A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
1; (05.05.1; 08.02.2; 08.09.2 CM Dra; 08.12.2; 08.16.2)

ASTRONOMY
AND
ASTROPHYSICS
April 28, 2000

A search for Jovian-mass planets around CM Draconis using eclipse minima timing

H.J. Deeg[1,2], L.R. Doyle[3], V.P. Kozhevnikov[4], J.E. Blue[5], E. L. Martín[6], and J. Schneider[7]

[1] Instituto de Astrofísica de Andalucía, Granada, Spain (hdeeg@bigfoot.com)
[2] Instituto de Astrofísica de Canarias, E-38200 La Laguna (Tenerife), Spain
[3] SETI Institute, 2035 Landings Drive, Mountain View, CA 94043, USA (ldoyle@seti.org)
[4] Astronomical Observatory, Ural State University, Lenin ave. 51, Ekaterinburg 620083, Russia (valerij.kozhevnikov@usu.ru)
[5] SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025, USA
[6] Division of Geology and Planetary Sciences, Caltech MC 150-21, Pasadena, CA 91125, USA
[7] CNRS-Observatoire de Paris, 92195 Meudon, France

Received ; accepted

Abstract. For the eclipsing binary system CM Draconis, eclipse minimum times have been monitored with high precision between 1994 and 1999. Periodic deviations of minimum times from a linear ephemeris may indicate the presence of an orbiting third body. Individual measurements of 41 eclipse minimum times result in a standard deviation from linear ephemeris of 5.74 seconds. A power spectral analysis of the residuals reveals only one periodicity with more then 2 seconds amplitude. This feature, with a periodicity between 750 and 1050 days has an amplitude of 2.8±0.5 seconds, and is also present with similar phases if the power spectral analysis is performed independently for primary and secondary eclipses. It would be compatible with a circumbinary planet of 1.5 -3 Jupiter masses at an orbital distance of 1.1-1.45 AU to the binary barycenter. The assignation of a planet to the CM Dra system can however only be upheld if this periodicity can be followed in future observations for several years. For low-mass eclipsing binary stars, the method of eclipse minimum timing allows one to reach mass limits for the detection of third bodies well below that feasible by radial velocity measurements.

Key words: Eclipses - binaries: eclipsing - Stars: individual: CM Draconis - Stars: low mass, brown dwarfs - planetary systems

1. Introduction

It has long been known that the presence of a third body orbiting both components of an eclipsing binary system will offset the binary from a common binary/third-mass barycenter thereby causing a periodic shift in the observed times of the binary eclipses. The amplitude of this shift is given by

$$\delta T = M_{\rm P} a_{||} / M_{\rm B} c,$$

where $M_{\rm P}$ is the third body's mass, $a_{||} = a \sin i$ the third body's semi-major axis along the line of sight, $M_{\rm B}$ the mass of the binary system, and c the speed of light. As pointed out by Schneider & Doyle (1995) and Doyle et al. (1998), eclipse timings with a precision of a few seconds could detect the presence of an orbiting Jovian-mass object around a low-mass eclipsing binary system. Also, Doyle et al. (1998) gives a sample of 250 eclipsing binaries for which Jupiter-mass planets may be detectable by such studies. In this paper we report on an analysis of eclipse timings that were obtained as part of a photometric search for extrasolar planetary transits undertaken during the six years 1994 - 1999 around the M4.5/M4.5 binary CM Dra by the TEP project (Deeg el al. 1998a – further TEP1 – ; Doyle et al. 2000 – further TEP2 –)

2. Data and Analysis

Eclipse minimum times were obtained from photometric time series data of CM Dra; the photometric reduction pipeline is described in TEP1. Photometric data included in this analysis have a maximum photometric rms error of 0.7% and were corrected for nightly extinction variations. Eclipses of CM Dra were extracted from the data with a cut-off of $\Delta m > 0.1$mag from the off-eclipse baseline. The eclipse minimum times were then measured with a 7-segment Kwee-van-Woerden algorithm (Kwee & Van Woerden 1956), and converted to heliocentric Julian dates with the 'setjd' routine in IRAF. The entire lightcurve with 1014 hours of coverage, taken by all telescopes of the TEP project between 1994 and 1999, contains 81 eclipses for which O-C times were measurable.

