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# Near-Term Detectability of Terrestrial Extrasolar Planets: TEP Network Observations of CM Draconis

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**Abstract.**

Results from a photometric search for extrasolar planetary transits across the eclipsing binary CM Dra are presented. The TEP (Transits of Extrasolar Planets) network has observed this star since 1994, and a lightcurve with 617 hours of coverage has been obtained. The data give a complete phase coverage of the CM Dra system at each of the 3 years of observations, with a noise of less than 5 mmag. New epoch and period values for CM Dra are derived, and a low flare rate of 0.025 $hr^{-1}$ has been confirmed. The absence of periodic variations in eclipse minimum times excludes the presence of very massive planets with periods of less than a few years. The lightcurve was visually scanned for the presence of unusual events which may be indicative of transits of extrasolar planets with 'massive earth' sizes. Six suspicious events were found which are being followed up for future transits, by planets with sizes between 1.5 and 2.5 $R_E$ (Earth Radii). However, none of these events has amplitudes compatible with planets larger than 2.5 $R_E$. Coplanar planets larger than 2.5 $R_E$ and with orbital periods of less than 60 days can therefore be ruled out with a confidence of about 80%. Planets smaller than 1.5 $R_E$ cannot be detected in the data without a sub-noise detection algorithm. A preliminary signal detection analysis shows that there is a 50% detection confidence for 2 $R_E$ planets with a period from 10 to 30 days with the current data. This data-set demonstrates that it is possible to detect terrestrial sized planets with ground based photometry, and that strong constraints on the sizes of planets orbiting in the plane of the CM Dra system can be set.

**Key words:** stars:individual:CM Dra - planetary systems - binaries: eclipsing - stars:low mass - stars: flare - techniques: photometric

## 1. Introduction

In this paper we describe the observations and analysis that have been performed in a search for photometrically detectable signals from the presence of extrasolar planets around the eclipsing binary CM Draconis. This is the first long-term observational application of the transit method for the detection of extrasolar planets. The transit method is based on observing small drops in the brightness of a stellar system, resulting from the transit of a planet across the disk of its central star. Such transits would cause characteristic changes in the central star's brightness and, to a lesser extend, color. The depth of a transit is proportional to the surface area of the planet, and the duration of a transit is indicative of the planet's velocity. If the central star's mass is known, the distance and period of the planet can then be derived. Once repeated transits of the same planet are observed, the period can be obtained with great precision. The transit method was first proposed by Struve (1952); later developments are described in Rosenblatt (1971), Borucki & Summers 1984, Deeg (1997). Previous observational tests have been prevented by the required photometric precision (which is about 1 part in $10^5$ in the case of an Earth-sized planet transiting a sun-like star), and by the generally low probability that a planetary plane is aligned correctly to produce transits. This probability of orbital alignment is about 1% for planetary systems similar to our solar system. An observationally appealing application is available with close binary systems, where the probability is high that the planetary orbital plane is coplanar with the binary orbital plane, and thus in the line sight. This makes the observational detection of planetary transits feasible in systems with an inclination very close to $90^o$

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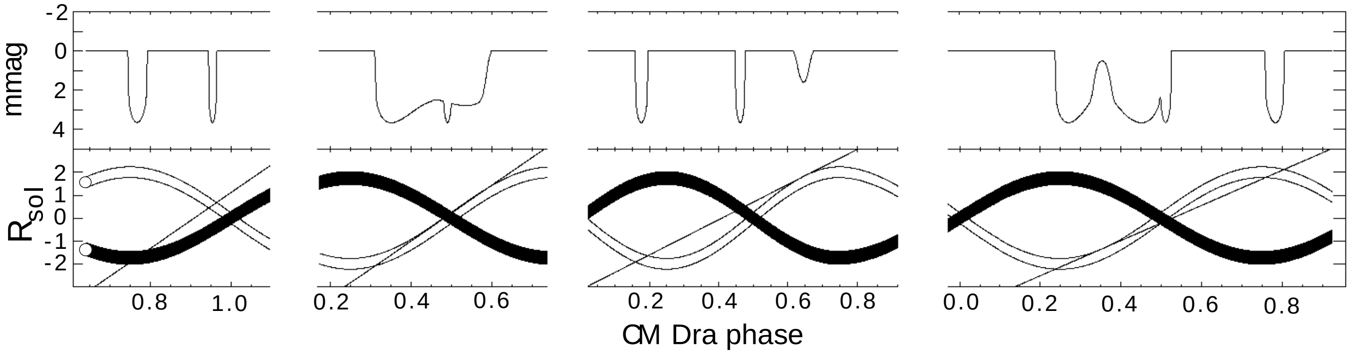

**Fig. 1.** Model lightcurves from planetary transits across CM Dra. The upper graph gives the brightness of the CM Dra system, normalized to an off-transit magnitude of zero. A model planet with 2 $R_E$ causes transits with a maximum brightness loss of 3.8 mmag (0.35 %). Mutual binary eclipses are removed here. The lower graphs show the elongation (in Solar radii) of the two CM Dra components (CM Dra A: black band, B: white band) and the model-planet (thin line) from the common barycenter. These graphs are of the same style as the well-known diagrams of the positions of Jupiter's moons, and the thickness of the bands is scaled to the sizes of CM Dra's components. From the left to the right, the two leftmost panels show transits caused by a planet with an orbital period of 9 days. The leftmost panel shows the normal case, with two short transits separated by several hours (0.1 CM Dra phase unit corresponds to ≈ 3 hours). The second panel shows the rarer case, where the planet transits when CM Dra is close to a mutual eclipse (here shown a secondary one at phase 0.5), and long transits occur. The complicated shape of this transit results from the planet covering zones of different surface brightness on CM Dra (considering limb-darkening and the planet's ingress/egress). The two rightmost panels show transits from a planet with a 36 day period. Such a planet has a transversal velocity that is slower than CM Dra's components, and multiple transits with complicated shapes are more likely to occur.

(Schneider & Chevreton 1990, Schneider & Doyle 1995). Furthermore, repeated planetary transits across the binary's components will result in unique sequences of transit-lightcurves, whose exact shape depends on the phase of the binary system at the time of the planetary transit (Fig. 1). Jenkins et al. (1996) demonstrated, that these unique sequences can be used for the detection of planetary signatures with amplitudes below the noise of the observed lightcurves, if signal detection techniques based on cross correlations with model lightcurves are applied.

