

# Detectability of Jupiter-to-Brown-Dwarf-Mass Companions Around Small Eclipsing Binary Systems

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**Abstract.** The presence of a third body orbiting an eclipsing binary system has long been known to offset the system about a binary/third-body barycenter causing periodic variations in the time of eclipses (due to the increasing or decreasing light travel time). Recent increased precision in the timing of eclipse minima should allow a survey of the prevalence of Jupiter to Brown Dwarf mass objects by this method using 1m-class telescopes achieving moderately good photometric precision (i.e. 1% or better) with temporal resolution on the order of seconds. Perhaps over 250 such small-mass eclipsing binaries may be successfully surveyed for

evidence of such third, outer-orbiting giant planets or brown dwarfs. We discuss the photometric and timing precision required to measure such changes, along with complicating factors that might affect the measured eclipse times of a current program to survey about one dozen binary systems with this method. The importance of such determinations to our general understanding of the formation of solar systems around binary stars is then pointed out.

## 1. Introduction

The presence of a massive third body orbiting around a close eclipsing binary system will cause an offset,  $d$ , of the barycenter of the binary star about the barycenter of the three-body system by an amount:

$$d = M_p a / M_\star \quad (1)$$

where  $M_p$  is the third body's mass (planet or brown dwarf, in our context),  $M_\star$  is the total (sum of both components) stellar mass, and  $a$  is the semi-major axis of the third body's orbit (see Corbet et al. 1994, for example). The resulting periodic total light-travel-time drift in the timing of the eclipse minima-to-minima period then just becomes:

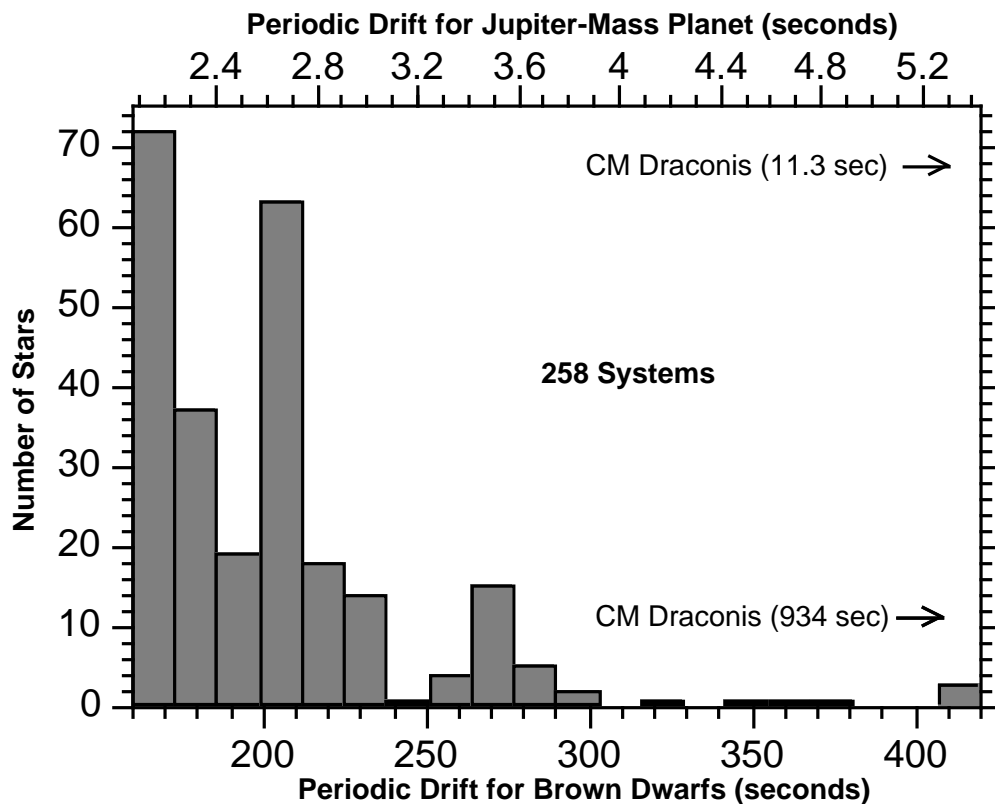
$$\delta T = 2 M_p a / c M_\star \quad (2)$$

where  $c$  is the speed of light. This offset time takes place every half-period of the third body's orbit. As pointed out in Schneider and Doyle (1995; see also Doyle et al. 1996), a low-mass eclipsing binary system could allow the determination of the presence of a jovian-mass object in orbit around it by sufficiently precise eclipse timings. This precision has recently become technically feasible with clocks set by radio timing signals, such as the GPS satellite navigation system. Required are occasional measurements of the minimum times of the eclipses over a time-span of  $\gtrsim 1/2$  period.