Send offprint requests to: H.J. Deeg

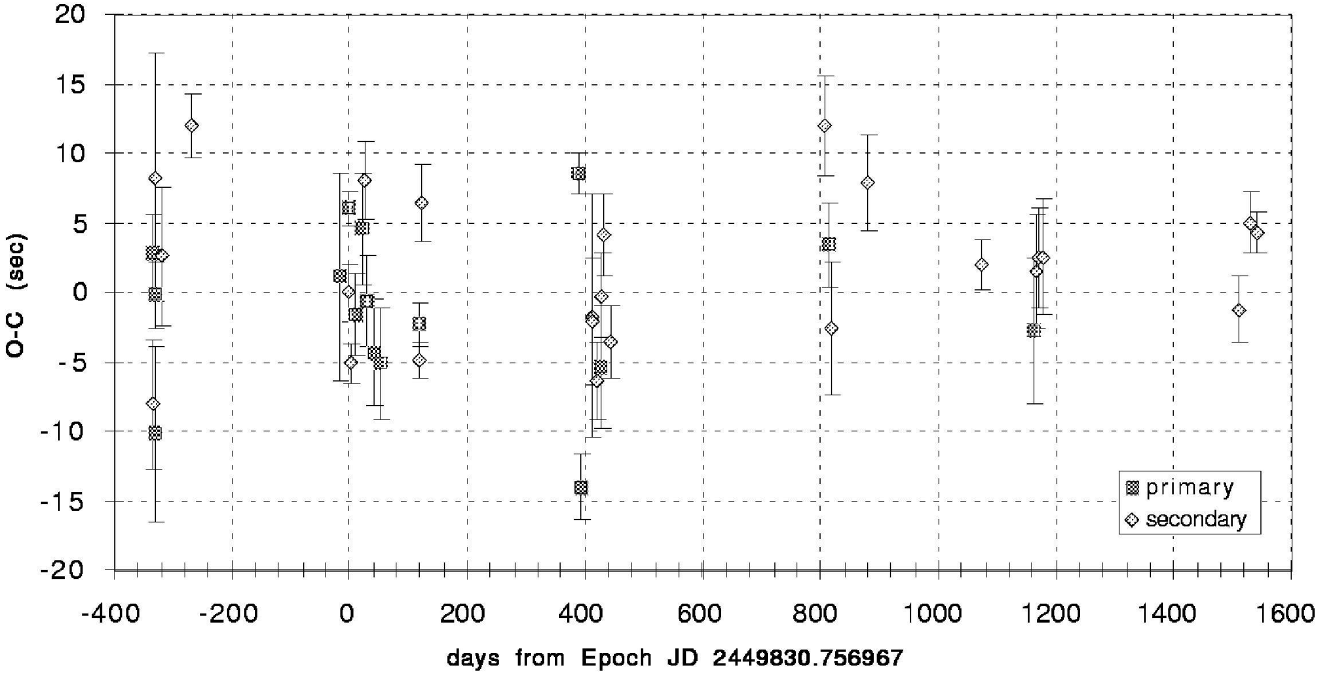

Fig. 1. O-C residuals of CM Dra from 1994 to 1999. Six groups, corresponding to the yearly observing seasons (April-August), can be discerned

For further analysis, however, we selected only data from a subset of telescopes which delivered the most consistent results for timing. These were the Crossley telescope at Lick Observatory, the JKT, INT and IAC80 telescopes at the Instituto de Astrofísica de Canarias, the 0.6m at Kourovka Observatory and the 1.2m of the Observatoire de Haute Provence. Inconsistent minimum times from those telescopes whose data were rejected were most likely caused by imprecise recording of the time, which depends in most systems on the computer that archives the data. We also excluded the eclipses observed by Lacy (1977), whose two primary eclipses had discrepancies of 25 seconds between them (based on a re-analysis of Lacy's data, see TEP 1). From the remaining data only those minimum times were kept where the lightcurve covered the entire ingress and egress of each eclipse without significant 'holes', and where the formal error given by the Kwee-van-Woerden algorithm was less than 10 seconds. The resulting sample, to be further investigated, contains minima timings of 16 primary and 25 secondary eclipses.