The near ideal characteristics of the eclipsing binary system CM Dra for an observational test on the presence of planets has been suggested by Schneider and Doyle (1995). The CM Dra system is the eclipsing binary system with the lowest mass known, with components of spectral class dM4.5/dM4.5 (see Lacy 1977, for all system elements). The total surface area of the systems' components is about 12% of the sun's, and the transits of a planet with 3.2 $R_E$, corresponding to 2.5% of the volume of Jupiter, would cause a brightness drop of about 0.01 mag, which is within easy reach of current differential photometric techniques. The low temperature of CM Dra also implies that planets in the thermal regime of solar system terrestrial planets would circle the central binary with orbital periods on the order of weeks. This allows for a high detection probability of planetary transits by observational campaigns with coverages lasting more than one planetary period. Planets with orbital periods of 10 - 30 days around CM Dra are especially interesting, since they would would lie within the habitable zone, which is the region around a star where planetary surface temperatures can support liquid water, and therefore the development of organic life (see Kasting et al. 1993; Doyle 1996). CM Dra is relatively close (17.6 pc) and has a near edge-on inclination of 89.82°. With this inclination, coplanar planets within a distance of CM Dra of ≈ 0.35 AU will cause a transit event. This maximum distance corresponds to a circular orbit with a period of about 125 days. There is also a low probability of observing orbits from planets inclined out of CM Dra's binary orbital plane, if the ascending or descending nodes of the planetary orbits are precessing across the line of sight (Schneider 1994). The observations of CM Dra presented in this paper are therefore the first attempt to obtain observational evidence of the existence of sub-Jupiter sized planets around main-sequence binary stars, and to evaluate the probability that such detections are possible. For these observations we used differential CCD-photometry and employed 1m class telescopes. To obtain sufficient observational coverage, the 'TEP' (Transits of Extrasolar Planets) network was formed with the participation of several observatories in 1994. Preliminary accounts of TEP network observations are given by Doyle et al. (1996), Martin et al. (1997) and Deeg et al. (1997). A list of the observatories that have been participating is given in Table 1.

## 2. Observations

The vast majority of the observations has been performed with CCD-equipped telescopes with sizes ranging from 0.6m to 1.2m. Although the techniques for high precision photometric work using photo multipliers have become very refined (e.g. Young et al. 1991), such work has concentrated mainly on objects significantly brighter than CM Dra, which is magnitude 11.07 in R-band. With one - or two - channel photometers requiring frequent sky or standard-star observations, their duty cycles are relatively low. The use of CCD cameras allows the simultaneous observation of several reference stars in the same field as CM Dra, and the duty cycle is only limited by the time to read out the CCD and to save the image to disk, both together being on the order of one minute. This allows tracing the lightcurve with measurements spaced 2-4 minutes apart. The close spacing of measurements is important in order to recognize observed brightness variations as potential planetary transits. Kjeldsen & Frandsen (1992) have demonstrated the feasi-

**Table 1.** TEP Network Telescopes and their Location

| Telescope | Location | f ratio | Longitude | Latitude | Altitude |
|---|---|---|---|---|---|
| IAC 80cm | Izaña, Tenerife<br>Canary Islands | f/14.4 | 16°31’W | 28°18’N | 2385m |
| JKT 1m | Roque Muchachos<br>La Palma, Canary Isl. | f/15 | 17°53’W | 28°46’N | 2365m |
| INT 2.5m | Roque Muchachos<br>La Palma, Canary Isl. | f/3.29 | 17°53’W | 28°46’N | 2340m |
| Mees 24” | Rochester, NY | f/15.2 | 77°25’ W | 42°40’ N | 690m |
| Capilla 24” | Albuquerque, NM | f/15.2 | 106°24’W | 34°42’N | 2835m |
| Crossley 36” | Lick Observatory, CA | f/5.8 | 121°39W | 37°20’N | 1210m |
| Kourovka 0.7m | Ural University<br>Ekaterinburg, Russia | f/14.3 | 59°30’E | 57°03’N | 320m |
| WISE 40” | Negev, Israel | f/7 | 34°45’ E | 30°36’ N | 875m |
| Skinakas 1.3m | Skinakas Obsv., Crete | f/8 | 24°53’ E | 35°23’ N | 1752m |
| OHP 1.2m | Obsv. Haute Provence<br>France | f/6 | 5°42’ E | 44°N | 650m |

**Table 2.** CCD systems

| Telescope | CCD system | Pixel size (arcsec) | field of view (arcmin) | $t_{exp}^{1}$ (sec) | Duty[2] fraction | Read-noise (electrons) |
|---|---|---|---|---|---|---|
| IAC 80cm[3] | Tek 1024(1994) | 0.43 | 7.2’ | 60 | 0.50 | 5.8 |
| | ” (1995,96) | ” | ” | 180 | 0.84 | 5.8 |
| JKT 1m | Tek 1024[4](# 4) | 0.33 | 5.65 | 50 | 0.20 | 6.9 |
| INT 2.5m | Tek 1024[4] (# 3) | 0.59 | 10.0 | 80 | 0.59 | 6.1 |
| Mees 24” | Kodak KAF4200[5] | 0.40[6] | 6.82 | 300 | 0.91 | 17.1 |
| Capilla 24” | RCA SID50EX | 0.67 | 3.57x5.72 | 120 | 0.77 | 57 |
| Crossley 36”[3] | custom[7] CCD(1994) | 0.58 | 20 | 90 | 0.58 | 19 |
| | custom[7] CCD(1995) | ” | ” | 60 | 1.0[7] | 19 |
| | KAF 4200(1996) | 0.71[6] | 12.1 | 120 | 0.76 | 17.1 |
| Kourovka 0.7m | two-star photometer | n/a | 20 ⊘ | 128 | 1.0 | n/a |
| WISE 40” | Tek 1024 | 0.7 | 11.9 | 240 | 0.86 | 6 |
| Skinakas1.3m | TH 7896A | 0.398 | 6.79 | 60 | 0.60 | 6 |
| OHP 1.2m | TEK512CB | 0.78 | 6.6 | 48 | 0.60 | 6.8 |

[1] $t_{exp}$ is the typical exposure time used for a CCD image of CM Dra

[2] The Duty fraction is the fraction of time the camera is collecting light while observing the object. It is given by: $t_{exp}/(t_{exp}+t_{read}+t_{disk})$, where $t_{read}$ is the CCD read-out time, and $t_{disk}$ is the time to save an image to the disk.

[3] Different cameras or settings were used at these telescopes through the years

[4] A nonlinearity not exceeding 140 e- was corrected from the CCD’s linearity calibration curve.

[5] Nonlinearity was corrected using precints by Deeg and Ninkov (1996)

[6] Used CCD camera in 2x2 bin mode

[7] This CCD system is described in Dunham (1995). Duty fraction of 1.0 results from use of CCD frame-transfer mode

bility of the use of CCD’s in high-precision time-resolved photometry, and emphasized their usefulness for the study of low-amplitude variables (see also Gilliland & Brown 1988). In addition, occasional small-scale variations in atmospheric transmission properties (for example, atmospheric density waves) that could appear as planetary transit events in conventional photometry can be isolated with a wide-field CCD photometric system, using a significant number of comparison stars within the field. We would also like to emphasize CCD’s relative ease of use, as the simultaneous observations of reference stars allows one to leave the telescope pointed towards CM Dra throughout a whole observing night, which is a tremendous advantage on simpler telescopes without computer control.

A list of the properties of the CCD systems used at the various telescopes is given in Table 2. Only at Kourovka Observatory a two-star photometer was employed. In all cases - except as noted - observations were taken through a standard R filter. The CCDs had a field of view of at least 5’ side-length, which allowed us to observe within the images of CM Dra at least 5 reference stars simultaneously - these were normally the stars numbered 1, 4, 15, 16 and 17 in Fig. 2. Exposure times at the various telescopes ranged from 30 to 300 sec, depending on the telescope's size and the dynamic range of the CCD (see Table 2). A maximum exposure time of 300 sec was set to acquire lightcurves with sufficient temporal resolution. At the two-star photometer at Kourovka Observatory, star HD 150172 was observed simultaneously as a reference. This star is very similar in brightness to CM Dra, and photometric counts were recorded every 128 seconds.