Although recent detections have indicated giant planets very close to their central star (Butler et al., 1997 and references therein), we will assume a third body at a distance of 5.2 AU around the binary star (i.e. the Jupiter - Sun distance) for the calculations in this paper. For estimates here, a 1 Jupiter-mass body ( $M_p = 0.00097 M_\odot$ ,  $M_\odot =$ one solar mass) is assumed at the low mass end for detectability, while the maximum is the the upper mass limit for substellar objects ( $M_p = 0.08 M_\odot$ ), recognizing that brown dwarfs might typically form at significantly greater distances from such parent star systems (these proceedings).

## 2. Precision of Measurable Systems

We note that the period changes in eclipse minima times due to a substellar third body may be superimposed upon many other effects of the binary light curve. However, it's effect would nevertheless have to be present if such a planetary mass were present (i.e. non-detections are valuable also). For consideration



here, we set the accuracy with which the timing of the eclipse minima can be determined to be within 2 seconds. In the figure we show a histogram of 258 such low-mass eclipsing binary systems (from the somewhat theoretical catalogue of Brancewicz and Dworak 1980, with some corrections) whose masses are small enough so that a jovian-mass third body at 5.2 A.U.s will result in drifts of a half-period of  $\delta T \geq 2$  seconds from Equation 2 (a list is available from L. Doyle). The upper x-axis is the expected drift due to a jovian third body at 5.2 A.U. while the lower x-axis illustrates the drift expected from a brown dwarf at the same distance. For jovian-mass objects the maximum yearly drift ranges from 0.5 to 1.3 seconds per year, while for a brown dwarf the maximum drift ranges from 45 to 114 seconds per year. Clearly the range of larger giant planets lies in a reasonable timing detection range (Hertz et al. 1995, as an example).

In Table 1 we show the systems we have observed in 1996 with precision timing at Lick Observatory's 0.9m Crossley telescope and at the 1.5m Carlos Sanchez telescope of the Instituto de Astrofisica de Canarias. The observations of CM Dra were taken at several telescopes during the TEP project in 1994-96 (Deeg et al, 1997, and this proceedings). The columns give: the common variable star name; the binary orbital period; the total drift in minimum times one would expect from these system for a Jupiter-mass third body at 5.2 AU distance from the binary barycenter (from Equation 1); and the maximum drift per year, which appears in that part of the orbit where the planet is moving in a small angle against the line of sight. Next is: the sampling frequency

Table 1. Observed Stars for Jupiter-to-Brown Dwarf Third Body Detections by the Eclipse Timing Method

Star Name	P (days)	$\delta T$ (sec)	Jup (sec/yr)	$T_s$ (sec)	$\delta t$ (sec)	n	$\delta t/\sqrt{n}$
CM Dra	1.2683897	11.30	1.27	120	7.4	45	1.1
44i Boo	0.267813	9.88	0.71	10	0.5	1	0.5
VW Cep	0.278316	4.57	0.81	75	1.3	6	0.5
UV Psc	0.861046	2.70	0.62	10	0.7	1	0.7
SW Lac	0.32072	2.69	0.62	45	1.1	1	1.1
V566 Oph	0.409641	2.65	0.62	10	0.7	1	0.7
BV Dra	0.350376	2.52	0.60	10	0.6	2	0.4
XX Cep	2.33731	2.52	0.60	75	10.7	2	7.7
ER Vol	0.698095	2.45	0.59	10	1.2	1	1.2
WX Cep	3.37845	2.40	0.59	50	12.7	1	12.7
FL Lyr	2.17815	2.34	0.58	60	8.9	1	8.9
RT And	0.628929513	2.01	0.54	10	1.1	4	0.5

(in seconds) that was achieved in our 1996 observations; the precision of *one* observed minimum from Equation 4 (with  $n=1$ ; see below); the number of eclipse minima we have presently observed; and the achieved present precision in timing of eclipse minima scaled by the number of observations. Clearly, some interesting constraints on the presence of jovian or larger sub-stellar objects around these systems may be expected.

Typical modeling of the light curves of eclipsing binaries includes the fitting of the normal components of the system (period, radii, luminosity ratio, mass ratio, inclination of the binary orbit to the observer's line-of-sight, periastron angle, ascending node angle, limb darkening of the components, mutual reflection effects, eccentricity of the orbit, and the distortion of the components shape in close binaries). In addition to these considerations, "special" effects may also contribute to complicating the light curve (see next section).

