Note that the vertical units are arbitrary.) The effects of extinction corrections, which block power at frequencies <5 day^{-1} in both curves, can be observed. Although the PSD's are both "red" above the extinction cut-off frequency, the transit spectrum is more highly confined in frequency, dropping off much more rapidly above 15 day^{-1} than the Class I data spectrum. This indicates that while the observation noise has appreciable power in the bandwidth containing the peak transit power, the two waveforms are separable in frequency. We note that the peak power for shorter transits would be shifted to higher frequencies relative to the transit PSD given here. The phase-behavior of typical planetary transit signals is also characteristically different from the photometric "noise" of our observations (noise including starspots, flares, atmospheric scintillation, etc.), with most noise sources varying over timescales much longer than, or much shorter than transits.

(Figure 3 Here)

In order to assess the detectability of planetary transit signatures in the Class I data, we cross-correlated the data with 36,000 models of planetary transits for planets with orbital periods between 10 and 30 days and a range of orbital phases between 0° and 360°. Though not a complete planetary "search", this exercise was sufficient to reach the present goal. In the language of detection theory, each cross-correlation value is a "detection statistic", normalized by the standard deviation of the observed data set. In addition, we determined the detection statistics that would have arisen if there actually were 2-R_e planets in the data at each chosen period/phase combination. Figure 3 illustrates the result, showing that 50% of the time, the detection statistic for a planet twice the size of Earth transiting CM Draconis would be above the detection statistics generated from the Class I data. A 3-Re planet would produce a detection statistic above the maximum observed statistic 90% of the time. Thus, we can rule out 3-Re planets showing transits in the Class I data set at the 90% confidence level. We cannot, however, rule out transiting 3-Re planets entirely, however, as the entire phase space has not been observed by this data set.

Figure 4 shows the fraction of transiting planets observable in the Class I data set as a function of orbital period, demonstrating that we would have observed the majority of possible transiting planets with periods less than 30 days in the Class I data from 1994-1996. A full search must await the completion of the photometric analysis of the 1997 observations. We have demonstrated, however, that ground-based photometry can place strong constraints on the size of possible planets in an extrasolar planetary system.

(Figure 4 Here)

4. Followup Observations

The detection of habitable-sized planets in the habitable zone of selected stars—small eclipsing binaries—is possible using 1-meter-class telescopes over a matter of months at commonly-obtained photometric precision [1]. This has been shown to be the case for CM Draconis,— BW3 V38, YY Geminorum, and RW Doradus being additional candidates. For even larger systems, longer observing times (due, in part, to possible longer terrestrial planet orbital periods) with larger telescopes will be necessary. The importance of the detection of such habitable planets can scarcely be overstated. A planet of the right size with the correct insolation could begin to provide a fundamental test of the assumption that, given the conditions for liquid water and organic molecules, biology will result. (Examination of habitable zones around M dwarf stars has been discussed elsewhere [27], [28]) Though perhaps difficult, followup observations to detect spectral lines associated with molecules present only if photosynthesis is taking place on a large scale would be exceedingly valuable. The 7600Å O_2 or the 9.6μm O_3 lines, for example, might be very good candidates for detection of biological influences in a habitable planet's atmosphere [29]. For the CM Draconis system these spectral lines would also be on the wings of the Earth's atmospheric lines as the radial velocity of CM Draconis is about -119 km/sec). These observational efforts might be considered the first step in laying the groundwork for such space missions as the *Kepler Mission* and the *Terrestrial Planet Finder*.

5. Detection of Jovian-Mass Planets

Judging from the aforementioned extrasolar planet discovered orbiting 16 Cygni B [12], and β Pictoris-like protoplanetary disc imaged around the close binary BD +31°643 [13], it appears that planets are able to form in binary star systems. While planets can coalesce around individual stars (although they might have a high eccentricity in wide binaries, as mentioned), one might ask, for example, if the inner portion of the circumstellar disc around BD +31°643 has indeed been able to form planets. The answer to this question—do giant planets form around close binary systems?— can also be answered today for a significant number of close binary systems using 1-meter-class telescopes. This is mainly due to the fairly recent establishment of the very high precision GPS (Global Positioning System) satellites and subsequent general availability of millisecond timing chips for data recording. This method for giant planet detection should allow a determination of the presence (or absence) of giant planets in a couple of hundred close binary systems [30], [1], [3]. The method is a new application of an older technique and works as follows [31].