## 3. Reduction

The CCD images were bias subtracted and flatfielded using the common procedures in the IRAF software. As the object field is uncrowded, aperture photometry was found to deliver more consistent results than methods based on point-spread-function (psf) fitting. Depending on the different telescopes' fields of view, between 5 and 9 suitable field stars were used as reference "standard" stars. To perform aperture photometry with a maximum signal-to-noise, optimum aperture sizes (Howell, 1989) for each star were determined. Frame-to-frame variations in the size of the stars' psf result from changes in seeing conditions or from changes in the telescope's focusing throughout a night. To correct for this on each frame, the psf of CM Dra (which was the brightest star in the field) was fitted by a circular Gaussian. All apertures are then expressed in multiples of the FWHM of this psf. These multiples were kept constant throughout a night's data. A suite of IRAF tasks for time-series photometry with optimized apertures in uncrowded fields, named '*vaphot*', was developed for these reductions. *vaphot* is available upon request from H. Deeg.

The reference magnitude was based on the sum of the flux of the reference stars, against which the differential magnitude of CM Dra was calculated. Individual reference stars may have unusual brightness variations in some nights, which may result from intrinsic variability or from flatfielding residuals, as described later. To recognize these variations, the difference between each reference star's magnitude and the summed reference magnitude was checked for variability, and often the rejection of one or two reference stars led to improved light curves of CM Dra with lower noise (see Deeg et al., 1997, for an example). The resulting lightcurves were cleaned of obviously erroneous measurements, as well as of events which are most likely flares of CM Dra (see Sect. 4.3). The differential magnitude was then scaled such that CM Dra's average magnitude outside of mutual binary eclipses was zero. All the steps described in this paragraph were performed independently for each night's observations.

The large color differential between the M4 stars composing CM Dra (V-R = 1.8) and the reference stars (V-R = 0.55 to 0.7, except reference star 4: V-R = 0.33, which is a white-dwarf proper-motion companion of CM Dra at a distance of $d \sin i = 445 AU$; Lacy 1977) caused slow airmass-related changes in CM Dra's brightness from differential extinction. In lightcurves with apparent slow variations caused by differential extinction, these variations were removed by subtraction of a fit, which was either a linear or a 2nd order polynomial fit to the off-eclipse lightcurve. With some rare exceptions, the events caused by a possible planetary transit occur on the time-scale of an hour, with ingress/egress lasting on the order of 10 minutes. The removal of the extinction slopes has therefore only a small effect on the signal content of the lightcurve resulting from planetary transits. This removal will also suppress amplitude variations from star-spots, which occur on approximately the same time-scale as the extinction, since the period of CM Dra's components is very likely locked to the binary period of 1.27 days. Final lightcurves were produced in 3 versions: A 'raw' one containing spurious points and flares, a 'cleaned' one where these events have been removed, and a 'fitted' one where the nightly slopes have been removed, as described above.

At some observatories the reduction procedure to obtain the 'raw' lightcurve had to be modified: The data from the CCD at the Rochester telescope exhibited a nonlinearity (Deeg & Ninkov 1995), which required a correction step before flat fielding. The raw reduction of the data from the Skinakas telescope was performed independently, using the MIDAS software (Palaiologou, personal communication). The photometer data from Kourovka observatory only required subtraction of the reference star's magnitude, followed by removal of the nightly extinction slope.

Of special interest for the detection of planetary transits are noise and error sources which can cause deviations in the data that may appear similar to planetary transits. The two major sources for errors with time scales of transit events ( $\gtrsim 40$ min) are (i) atmospheric instabilites and (ii) flatfielding errors.

(i) Atmospheric effects: The reference stars where traced for changes in their relative brightness amongst each other. If such changes occured above the normal noise, these particular data were rejected. As mentioned, CM Dra is a much redder star than any of the reference stars in the field, whose colors are all within a relatively narrow range. The brightness ratio between CM Dra and the reference stars is therefore more sensitive to second order extinction changes (i.e. changes in the color-dependency of the extinction within the bandpass of the R-filter) as are the brightness ratios among the reference stars themselves. In rare cases, it may be feasible, that temporary effects (for example, a band of very fine cirrus, or dust) in the atmospere can cause strong second order extinction changes, without sufficient first-order extinction variations to warrant a rejection of the data.

(ii) Flatfielding: Errors from flatfielding may appear if the spatial distribution of the stellar light on the CCD undergoes positional changes between images. This happens if the telescope tracking allows the stars to appear in slightly different positions in subsequent exposures. Imperfect flatfielding corrections will then appear as brightness variations among the stars. Flatfielding effects may strongly affect the data, if a star happened to move over a bad CCD pixel or column, or over a dust-corn on an optical surface. Although care was taken to keep these 'features' away from any star, and especially from CM Dra, sometimes they may not have been recognized, or dust-corns may have changed their positions. If such a flatfielding variation affected any one of the reference stars, it caused an unusual change in its brightness relative to the other reference stars, and this reference star was not used in that night's summed reference magnitude. More difficult are cases in which the program star (CM Dra) may have been affected by flatfielding variations. To avoid this, we tracked the positional changes throughout each night, and rejected data with suspicious brightness variations of CM Dra, *if* they correlated with positional movements.

Even in a well-tracking telescope, where the center positions of the stars do not notably change throughout a night, flatfielding effects may appear if changes in the seeing cause

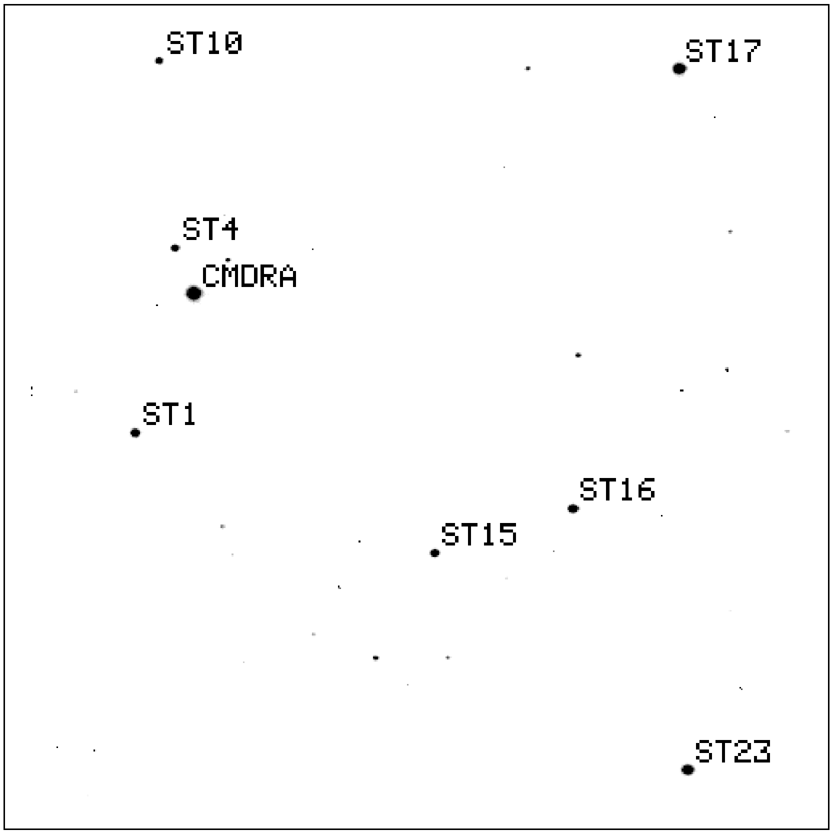

**Fig. 2.** Field of CM Dra with the most commonly used reference stars marked. N is up and E is left. The side length of the field is 7.2 arcmin

