The TEP Network - a Search for Transits of Extrasolar Planets: Observations of CM Draconis in 1994

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Abstract

The TEP (Transits of Extrasolar Planets) network undertakes the only current search for terrestrial sized planets around MS stars. TEP was formed in 1994 to observe transits of extrasolar planets around eclipsing binaries. The current search concentrates on CM Draconis, which is the lowest mass eclipsing binary known (dM3/dM4). It is also relatively close (17 pc), has a period of 1.26 days, and its orbital plane is nearly within our line of sight (i=89.8°). These conditions give a unique opportunity to determine the existence, or non-existence, of planets around this binary by photometric means with a high degree of certainty. Planetary orbits, if present, will be within the orbital plane of the binary components, and - due to the small size of the components- create photometrically detectable transits. The transit of a Jupiter sized planet will cause a brightness drop of 8%, an Earth sized planet one of 0.08%, which is detectable with subnoise detection algorithms. The low mass and temperature of the binary components leads to the expectation, that comparable planets will form much closer to the central stars than in our Solar System, and will have orbits of a few weeks to months. An observing campaign gathering several months of lightcurves of CM Dra will lead to a high probability to detect a planetary transit, even when the data are taken non-continuously. The TEP network has been observing CM Dra from several 1m-class telescopes in the springs of 1994 and 1995, and obtained sofar about 500h of coverage with 16000 CCD images. Presented are the data from the first observing campaign in 1994, covering about 180h of observations with 3900 measurements.

Keywords: Eclipses; Planets and Satellites: General; Stars: Binaries: Eclipsing; Stars: Individual: CM Draconis, Techniques: Photometric

1. Introduction

The detection of extrasolar planets is one of the most important, yet difficult observational problems in astronomy today. A wide variety of detection methods has been proposed or is pursued, as is exemplified by the recent discovery of a Jupiter mass planet around 51 Peg. The detection of planets with masses on the order of the Earth around a main-sequence star system is of particular interest, as such solid planets are the only ones thought to be able to support life in the universe. The TEP (Transits of Extrasolar Planets) project is the only currently ongoing effort with a realistic chance to detect earth-sized planets. It is a photometric method, which depends on the monitoring of small, main sequence, eclipsing binaries for planetary transits.

From orbital precession considerations (Schneider and Doyle, 1995) it can be inferred that the plane of any planetary orbit will be very close to the plane of a binary system. In an eclipsing binary system with near 90° inclination, this means that a planet will cross the line of sight between the binary and the observer, a situation that is shown in Fig. 1. Planetary transits will produce unique quasi-periodic brightness variations, dependent on the phase of the binary at the planetary transit, the period of the planet, and the size of the planet (Fig. 2), which photometry can detect. The most suitable system for these observations is CM Dra, (see Lacy, 1977; Metcalfe et al., 1995, for basic parameters) the smallest known eclipsing binary. CM Dra is unique in its small size ($R = 0.23, 0.25\ R_{\odot}$), its low temperature (two M4 stars), its nearly edge-on inclination of 89.8°, and its proximity of 16.9 pc. These properties are advantageous for several reasons: First, in systems of low luminosities and temperatures it is expected, that terrestrial planets will form in a region much closer to the central star. If planets comparable to those of the solar system have formed around CM Dra at distances of similar flux, then the orbital period of these planets would be on the order of weeks (Table 1), giving a high probability to observe transits in observing runs of moderate length. Second, planetary transits across CM Dra (total surface area: 12% of the sun) would cause brightness drops an order of magnitude larger than the transits of similar planets across stars of solar size. Transit signals of planets with 2.6 Earth radii (halfway in area between Earth and Neptune), for example, would produce a drop in brightness of about 0.6%, a precision in photometry we have achieved in our 1994-1995 observations using 1-meter class telescopes. For the detection of smaller planets (an earth sized planet would cause a drop of 0.08%), whose transit signals with a S/N of $\lesssim$ 1 are hidden in the noise, cross-correlation techniques have been developed (Jenkins et al. 1995): A model of the eclipsing binary lightcurve convolved with all possible planetary transit signatures (varying period and phase of the planet) can be used as a matched filter to detect planetary transit signals below the observational noise level. For the future we plan observations with larger telescopes, as the detection limit improves directly with the light collecting area of the telescope (Jenkins et al., see entries with 100% in Table 2), and the detection probabilities using cross correlation increase dramatically too. Sufficient continuos observational coverage of CM Dra will decide the existence -or non-existence - of a planetary system with high confidence, and provide the first bona fide evidence on the formation of terrestrial-sized planets around another main-sequence star system.