3. Results

In Fig. 1, the O-C (observed - computed) minimum times of these 41 eclipses are plotted. The computed minimum times T_n are based on the linear ephemeris given by TEP1, where $T_n = T_o + nP_{\rm orb}$, with a period of $P_{\rm orb} = 1.268\,389\,861 \pm 0.000\,000\,005$days, an epoch of primary eclipses of T_o = HJD2449830.757 00 ± 0.000 01, and an epoch of secondary eclipses of T_o = HJD2449831.390 03 ± 0.000 01. This ephemeris was derived from eclipses measured between 1994 and 1996. The eclipses observed afterwards, in 1997-1999, do not exhibit any trends away from that ephemeris, and therefore no attempts have been made to derive a new one. The standard deviation of all O-C times from 1994-1999 against the elements listed above is 5.87 seconds for primary, 5.47 s for secondary, and 5.74 s for both eclipses together.

To evaluate the minimum times for the presence of periodicities, we performed a power spectral analysis using the method of sine-wave fitting common in solar oscillation studies (Kjeldsen & Frandsen 1992). In this method, sine waves with increasing periods are fitted to the O-C values, using amplitude and phase as fitting parameters. (This is identical to fitting a sinusoidal ephemeris, $T_n = T_o + nP_{\rm orb} + A \sin[2\pi(t-\tau)/P + \kappa]$ with stepwise increasing periods P, and recording amplitude A and phase κ of the best fit.) This method has the advantage over the Lomb periodogram spectral analysis (Lomb 1976, Press 1992) that amplitudes are derived with an absolute scale, whereas the Lomb method derives only relative amplitudes.

The power spectra (Fig. 2) were obtained separately for primary and secondary eclipses, as well as for both eclipses combined. As can be seen, the highest peaks have amplitudes around 4 seconds. The only notable feature is a

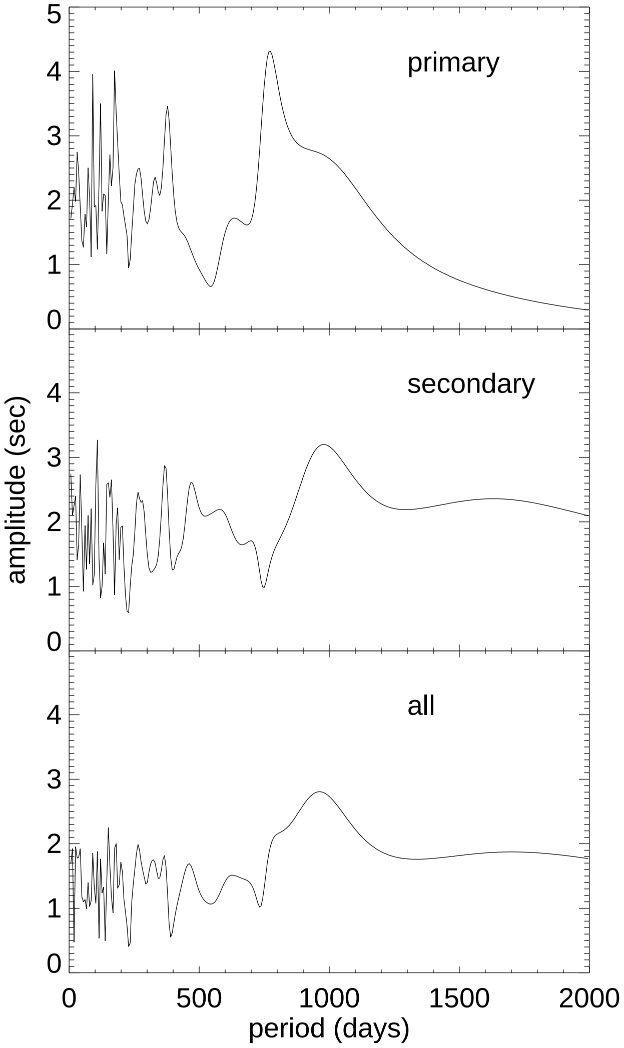

Fig. 2. O-C power spectra, from primary (upper panel), secondary (central panel), and from all eclipse times (lower panel)

peak between 750 and 1050 days, occurring in both kinds of eclipses. This is the only feature significantly above 2 seconds amplitude in the power diagram of primary and secondary eclipses combined (Fig 2c). It has a maximum amplitude of 2.8 seconds at a period of 970 days. Also, the phases of the powerspectra (Fig. 3) are close for primary and secondary eclipses in that period range, being identical at a period of 890 days. Above periodicities of 2000 days, there is a smooth decay of spectral power, which is a consequence of the length of coverage of our data - the distance between the first and the last eclipse in the data set is 1879 days.