variations in the relative illumination among the CCD pixels. If seeing was monotonically de- or increasing throughout a night (which was the most frequent case), or correlated with the airmass, the consequent flatfielding effects will have been removed by the linear or second order fit to the data mentioned previously. Furthermore, data were rejected where brightness variations of CM Dra correlated with variations in the seeing.

In summary, care was taken to avoid error sources that could create transit-like signatures in the data. However, such error sources could not be excluded with certainty to be the source of any *individual* feature in the data that may appear interesting. Verification of transit features is only possible by repeated observation of transits from the same planet.

## 4. Results

The final lightcurve presented here contains 17176 points acquired over three years, and gives a complete phase coverage for CM Dra (Fig. 3) at each of the three observational seasons. A break-down of the observational coverage is given in Table 3 and in Fig. 4. The 'typical rms noise' column in Table 3 is the noise of the final lightcurves from each telescope on good nights. On some very good nights, the rms of the larger telescopes was better than 2 mmag, whereas a noise of about 6 mmag was the cut-off for data to be included into the final lightcurves.

### *4.1. The noise of the lightcurve*

Figure 5 shows power spectra of the observed data over-plotted with spectra from model planetary transits with periods of 10, 20 and 45 days. The power spectra were calculated by phase dispersion minimization with the program POWER (Kjeldsen, personal communication). For the detection of planetary transits which may be hidden from ordinary view in the noise of the lightcurve, it is important to note the differences in the power spectra. The observational data have a relatively flat spectrum, with a maximum at frequencies around 7 $day^{-1}$, corresponding to a period of 200 minutes. The power of the planetary transits peaks much more pronounced between 5 and 12 $day^{-1}$ (corresponding to periods between 1 and 2.5 hours, which is the

**Table 3.** Overview of observational coverage for the 3 years

| Telescope | Observing coverage (hrs)[1] | | | number of data points | | | typ. noise |
|---|---|---|---|---|---|---|---|
| | 1994 | 1995 | 1996 | 1994 | 1995 | 1996 | (mmag) |
| IAC 80cm | 38 | 62 | 22 | 1036 | 1101 | 473 | 4 |
| JKT 1m | - | 39 | - | - | 765 | - | 3 |
| INT 2.5m[2] | - | - | 42 | - | - | 986 | 3 |
| Mees 24" | 53 | - | - | 767 | - | - | 5 |
| Capilla 24" | - | - | 18 | - | - | 298 | 4 |
| Crossley 36" | 65 | 50 | 46 | 1670 | 2714 | 991 | 4 |
| Kourovka 0.7m | | | 68 | - | - | 1926 | 5 |
| WISE 40"[3] | - | - | 28 | - | - | 390 | 4 |
| Skinakas 1.3m | 19 | - | - | 1245 | - | - | 4 |
| OHP 1.2m[3] | 11 | 34 | 22 | 547 | 1452 | 815 | 3 |
| total | 186 | 185 | 246 | 5265 | 6032 | 5879 | |

[1] Observing coverage is the length of the time for which a usable lightcurve of CM Dra was obtained. Coverage was considered continuous for interruptions of less than 15 minutes. [2] Observations were taken through a redshifted H$\alpha$ filter. [3] Some of these observations were taken in V band.