A well established technique for the detection of a third mass in orbit around shorter-period eclipsing binary systems has been to detect a periodic drift in the *O-C* (observed minus calculated model) residuals for the times of eclipse minima (that is, the eclipses will occur somewhat earlier or later than expected with a regular periodicity in the epoch or time of eclipse). Although there are various processes that could alter the eclipse times of close binaries [30], the periodicity produced by a third body can be uniquely identified. The magnitude of such a drift in the eclipse minimum (due to the system offset about the binary/giant-planet barycenter and consequent periodic increase or decrease in light travel time) will have a total magnitude δT of:

$$\delta T = 2M_p a / cM_* \tag{1}$$

where M_p is the planet's mass, a is the planetary orbital semi-major axis, c is the speed of light, and M_* is the total stellar mass (both components) of the eclipsing binary system. This, of course, will occur every half-period of the planet's orbit and be most pronounced when the planet is at elongation (i.e. near maximum radial velocity). The precision of the GPS timing is, of course, known to be well within milliseconds. But which binary and giant planet mass ranges, and planetary semi-major axes will allow measurable results? We can, as a reasonable first look, take the eclipsing binary catalogue of Brancewicz and Dworak [18]. (Most masses in this catalogue have been determined only theoretically, but taken as a whole the catalogue should be roughly indicative of the number of small-mass eclipsing binary systems available). We further conservatively assume that if the secondary companions' masses in this catalogue are unknown, they are equal to the primary's mass. Finally, we take the hypothetical giant planets' orbital semi-major axes to be 5.2 AU from their parent binary barycenter, (i.e. the Sun-Jupiter distance). Such planets should certainly be stable [11].

Constraining the detectability to a total periodic drift (δT) of at least 2 seconds in amplitude for a one jovian-mass planet around each binary system we nevertheless have found that over 250 such systems would qualify (a complete listing is available from the authors). Of course, many of the new giant planets discovered are substantially more than one jovian mass [20]. We recognize also that if the planetary semi-major axis is too close to the binary system, the drift will occur more often, but the offset amplitude would not, for example, be sufficient to detect the planet. This method will not detect the 51 Pegasi-type planets that appear to occur about 3% of the time for main sequence, solar-like stars.) Thus the existence (or absence; the effect must take place) of such planets around many small-mass eclipsing binaries, however, is determinable.

Recognizing, in general, that the timing uncertainty is inversely proportional to the number of samples obtained for a particular eclipse, and proportional to the period, sampling times, and precision of the photometry, the following equation for the timing uncertainty will hold for reasonable sampling periods [30]:

$$\delta t \approx 53\sigma_p P_* \sqrt{T_s / n} \tag{2}$$

where P_* is the binary period, T_s is the sampling period in seconds, n is the number of observed eclipse minima, and σ_p is the photometric precision. Again, since we assume white Gaussian noise, this equation is only approximate. (Star spots and flares will, for example, undoubtedly ensure that the noise is not white, and we know that the real noise of our observations is actually slightly red, as shown by Doyle [1].) Flares are relatively short, however, and can be removed from the light curve. Star spots will exhibit a period consistent with that of the close binary system as these systems are close enough to be tidally locked in rotation. This equation, then, provides a reasonable estimate for the accuracy to be achieved in our eclipse timing.

We have discussed complicating sources of period change in eclipsing binaries, including starspots, mass transfer, mass loss, stellar oscillations, microflares, apsidal motion, and relativistic effects elsewhere [30]. However, most of these effects are not periodic, or have periods very much longer than the ones we are proposing to detect. The exception might be mass transfer, but of the binaries we have so far considered (Table I) only three fill their Roche lobes such that mass transfer can take place. However, once again, over the times we are considering, such a mechanism is unlikely to be periodic.

(Figure 5 Here)

As mentioned, we analyze each image using aperture photometry. The brightness of the eclipsing binary is differenced with the sum of the brightnesses of select field stars. (Catalogued standard stars are not needed for our differential photometry in this case, but we do monitor the brightness variations of each field star to ensure that we can exclude any variables; in addition to atmospheric extinction corrections, etc.) We then converted the GPS-recorded time at which each image was taken to heliocentric Julian Day time, and thereby have a calibrated light curve, an example of which is given in Figure 5 (for a secondary eclipse event of the smallest star in our sample, CM Draconis). The precision of our photometry in each case is, again, better than 1%.

Altogether we have taken data on 10 small-mass eclipsing binaries to date and the data are summarized in the Table I, where the variable star name is given, the binary period in days, the total amplitude of the eclipse minima timing offsets (δT, as given above) expected for a 1.0-jovian-mass planet at 5.2 A.U. from its star, the total number of eclipses (n) that we have observed for each system, and the calculated precision (δt) of our eclipse minimum determination for that star—conservatively taking the upper limit of our photometric precision to be exactly 1%.