Of concern may be the occurrence of star-spots, which are expected on the low mass components of CM Draconis. They can be readily separated from planetary transits, as they are tidally locked to the binary rotation, and starspot cycles are much longer than the duration of a transit. As CM Dra is the lowest mass eclipsing binary known, the project is also expected to produce significant spin-offs in the knowledge about flare rates and surface granulation of low mass stars, and will lead to a better characterization of the orbital elements of CM Dra.

2. The TEP observations

Observations of CM Dra in the frame of the TEP network began in spring 1994 at several 1m class telescopes equipped with CCDs (Table 3). Through August 1995, about 530 hours coverage in 16000 individual CCD frames has been obtained. We used telescopes with CCD camera for reasons of sensitivity and availability. Although the techniques for high precision photometric work using photomultipliers have become very refined (e.g. Young et al, 1991), this work has mostly concentrated on objects significantly brighter than CM Dra, which has an R magnitude of 11.07. The use of CCD cameras allows the simultaneous observation of several reference stars in the same field as CM Dra, resulting in a high duty cycle (i.e. the ratio of time that the object is observed over the whole observing time), which is only limited by the time to read out the CCD and save the image to disk, typically taking about a minute after exposures of several minutes. The CCD observations allow tracing of a lightcurve with measurements spaced 2-5 minutes apart. This close spacing of measurements is important, as the shape of a dip in a lightcurve is an important factor to recognize such an event as a planetary eclipse. Kjieldsen and Frandsen (1992) demonstrated the feasibility to use CCD's in high-precision time-resolved photometry, and emphasized their usefulness for the study of low-amplitude variable stars. We would also like to note their relative ease of use for these observations, as a telescope does not have to be repositioned all night, which is a tremendous advantage on small telescopes, which are frequently without computer control.

Image processing of the CCD frames is done with standard tasks from the IRAF package. As the field of CM Dra is uncrowded, aperture photometry was found to give the most reliable results. A dedicated IRAF-package, 'vaphot', was written to perform the photometry of large numbers of CCD frames efficiently, using optimized apertures that give the best signal-to-noise ratio possible (Deeg, 1996, in prep). The photometry gives instrumental magnitudes of CM Dra and of the reference stars on the CCD frame; an example of the further analysis of a night's data is shown in Fig. 3. The sum of the flux of the reference stars gives a reference magnitude; against which the differential magnitude of CM Dra is calculated. For each reference star, residuals of its magnitude against the summed reference magnitude (boxes with st-1 to st-17 in Fig. 6) were visually checked for variability and outliers. Frequently, the rejection of one or two reference stars led to light curves of CM Dra with lower noise. Disregarded were also CCD frames in which the reference stars deviated substantially from their average brightness ratios among each other (see box with 'deviation among ref. stars' in Fig. 3), usually indicating periods of poor atmospheric conditions. After the off-eclipse light curve of CM Dra has been normalized to a zero magnitude, it is included in the final composite lightcurve. Overlapping data-sets from two telescopes should in principle result in noise improvements for the final lightcurve, if the quality of both data sets is approximately equal (Moskalik, 1993), a condition which has rarely been met in our observations. Overlaps from distant telecopes are however invaluable, as only in these cases the atmospheric origin of 'features' in Cm Dra's lightcurve can be excluded with certainty.