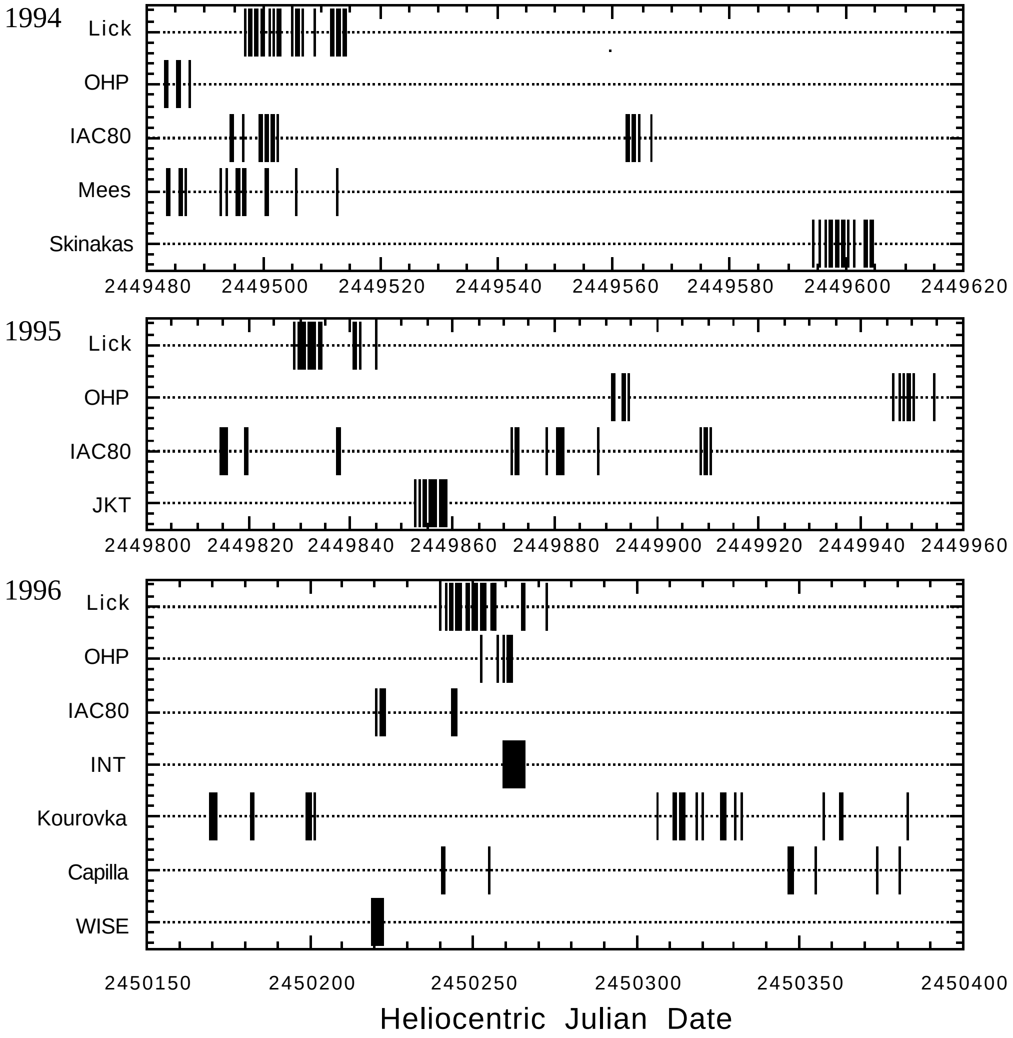

**Fig. 4.** Coverage diagrams of the individual telescopes for 1994-1996

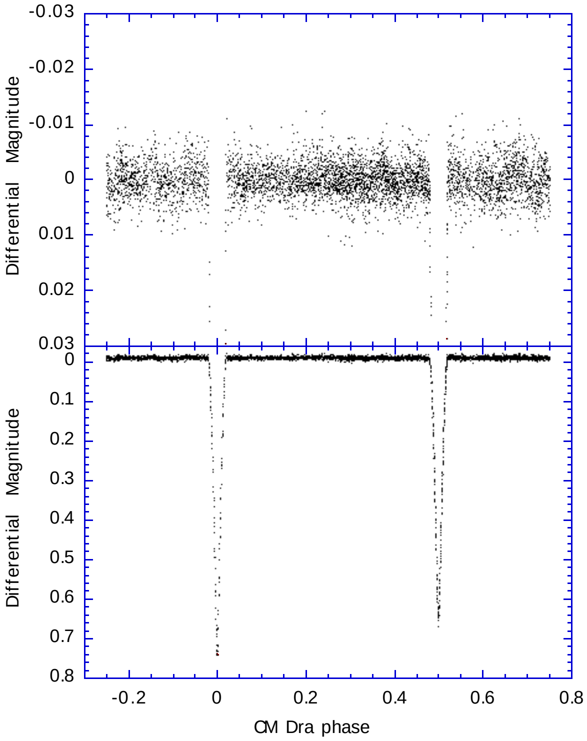

**Fig. 3.** Plot of the composite lightcurve of CM Dra against phase, containing the 17176 data points obtained in 1994-1996. The two panels show the same lightcurve with different magnitude scaling

typical length of planetary transits), and there is little power left at frequencies above 20 $day^{-1}$. For this analysis, the mutual eclipses of CM Dra, as well as the nightly extinction slopes have been removed which accounts for the absence of power at frequencies below 5 $day^{-1}$. This also fortuitoisly removes most of the power from signals that appear with the period of CM Dra (such as starspots). As can be seen in Fig. 5, there is very little power left at CM Dra's period of 0.79 $day^{-1}$. Also absent is the first harmonic at 1.58 $day^{-1}$, which might be strong, since primary and secondary eclipses have nearly equal amplitudes.

### *4.2. Eclipse minima timing*

An analysis of the minimum times of the mutual eclipses of an eclipsing binary may reveal the presence of a third body in this system. In such a case, the orbital period of the third body should cause periodic changes in the time of the minima, as the distance to the binary system is offset by its motion around the 3-body barycenter. In the CM Dra system, for example, a planet with the mass of Jupiter at a distance of 5 AU would cause a periodic shift of minimum times with an amplitude of 5.5 seconds (Doyle et al. 1997).

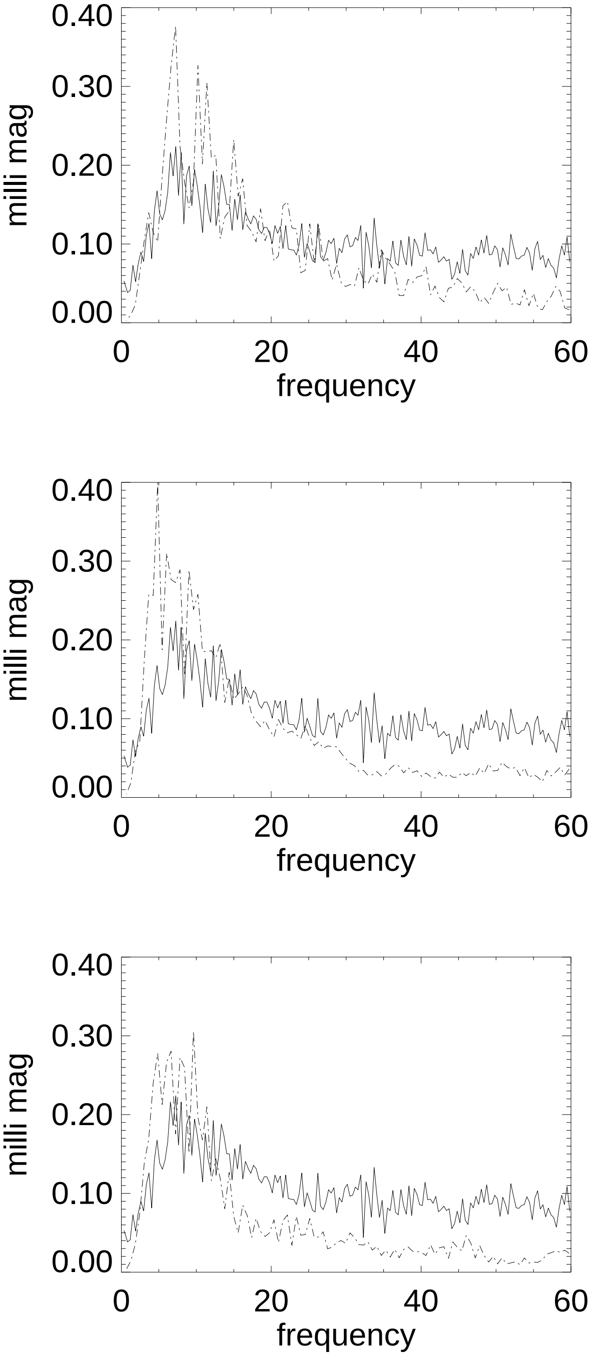

**Fig. 5.** Smoothed relative power spectra of the observed lightcurve from 1994-1996 (solid line), over-plotted with power spectra for models of planet transits with 10, 20 and 45 day periods. The unit of the frequency axis is cycles per day. The vertical scale is in milli-magnitudes, however it is important to note that this scale applies only to the observed lightcurve. The power spectrum of the model-transits cannot be scaled to measurable units, since the duration of the transits is very short in comparison with the time between transits, where the model lightcurve has no signal. The models were calculated for the same time-points as the observed data. For both the observed data and the model-lightcurve, low frequent power (nightly extinction) was removed in the same way (see description in Sect. 3). In all cases, the power of the modeled planetary transits is concentrated towards frequencies of 5-15 $day^{-1}$, whereas the power from the noise in the observed data is relatively flat.