(Table I Here)

Clearly, for the first six systems, we have already been able to constrain their epochs of eclipse minima to within the total offsets expected by a jovian planet if the hypothetical planet has been moving away or toward our line-of-sight at this time. For the next three, the minimum mass ($M_p \sin i$, where i is the planetary orbital inclination) detection limit would be about 1.3 Jupiter masses (the offset scales directly with the planet's mass). And finally, the last would constrain a minimum 2.6 jovian-mass planet in the system, still on the order of the minimum mass range of the state-of-the-art radial velocity techniques so successful to date. It should be emphasized, again, that non-detections are also essentially conclusive, as the presence of any jovian planets around these binary star systems must periodically offset the times of eclipse minima. We await this year's measurement reductions to see if periodicities emerge.

The present successful radial velocity searches for extrasolar giant planets of necessity have excluded close binary systems from their determinations as they complicate the spectra significantly. Here we outline a way in which the prevalence (or absence) of giant planets around such close binary systems may be determined. In addition, a statistically significant number of target stars (over 200) may be observed for such extrasolar planets, with non-detections (although not as exciting as detections) also informing us about giant planet formation around such systems. In the case of planet formation around eclipsing binaries, even giant planets may be expected to form close to the binary orbital plane [3] so that detected planetary systems (with known orbital periods and orbital phases) might continue to be monitored for transits, as well, giving planetary radii. We emphasize that any such transiting planets would also make promising candidates for detection of planetary atmospheric lines.

Thus we may be able photometrically to find both close terrestrial-like planets as well as more distant giant planets with the same type of data — a complete Solar System detection technique.

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FIGURE CAPTIONS

Figure 1. CM Draconis photometry at Lick Observatory

Figure 2. Power spectral densities (in arbitrary units) for class I data from 1994-1996, and for a 1.5-hr transit.

Figure 3. Detection statistic distributions for the class I data from 1994-1996, and for hypothetical 2-R_e planets in these data.

Figure 4. Fraction of observable planets as a function of orbital period for class I data from 1994-1996.

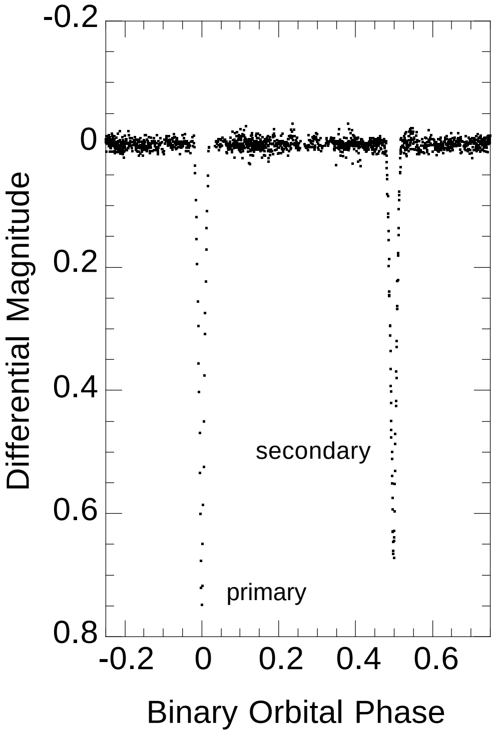
Figure 5. Typical secondary eclipse of CM Draconis

TABLE CAPTIONS

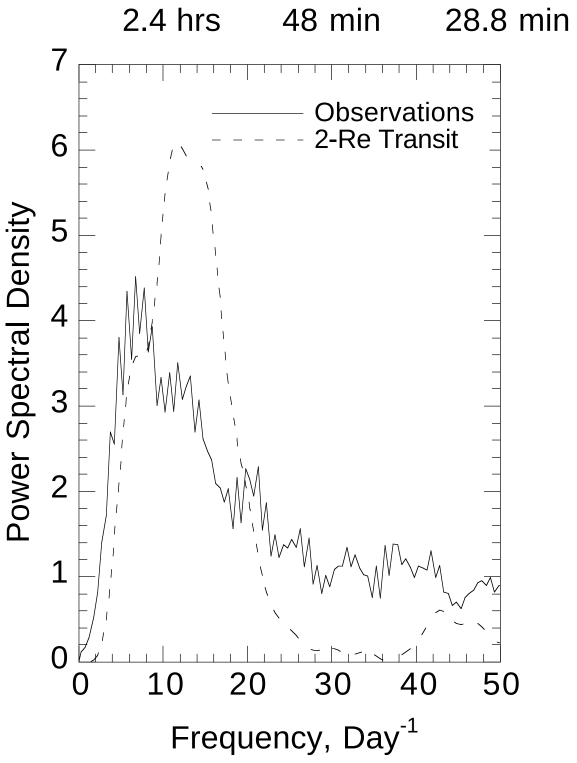
Table I. Observed Stars for Jupiter Detections by Eclipse Timing Method

Jenkins et al. Table I.