3. Results form 1994 Observations

Completely reduced has been the 'core-time' of the 1994 observing campaign, with 3900 CCD frames included in the final database, taken between 10 May and 11 June, 1994. A composite lightcurve of these observations is shown in Fig. 4. The precision of the differential photometry with the 1m class telescopes is about 0.6 % in flux in good nights. The phase coverage from the same data is shown in Fig. 5. Prominent is a feature at phase 0.55 to 0.7 from observations at IAC on May27, 1994 (JD 2449500.5), below the majority of data points. In that night, the brightness of CM Dra started about 8% below the normal zero level and increased to normal within four hours. In the next two hours it decreased again by 4% and in the last two hours returned to its normal level. Data from this night have been reduced independently by two observers, and several photometry methods have been employed, confirming these brightness variations. They cannot be traced to any atmospheric or reference-star variations. A planetary transit as a cause for this feature is very unlikely however, as the strength of the brightness variations would have to be a caused by a very large object, and the two dips differ strongly in amplitude. Several other, less obvious dips in CM Dra's lightcurve have however been found, whose origin is not incompatible with a planetary transit. Any confidence in the observation of actual plantary transits can however only be ascertained by the observation of repeated - and predictable! - transits.

Fig. 6 shows the closely spaced phase coverage that has been obtained for CM Dra's primary eclipse. This dense coverage may allow the derivation of spin-off results about this interesting low-mass binary. For example, precise photometry of the eclipses may allow a preciser determination of the components radii, leading to a determination of the specific brightness of the system. This allows a more precise derivation of the helium content of this old (Pop II) system, possibly setting limits to the primordial helium abundance (Metcalfe et al., 1996). A further spin-off from precise eclipse-measurements may be the detection of jovian-mass planets from periodic shifts in the epoch of the binary eclipse minima due to the motion of the binary-giant planet barycenter (Doyle et al., 1996). A Jupiter mass planet at 5.2 AU would cause a shift of 11 sec between its orbital extremes along the line of sight, and this should be easily detectable in the photometric data, once a lightcurve of several years coverage has been built up.

Electronic information about recent developments of the TEP project can be found at http://www.iac.es/galeria/hdeeg/tep/tephome.html.

References

Brandmeier, S. and Doyle, L.R., in 'Circumstellar Habitable Zones; Proc. of the first Internat. Conf.', ed. L.R. Doyle, Travis Publications, Menlo Park, California

Doyle, L.R., Dunham, E.T., Deeg, H.J., Blue, J.E., Jenkins, J.M., 1996, J. of Geophys. Res. - Planets., in print

Doyle, L.R, Jenkins, J.M., Schneider, J., Deeg, H.J., 1996, in preparation

Jenkins, J.M., Doyle, L.R, Cullers, D.K., 1996, Icarus, in print

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

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

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

Moskalik, P.,1993, in Proc. of the second WET Workshop, eds. E.G. Meǐstas & J.-E. Solheim, Baltic Astron., 2, 485

Schneider, J. and Doyle, L.R.,1995, Earth, Moon and Planets, Vol 68, in print

Young, A.T. et al: 1991, PASP, 103, 221

Tables

Table 1. Planetary period of terrestrial planet equivalents around CM Dra

Planet	CM Dra Equivalent Orbital Period
Mercury	4.3 days*
Venus	10.9 days
Earth	17.7 days
Mars	33.3 days

*Note: The minimum stable period around CM Dra is 7.62 days.

Table 2 Detection probablilities for signals at several S/N levels. Depending on the telescope size, the S/N levels correspod to detections of Planets of different sizes. The detection probablilites are averaged for Planets with 8-30 day periods (adapted from Jenkins et al, 1995).