**Table 4.** List of flares observed in 1994-1996

| Julian Date (jd-2400000) | duration (days) | amplitude (mag) | nightly rms (mag) | telescope | remarks |
|---|---|---|---|---|---|
| 49483.587 | >0.021 | 0.023 | 0.0075 | OHP | end of flare not observed |
| 49495.78 | 0.036 | 0.017 | 0.0050 | Mees | |
| 49563.475 | 0.030 | 0.027 | 0.0042 | IAC80 | first peak of double flare |
| 49563.505 | 0.025 | 0.026 | 0.0042 | IAC80 | second peak of double flare |
| 49598.396 | 0.035 | 0.018 | 0.0035 | Skinakas | clear flare in good night |
| 49600.379 | 0.021 | 0.030 | 0.0044 | Skinakas | clear flare in good night |
| 49601.409 | 0.025 | 0.05 | 0.0041 | Skinakas | clear flare in good night |
| 49854.495 | 0.025 | 0.046 | 0.0026 | JKT | clear flare in good night |
| 49891.440 | 0.020 | 0.041 | 0.0027 | OHP | clear flare in good night |
| 50238.848 | 0.035 | 0.020 | 0.0030 | Lick | uncertain, as shortly after clouds |
| 50243.757 | 0.025 | 0.020 | 0.0026 | Lick | first of two flares that night |
| 50243.872 | 0.017 | 0.013 | 0.0026 | Lick | uncertain second flare, only 1 high point |
| 50244.510 | 0.030 | 0.018 | 0.0058 | IAC80 | noisy night |
| 50262.615 | 0.009 | 0.025 | 0.0035 | INT | unclear, at begin of secondary eclipse |
| 50263.464 | 0.026 | 0.047 | 0.0036 | INT | first peak of double flare |
| 50263.502 | 0.018 | 0.035 | 0.0036 | INT | first peak of double flare |

This method is however unsuitable for the detection of planets with masses significantly smaller than giant planets. The three years of observational coverage of CM Dra contain 16 primary and 19 secondary eclipses, on which the time of minimum brightness could be measured reliably, with uncertainties of less than 10 seconds. Minimum times were measured with the 7 segment Kwee-Van Woerden method (Kwee & Van Woerden 1956). We also re-measured the minimum times of the three eclipses observed by Lacy (1977). Against the epochs cited by Lacy, re-measuring gave discrepancies of 10 and 35 seconds for his two primary eclipses, and a discrepancy of 6 seconds against the one secondary he observed. We therefore prefer to assign new epochs to CM Dra as follows: primary eclipse: JD 2449830.757 00±0.000 01, secondary eclipse: JD 2449831.390 03±0.000 01, and a period of 1.268 389 861±0.000 000 005 days, based on a fit to the 35 minimum times from 1994 to 1996 and the remeasured values for Lacy's primary eclipses. With these new elements, our observed - calculated (O-C) minimum times have a scatter of only about 6 seconds. This small scatter excludes periodic changes in the minimum times with amplitudes larger than 9 seconds and periodicities of less than about 4 years. We therefore cannot support the claim made by Guinan et al. (1998) of a 70.3 day periodic variation in minimum times with an amplitude of 18 seconds, that would have been indicative of a very massive planet (see also Deeg et al. 1998).

### *4.3. Flares*

Several flare events of CM Dra were observed. In Table 4, the time of the peak maximum, the total duration, maximum brightness, the average noise(rms) of that night, and the observing telescope are given. Lacy (1977) already noted the low flare rate of CM Dra compared against the rate of $2hr^{-1}$ expected for a Population I flare star. Our observations confirm a low flare rate of $\approx 0.025hr^{-1}$ over the 3 years of observations, although only 2 flares were observed in 1995, corresponding to a rate of $\approx 0.011hr^{-1}$. Since only flares with durations of more than several minutes (identified flares had to contain more than one data-point, as spikes of single points may also be caused by cosmic rays hitting near CM Dra) and with amplitudes of $\gtrsim 0.015mag$ could be identified clearly, the observed flares represent a minimum flare rate. Since CM Dra is a tidally locked system, we cannot derive any information about its age from the flare rate. However, for a relatively fast rotator, CM Dra's flare rate is notably low.

Since flares introduce a spurious signal into the lightcurve, they have been removed from the final lightcurves that are being used in the further analysis to detect planetary transits.

### *4.4. Potential planetary transits*

The goal of these observations has been the detection of transits from planets orbiting the CM Dra system. The lightcurves were therefore visually scanned for the presence of events which might be indicative of planetary transits. Such events, further called *transit candidates*, are typified by being temporary faintenings of CM Dra's brightness by a few millimagnitudes, with normal durations of 45 - 90 mins. Transit events may last as long as a few hours, but only if CM Dra is very close to a primary or secondary eclipse in the middle of the event. Several potential transit events have been observed and are included in Table 5. Their light-curves are shown in Fig. 6. It is not possible to derive elements of potential planets (with the exception of their diameter), if any *one* of these transit candidates is considered isolated, since the duration of a planetary transit depends only weakly on the planetary period. An exception is the transit candidate at JD 2449909.53 (Fig. 6e), where the long transit duration is only compatible with a planet with a period of less than 9 days, or a period between 25 and 32 days. Even if a hypothetical planet has already caused two observed transits, its period will generally still be ambiguous because of the unknown number of orbits completed between the two transits.

*If* there are any short-period ($\lesssim$ 60 days) planets around CM Dra, it would not be unlikely that these have already been observed more than twice in our 617 hrs of observational coverage. For example, a planet with a period of 10 days will cause