Ground-based differential photometry can be achieved with precisions of about 0.1% (about 0.001 magnitudes; Young et al. 1991). However, in order to provide temporal resolution, one must sacrifice photometric precision. One can ask what the precision with which we can determine the epoch of CM Draconis would be, for example. In general, the timing uncertainty is inversely proportional to the square-root of the number of samples obtained for a particular eclipse. Assuming for the moment that the observational noise is white Gaussian noise (WGN) with variance  $\sigma_w^2$ , and that the epoch is the only free parameter (i.e. all other parameters such as stellar radii, orbital inclination, orbital period, etc. are fixed), the standard propagation of errors can be used to address this issue. Let the set  $t_i, i = 1, \dots, N$  represent the time tags of the lightcurve, and  $B(t_i, t_0)$  be the eclipse model for epoch  $t_0$ . Then the uncertainty in the epoch,  $\sigma_{t_0}$ , is given by (Press et al., 1986):

$$\sigma_{t_0} = \sigma_w \left( \sum_{i=1}^N \frac{\partial^2 B(t_i, t_0)}{\partial t_0^2} \right)^{-1/2} \quad (3)$$

For 1% photometry, with 5 sec sampling (as achieved for the CCD system used by Doyle et al. 1996), this results in a 1.5 sec uncertainty in the epoch for *each minimum*, where the derivatives have been calculated numerically. The following equation has been calculated with an eclipse-model of CM Dra, but will also allow estimates for other systems with reasonable sampling periods:

$$\delta t \approx 53 \sigma_p P_* \sqrt{T_s/n} \quad (4)$$

where  $P_*$  is the period of the binary in days,  $T_s$  is the sampling period in seconds,  $n$  is the number of observed eclipse minima, and  $\sigma_p$  is the photometric precision. Of course, this analysis assumes WGN so Equation 4 is only approximate. Star spots and flares will undoubtedly ensure that the noise is not white (the real noise of our observations is slightly red, as shown in Doyle et al. 1996). This equation, then, provides only a reasonable *estimate* for the accuracy that can be achieved in eclipse timing.

### 3. Complicating Factors

Many processes can contribute to the modification of the eclipsing binary light curve, with subsequent changes in the apparent time of an eclipse minimum. It is the processes that are periodic with the binaries' orbital period that we will be most concerned with here.

#### 3.1. Starspots

Starspots can substantially change the light curve by causing a periodic sine-like amplitude variation due to starspot rotation across the stellar limb (e.g. Zeilik et al. 1989; Heckert and Ordway 1995) For late-type, convective mantle dwarf component binaries with separations less than about 10 solar radii (the systems listed in Table 1 all qualify), stellar rotation should be synchronized with the binary orbit in less than about  $10^6$  years (Zahn 1975). In addition, at 10 solar radii separation, the stellar components should be able to circularize their orbits in about  $1 - 2 \cdot 10^8$  years. Effects from starspots will therefore appear at constant phases in the lightcurve of an eclipse. This may cause asymmetries in eclipse lightcurves and variations in the minimum times, with changes on a months-to-years timescale, over the starspots' lifetimes (see e.g Zeilik et al. 1989, for RT And). A reliable removal of the starspots' effects from the lightcurve can be achieved with star-spot fitting programs (Rhodes, et al. 1990), as 'spot-free' minima times are needed to compare results from observations spanning several years.

#### 3.2. Mass Transfer and Mass Loss

Contact or semi-contact systems (such as VW Cephei in Table 1, which is also a known triple system) could be exchanging or losing mass at a substantial rate

(i.e. enough to affect the binary period). In modeling such close systems, the distorted shape of the component stars can be extreme. Mutual reflection effects can also be high enough so that limb darkening in the reflection effect may also have to be taken into account (Hall and Henry 1990, as example).

In the case of mass *transfer* with conservation of angular momentum, the shortest semi-major axis of the binary pair will occur when the stellar masses are equal (Bowers and Deeming 1984). This is clear from the decreasing product of the two masses (from unity) in the simplified (spherical components) expression for the angular momentum of such a system:

$$J = M_1 M_2 (d G M_\star)^{1/2} \quad (5)$$

where  $M_1$ ,  $M_2$  and  $M_\star$  are the individual stellar masses and the total mass of the system, and  $d$  is the components' separation. Thus, as mass is transferred from, for example, the secondary component to a more massive primary, the orbital velocity of the secondary will quicken as the barycenter shifts away from it (the system remaining synchronous), and from Kepler's third law the period of the system would increase as  $a^{3/2}$ . Such mass exchange could be periodic although nuclear evolution of the mass-losing star could be slowed substantially for large mass inversion events so that one might generally expect long time scales for any periodic effects, with the eclipse period generally increasing linearly. Evidence of mass exchange may show up in the light curve as brighter material at opposition configurations so that the existence of an exterior third body could be excluded in many of these cases and, in extreme cases, would start to show up in a flattening of the eclipse minima (i.e. effect of uneven stellar radii).