4. Discussion

The power spectra (Fig. 2) indicate that there are no periodic O-C minimum time variations with amplitudes of larger then 3-4 seconds present, for all periods less than 2000 days. This absence of amplitude variations allows us to *exclude* the presence of very massive planets around the CM Dra system, as indicated by the hatched region in the search-space diagram (Fig. 3). Excluding the peak around 1000 days period, the power spectra from all data (lower panel of Fig. 2) is relatively flat with an amplitude of about 2 seconds. This white-noise like flatness indicates an intrinsic imprecision in our data of about 2 seconds. This is most likely the results of the precision of the eclipse minima times being limited by the photometric noise of the eclipse lightcurves. O-C deviations of about 2 seconds constitute therefore a lower detection limit. Finally, the peak in the power spectra between 750 and 1100 days with an amplitude of 2.5 ± 0.5 seconds and a good match of phases from primary and secondary eclipses may be the consequence of a third body, but is close to the observational noise. If this amplitude variation is caused by a third body, it would correspond to a circumbinary planet of 1.5-3 Jupiter masses at an orbital distance from CM Dra of 1.1 - 1.45 AU. We note that such a body would cause a periodic variation in the radial velocity of CM Dra with an amplitude of $65 \pm 20\mathrm{ms}^{-1}$. Though sufficient precision to detect such radial velocities amplitudes has routinely been obtained in planetary detection programs, these program are always concerned with single stars. For eclipsing binaries, the mutual orbiting of the binary components causes large radial velocity amplitudes on the order of km/s, which obstruct the separation of the much smaller radial velocity amplitudes from a third body. In the case of CM Dra, the velocities of the binary components reported by Metcalfe et al. (1996) are 72 and 78 km/s, and the precision of these data would only allow the separation of third body amplitudes of more than 200 m/s (Latham 2000). Finally, the limited time-baseline of our observations does not allow the detection of periodicities longer then about 2000 days. The absence of very heavy third bodies with periods up to a few times longer is however rather certain due to the good general adherence

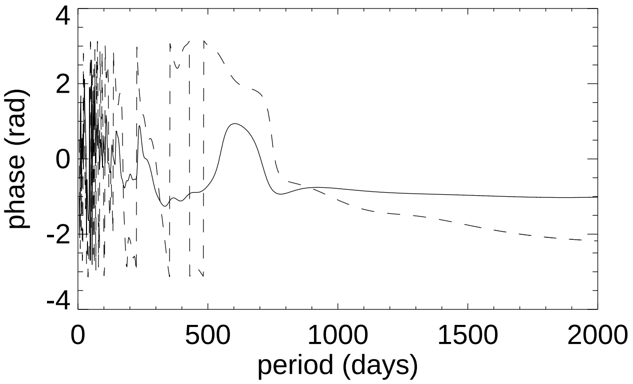

Fig. 3. Phases of O-C power spectra. Solid line is from primary eclipses, and dashed line from secondary ones. The phases are wrapped to the range $\pm\pi$.

of the O-C times to a linear ephemeris. Influences from third bodies *w*ithin the Solar System onto the heliocentric eclipse minimum times are not of consequence. The strongest influence, by Jupiter, causes a 12-yearly deviation, but due to the high ecliptic latitude of CM Dra (76.3 deg) its amplitude is limited to 0.58 seconds.

The *absence* of periodicities above 3-4 seconds amplitude - and the exclusion of corresponding massive planets - may be stated with certainty, even if the data analysis may not have accounted for every factor that may introduce spurious periodicities. The claim by Guinan et al. (1998) of a periodicity in minimum times of 70 days with an amplitude of 18 seconds, corresponding to a third body with a mass of $0.01 M_\odot$, is clearly invalidated (see also Deeg et al. 1998b).

The *presence* of apparent periodicities with ≈ 3 seconds may however also be a consequence of slowly changing starspots which distort the symmetry of the eclipses. Although we have not been able to find any relevant variations in lightcurves of CM Dra through the different observing seasons 1994-1999, the possibility of starspots can not be entirely excluded. In any case, further monitoring with high precision minimum timing of the CM Dra system is needed to ascertain the continuing presence of the 700-1050 day periodicity.