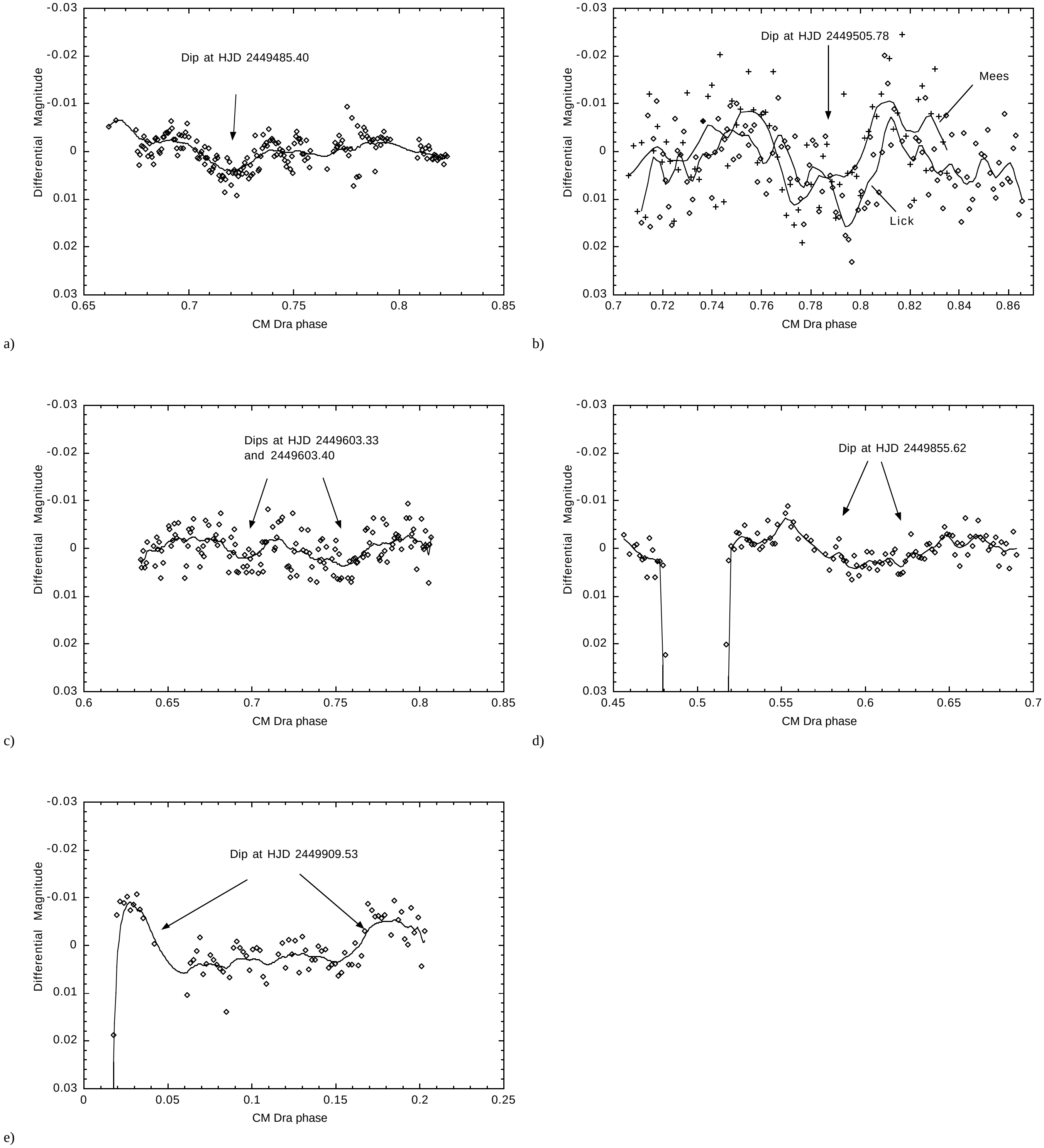

**Fig. 6.** The six planetary transit event candidates from Table 5. The lightcurves are plotted against the phase of CM Dra. The data are shown as squares; the line indicates a smoothing fit to the data. a) Event at Heliocentric JD 2449485.395 observed at OHP. b) The event centered at JD 2449505.78, observed simultaneously at Lick (squares) and Mees (crosses) observatories. The light drop appears about 10 minutes later in the Lick observations; this delay may be caused by noise in the data. The amplitude in the Lick data is 0.001 mag, whereas in the Mees data it is 0.0014 mag. c) Double dip at JD 2449603.33 and 2449603.40. d) Dip at JD 2449855.62, occurring shortly after a secondary eclipse. e) A long flat dip observed at JD 2449909.53. This event occurred shortly after a primary eclipse that was observed at the beginning of this night, and had a duration of 180-240 minutes.

**Table 5.** List of photometric events which might be caused by planetary transits

| Julian Date (jd-2400000) | duration (days) | amplitude (mag) | nightly rms (mag) | telescope | remarks |
|---|---|---|---|---|---|
| 49485.395 | 0.046 | 0.007 | 0.0065 | OHP | |
| 49505.775 | 0.05 | 0.01 | 0.0077 | Mees | observed also at Lick? |
| 49505.785 | 0.05 | 0.008 | 0.0065 | Lick | observed also at Mees? |
| 49603.33 | 0.033 | 0.004 | 0.0038 | Skinakas | first of double dip? |
| 49603.399 | 0.06 | 0.005 | 0.0038 | Skinakas | second of double dip? |
| 49855.620 | 0.098 | 0.005 | 0.0022 | JKT | |
| 49909.535 | 0.16 | 0.01 | 0.0032 | IAC80 | long flat dip |

2 transits (one transit for each component of CM Dra) every 240 hrs, giving an average of 5.1 observed transits within the 617 hours. The exact number of observed transits depends, of course, on the exact period and orbital phase -or epoch- of a planet (at 0°phase, the planet is crossing in front of the binary barycenter). The numbers of transits that are expected in our actual lightcurve are given in Fig. 7 for two examples of hypothetical planets with periods of 10.14 and 45.14 days (the odd periods were chosen to avoid aliasing effects). For a 10.14 day planet, the observed lightcurve would contain between 1 and 12 transits, depending on the planet's phase. A 45.14 day planet could have caused up to 5 transits, but there is also a 15% chance of missing this planet entirely. The probabilities that certain numbers of transits from planets with various periods are within the 617 hrs observational coverage is given in Table 6.

**Table 6.** The probabilities (in percent) of the number of transits observed within the observational coverage from planets with selected periods. For example, if there is a planet with a period of 30.14 days present, the probability that it has caused 1-2 transits in the observations from 1994-1996 is 53 %

| Planet period | No transits (%) | 1-2 transits (%) | more than 3 transits (%) |
|---|---|---|---|
| 10.14 days | 0.0 | 2.4 | 98 |
| 15.14 days | 2.1 | 13 | 85 |
| 20.14 days | 2.4 | 31 | 67 |
| 30.14 days | 5.7 | 53 | 41 |
| 45.14 days | 15 | 63 | 22 |
| 60.14 days | 20 | 69 | 10 |

Assuming that we may have already observed transits of a potential planet 3 or more times, we searched for periodicities among the transit candidates, using those shown in Fig. 6, and a few less pronounced candidates. Among these *transit* candidates, several thousand possibilities for *planetary* candidates (with 3 or more already observed transits!) were found. Each *planetary* candidate represents a combination of a possible planetary orbital period and epoch, the later one being defined as the time, when the planetary candidate is crossing in front of the barycenter of CM Dra, as stated. Modeled lightcurves of these planetary candidates (assuming radii of 1.5, 2 and 2.5 $R_E$, and using the model-code that generated the curves shown in Fig. 1) were cross-correlated against the observed lightcurve. This led to a list of several 100 planetary candidates which reasonably fitted the observed lightcurve. For the best 10 of these planetary candidates, transit times were predicted, and pointed observations at these predicted times were undertaken in the Spring of 1997 at the IAC80 telescope. Unfortunately, no transits were observed at any of these predicted times. Except for these 10 tested planetary candidates, however, these results cannot rule out any other planets in this size range yet. Since it is impossible to observe at predicted transit times for the whole list of several 100 planetary candidates, we are currently again engaging in observations that will increase transit coverage in general, in order to reveal further smaller transit candidates. We want to emphasize, that the observed transit candidates of Fig. 6 are examples of events that can be caused by planetary transits, but only *repeated* observation of transits from the *same* planetary candidate can verify their true nature.

Whereas there are multitudes of planetary candidates that may have caused the light drops reported in Table 5, we note that there are no observed light-drops with amplitudes larger than 0.01 mag. Cross-correlations between model-lightcurves of planetary transits and the observed light-drops showed that in no case can planets much larger than 2.5 $R_E$ be responsible for these observed light-drops. Our observational coverage gives a confidence of about 80% that such larger planets with periods of less than 60 days can be excluded. For periods of less than 20 days, this confidence is 98%. If the light-drops of Table 5 and Fig. 6 are indeed from planetary transits, they must result from planets with sizes between 1.5 and 2.5 $R_E$.