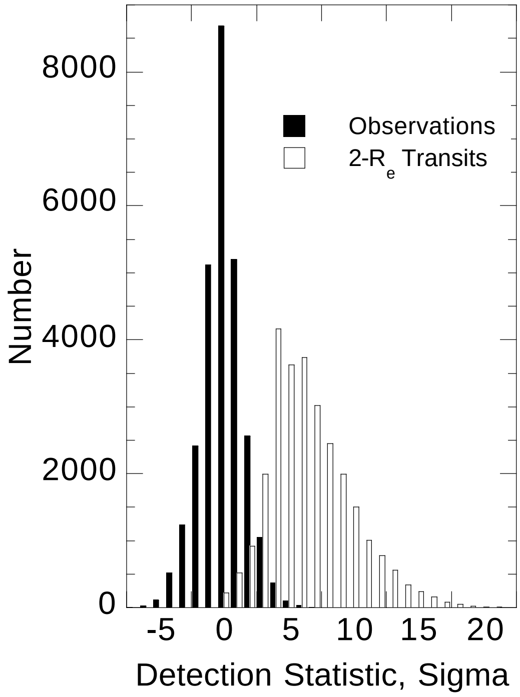
Star Name	P(days)	δT (sec)	n	δt
VW Cep	0.278316	4.57	6	0.21
BV Dra	0.350376	2.52	6	0.24
CM Dra	1.2683897	11.30	61	0.33
RT And	0.62892953	2.01	11	0.38
BX And	0.611012	2.65	2	0.72
TZ Lyr*	0.528823	3.35	3	0.97
XX Cep	2.33731	2.52	6	3.03
WX Cep	3.37845	2.40	4	3.10
FL Lyr	2.17815	2.34	3	3.13
WW Dra	4.62958	2.52	3	6.64



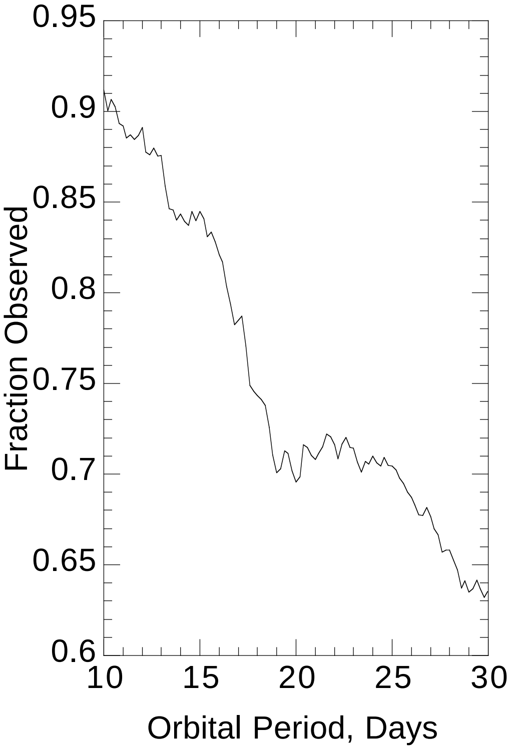
Jenkins et al. Figure 1



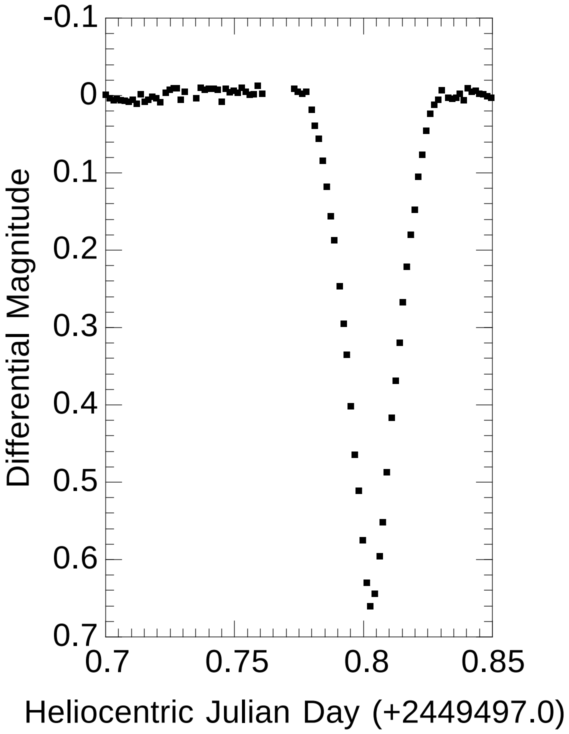
Jenkins et al. Figure 2



Jenkins et al. Figure3



Jenkins et al. Figure 4



Jenkins et al. Figure 5