	S/N					
	0.33	0.45	0.60	0.86	0.92	1
Telescope size	Planet Radius (R_{Earth})					
1m	1.5	1.75	2	2.25	2.5	2.6
2.5m	0.95	1.11	1.27	1.42	1.58	1.64
4m	0.75	0.88	1	1.13	1.25	1.3
Observing Time*(months)	Detection Probability					
1	0.83%	8.2%	24%	77%	85%	100%
2	7.1%	31%	55%	84%	91%	100%
3	19%	52%	77%	92%	95.4%	100%
4	31%	68%	90%	96.5%	98.0%	100%
5	43%	82%	96.4%	98.8%	99.29%	100%
6	55%	90%	98.8%	99.60%	99.77%	100%

*The probabilites are calculated for continous obsering runs. For non-continous coverage of short $\lesssim$ 2months observing runs, where only a few transits of longer period planets are expected (such as 1 transit of a 30 day planet in a 1 month run), planets may be missed and the probablilities are less predictable. In particular, the rightmost column indicating direct detection (no cross correlation) will be < 100%.

Table 3 Collaborating Observatories in the TEP project 1994-95

Observatory	Longitude	Latitude	Telescope aperture	Coverage of CM Dra in 1994
IAC, Canary Islands	15 W	+28	0.8 m	46h
R.I.T., New York	78 W	+41	0.6 m	59h
Lick Obs. , California	122 W	+38	0.9 m	73h
Taejon Astro. Obs., Korea	127 E	+36	1.0m	-*
U. of Crete, Greece	25 E	+35	1.2m	46h**
Meudon, France	3 E	+43	1.3 m	11h

*first observations in 1995

**observations in Aug-Sept 1994 only, data not included in Figs. 4-6.

Figure Captions

Fig. 1: Schematics of a planet approaching a transit across an eclipsing binary. Sufficiently precise photometry may allow observations of such a transit. This figure is also the logo of the TEP network.

Fig. 2: Examples of planetary transits and resulting lightcurves. The axis indicate the phase of CM Dra and the distance between the components in Solar Radii. The lightcurves are schematic only and do not show details of limb darkening or grazing transits. Also, they do not show the binaries' mutual eclipses. The first 3 lightcurves are for a planet with a 20 day period - only CM Dra is in different phases a the planet's crossing. The period of CM Dra is 1.26838965 days (Lacy, 1977), and individual planetary eclipses can take between 40 minutes and 13.7 hours (Brandmeier and Doyle, 1995). For longer-period planets, such as the 40 day planet shown in the fourth example, a crossing may cause sequences of 3 or more eclipses. Observations of several crossings of the same planet will give a unique sequence of transit lightcurves.

Fig. 3: Example of the analysis of the results of one night's observations (May28, 1994, taken at the IAC-80cm telescope). The instrumental brightnesses of the reference stars are summed and the sum is re-converted to magnitudes (box with "sum of reference stars"). In the figure, the increase in that magnitude-sum indicates a night were sky-transparency decreases. The difference between that magnitude-sum and the instrumental magnitude of CM Dra gives the differential magnitude of CM Dra, which is set so that it is zero off-eclipse (box with "CM Dra"; there is an eclipse at about 0.1 frac. days). An average offset for a night between the magnitude sum and the instrumental magnitude of each reference star is calculated; the boxes "st1" to "st17" indicate the residuals between that average offset and the measured offset at each frame. The box with "deviation among ref. stars" gives the sum of the absolute values of the residuals - an increase in the scatter among the reference stars throughout the night is notable. The lowest two boxes indicate the skybrightness, and the FWHM of the point-

spread-function of the star images on the CCD. This analysis is done for each observing night's data before they are entered into the final database.

Fig. 4: Composite lightcurve of CM Dra from observational coverage May10-June11, 1994. The curve consists of 3960 data points, from a total observational coverage of about 180h. The brightness of CM Dra is set to zero off-eclipse.

Fig. 5: As Fig. 4 but here the differential magnitudes are plotted against Cm Dra's phase. The magnitude scale has been set to show the features in the off-eclipse lightcurve.

Fig. 6: Enlargement of the phase coverage for the primary eclipse. The phase is relative to an epoch of Heliocentric JD 2449830.757029305, determined from an eclipse taken with a rapid CCD photometer Lick Observatory.