Fig. 4 shows the search space of exoplanets around CM Dra covered by the eclipse timing observations described here and by the observations of transits from TEP1 and TEP2. The transit observations covered coplanar planets ($\sin i \approx 1$) on short period orbits, between 7 days (the shortest stable orbit around CM Dra) and 60 days (as a limit where observational coverage gets sparse), with a maximum detectable periodicity of 100 days (the limit where even coplanar planets would not cause transits because of the 89.82° inclination of the system). We assumed a mass limit of $m/m_{\rm Earth} \approx 10$, corresponding to the lower size limit of about 2.5 Earth Radii for detections with transits. The lower mass limit from the O-C timing method is derived from the absence of amplitudes over 2.5 seconds, except between 700 and 1050 days, were a planet candidate is indicated.

The two methods employed do cover rather complementary regimes: Whereas the strength of the transit method is the detection of relatively small planets on close orbits, O-C minimum timing is best for the detection of long period planets with at least Jupiter-like masses. The usefulness of the radial velocity method is limited in binary systems, though it might also lead to the discovery of massive third bodies around them. To verify the persistence of the 700-1050 day periodicity and the possibility of a planet, observations of CM Dra's eclipse minimum times need to be continued during the the next several years.

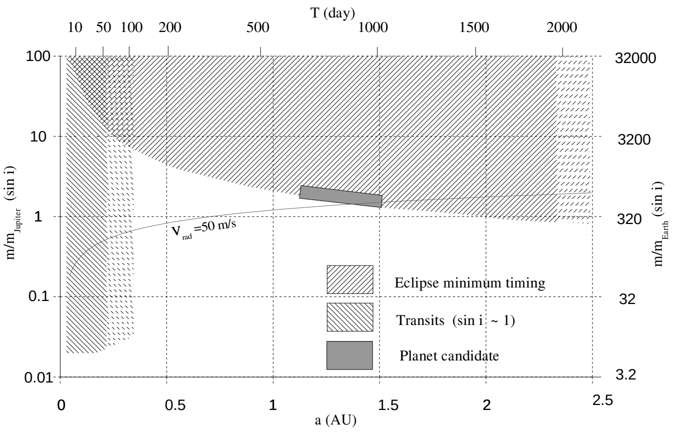

Fig. 4. Search space covered by the O-C timing observations and by transit observations reported in TEP1, TEP2. The hatched regions are those where planets can be excluded from the eclipse minimum timing and the transit search reported in TEP2. The small rectangular gray region corresponds to the planet candidate from the power-spectra based on O-C minimum timing. Regions left blank are those where these detection methods have not had sufficient sensitivity. Also indicated is a line where an orbiting third body would cause a radial velocity variation of 50 m/s in the spectrum of the eclipsing binary.

5. Acknowledgments

We thank R. Garrido, A. Gimenez and the anonymous referee for helpful suggestions and Ayvur Akalin for help with the Kwee-Van-Woerden algorithm.

References

Deeg H.J., Doyle, L.R., Jenkins, J.M., Martín E.L, 1998, IAUC 6875

Deeg, H.J., Doyle, L.R., Kozhevnikov, V.P., Martin, E.L., Oetiker, B., et al. 1998 A&A 338, 479 (TEP1)

Doyle L.R., Deeg H.J., Jenkins J.M., Schneider, J., Ninkov, Z., et al. 1998, Detectability of Jupiter-to-Brown-Dwarf-Mass Companions around Small Eclipsing Binary System, in Rebolo R., Martín E.L., Zapatero-Osorio M.R. (eds.) Brown Dwarfs & Extrasolar Planets. ASP Conference Proc. Vol. 134, p. 224

Doyle, L.R., Deeg, H.J., Kozhevnikov, V.P., Oetiker, B., Martin, E.L., et al. 2000, ApJ, in print, astro-ph/0001177 (TEP2)

Guinan E.F., Bradstreet D.H., Ribas I., Wolf M., McCook G., 1998, IAUC 6864

Lacy C.H., 1977, ApJ 218, 444

Latham, D.W., 2000, personal communication

Lomb, N.R., 1976, Ap&SS, 39, 447

Kjeldsen H., Frandsen S., 1992, PASP 104, 413

Kwee K.K., Van Woerden, 1956, BAN 12, 327

Metcalfe, T.S., Mathieu, R. D., Latham, D, W.; Torres, G. 1996, ApJ 456, 356

Press W.H., Teukoslky S.A., Vetterling W.T., Flannery B.P., 1992, Numerical Recipes in Fortran, 2nd Edition. Cambridge Univ. Press

Schneider J., Doyle L.R., 1995, EM&P 71,153