The effect of mass loss (therefore angular momentum loss) from the entire system for synchronous stars would be a non-periodic decrease in the length of the semi-major axis. If the binary period is to be kept constant (tidally locked components), the shortening of the semi-major axis would increase the eclipse obscuration, so the depth of eclipse minima would also increase. In general, however, mass loss may be expected to increase the binary period in a non-periodic manner. (An interesting exception may be the binary pulsar PSR B1957+20 in which mass loss induces magnetic activity that holds one companion out of synchronous rotation, periodically dissipating energy via tidal torque; Applegate and Shaham 1994).

From statistical studies (De Jager et al. 1988), the mass loss rates of average late-type dwarfs  $> 1$  Gyr in age should certainly be less than about  $10^{-10}$  solar masses per year (likely orders of magnitude less). For the stars listed in Table 1, then, the mass loss rates would evolve the systems at much longer time scales than those we are interested in. In addition, we remember that the effect is linear and should not cause a periodic shift in the timing of the primary or secondary minima. As a note, for mass not lost from the system but external to the stellar orbits, the effects of gas drag would also be to shorten the semi-major axis in a non-periodic way (Iben and Tutukov 1993 address this mechanism with regard to planetary nebulae with binary central components).

### 3.3. Stellar Oscillations and Microflares

Changing stellar radii may cause effects in the lightcurve that may appear as periodic drifts in the eclipse period and therefore, – by itself – could be inter-

preted as the effects of a third body orbiting the system (Corbet et al. 1994, for example). However, as pointed out by Hertz et al. (1995) for the case of the low mass X-ray binary EXO 0748-676, when the light curve cannot be fitted either with a constant period or constant period derivative, a third body explanation is, at best, not the whole story. In this case it was pointed out that the times of eclipse ingress, egress, duration, and period were all varying, and that these changes were correlated from one period to the next. It is clear, that if a third body alone was the cause of period change, the eclipse duration itself should not vary, and the times of the ingress and egress should not be correlated with the period drifts. In cases where these effects are not separable, stars exhibiting them may need to be removed from the observational sample.

It may be appropriate here to also address the effect on period drift of any variations in the luminosity of the components near eclipse minima. Micro and mini-flares on the star that are not detected with the available photometric resolution would result in adding noise to the photometric precision of the light curve and thereby cause a shift in the best fit of the eclipse minima. They might thus effect a slight change in the precision of any period determinations. However, photometric shifts due to microflares should also not be periodic. In addition, their effect on the light curve is not likely to have the effect of uniformly changing the period from one measured minima to the next, that is, microflares are not likely to occur in such an organized fashion. Therefore, with care and comparison of several eclipse minima, this effect should also be isolatable.

### 3.4. Apsidal Motion

Eccentric close binary stars can show the effects of precession of the periastron in periodic shifts in the times of eclipse minima. These periodic changes could likely be on the order of the time of interest here for detection of Jupiter-to-Brown Dwarf mass third bodies in close orbits around the binary (Schneider 1994). However, apsidal motion should also cause slight periodic changes in the times of ingress, egress, and eclipse duration, as well, depending on the eccentricity of the system. (Apsidal motion in the young system V477 Cygni, for example, has been observed to cause a widening and shifting of the secondary eclipse minima; Gimenez and Quintana 1992, and references therein.) Again, correlation of the eclipse duration, times of ingress, and egress with period would be indicative of other effects than just an external third body. Finally, the period of the relativistic periastron precession of the systems surveyed in Table 1 is on the order of 100 years; significantly longer than the periodicities we are attempting to detect, and therefore easily separable.

## 4. Conclusions

There are a substantial number of eclipsing binary systems where a survey of the existence of gas giant planets to brown dwarfs around close, small-mass eclipsing binary systems might be performed by timing the eclipse minima precisely and achieving reasonable photometric precision. With the sampling rates and photometric precision presently achievable, such a survey becomes feasible as the effects of such predicted third bodies should be separable from many alternative effects operating on the light curve.

The importance of such a survey to our understanding of the formation rate of sub-stellar masses around binary stellar systems would also be crucial to our understanding of the evolution of the protosolar and other protostellar nebular processes and solar system formation processes in general. This method may provide a somewhat easier way to sample a statistically significant number of systems for evidence, then, of such sub-stellar companions.

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