A signal detection approach was taken for preliminarily assessing confidence in the detectability of planets in this size range within the current data set. For this, 36000 model transits were generated for 2 $R_E$ planets with periods of 10 days through 30 days (the habitable zone around CM Dra), and included in the data. Subsequent detection attempts (Fig. 8) showed that 50% of the time, the detection statistic for a 2 $R_E$ planet transiting CM Dra would be above the detection statistics generated from our photometric data (the number of times the cross-correlation values for the transit curve were higher than the noisy observational data). Thus, our data from the 1994 through 1996 observing seasons allow us a confidence level of 50% that an actually existing 2 $R_E$ planet would have been detected. For a 3 $R_E$ planet, a similar test gave 90% confidence.

We would like to note, that one transit candidate reported by our group (Martín et al. 1996) turned out to result from a problem with the flatfielding of that night's images. There

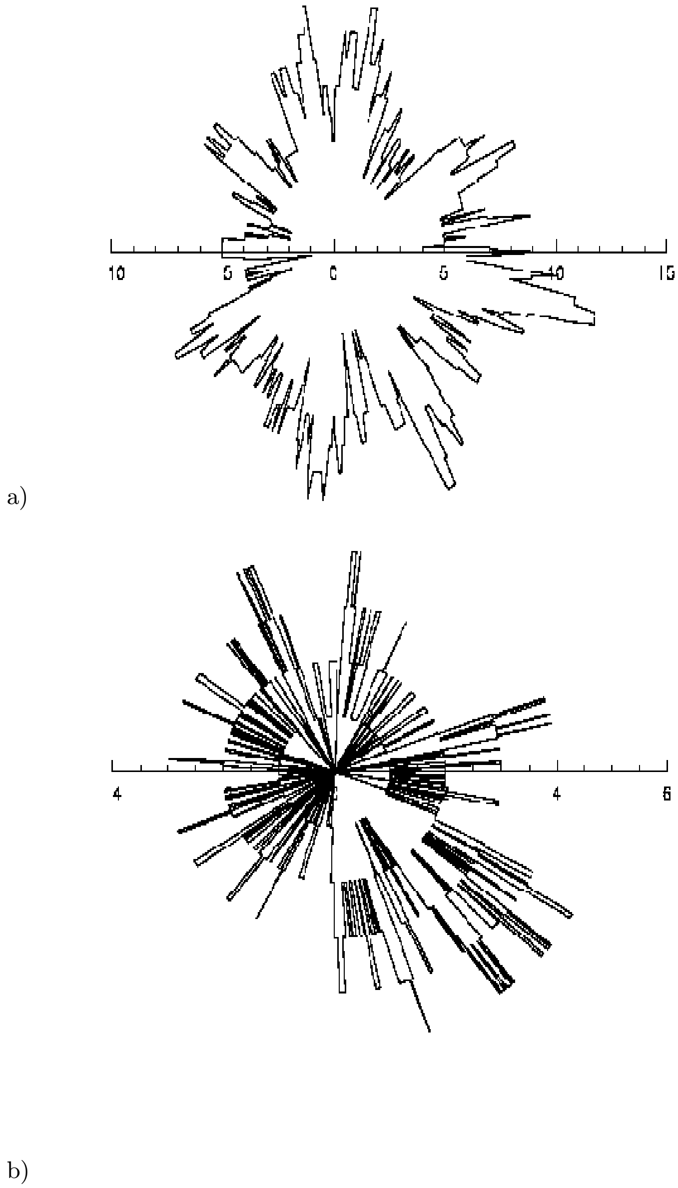

**Fig. 7.** The expected number of transits that would have been observed in our actual lightcurve of 617 hrs, for a hypothetical planet with a period of a) 10.14 days and b) 45.14 days. The clockwise direction is the planet's phase (going from 0 to 360 degrees) and the radial direction gives the number of transits. The phase is defined here as the phase of the planet at JD 2450000.0; phase zero means the planet is in front of the barycenter of CM Dra).

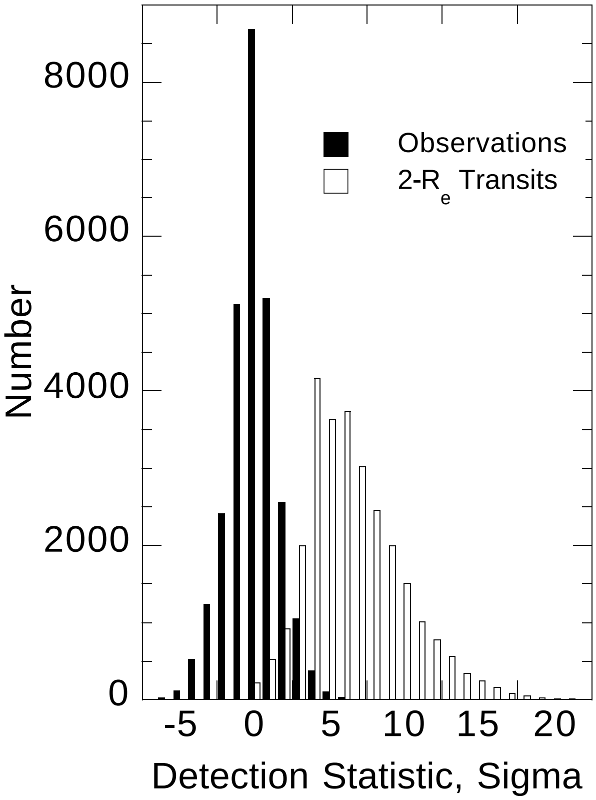

**Fig. 8.** Shown are the generated detection statistics for a hypothetical 2-Earth-Radii planet (right) that would cause transits of 1.5 hours each in our observational light curve (left). The degree of overlap of the two peaks (detection on the right and non-detection on the left) is a measure of detectability of the transit signals - if they overlap completely, no detection is possible. Clearly a detection can take place reliably at least 50% of the time, demonstrating that we have already reached a detection limit well into the terrestrial-sized planet range (a 2-Earth-Radii Planet is 1% the size of Jupiter).

were also reports (Guinan et al. 1996, 1997) of CM Dra being fainter by 0.08 mag throughout the whole night of June 1, 1996. If this event would have been caused by a planet with about 0.94 Jupiter diameters, the long duration of the transit would indicate a planet with an orbital period of about 2.2 years. For such long periodic planets, the probability that their orbital plane crosses in front of CM Dra, as well as the probability of catching a transit at the right time, are both very low. Most important however, such a planet should have caused periodic variations in the minimum times of CM Dra's primary eclipse of over 10 seconds, which have *not* been detected (see Sect. 4.2). We never encountered any brightness variations this large and this long in duration (the latter would have been due to our reduction procedure, where we set the brightness of CM Dra relative to its reference stars to zero for each night). Our data are therefore less sensitive to slow-changing atmospheric extinction variations but would miss unusually long transits that began before *and* ended after the nightly observations. However, since none of the reference stars anywhere near the field has a red color similar to CM Dra, relative brightness changes may have been caused by differential color extinction. In addition, Guinan et al.'s observations were done in I band, which is notorious for variations caused by OH$^-$ in the atmosphere. We believe therefore, that the event reported by them was most likely caused by a night with abnormal extinction, or was due to a flatfielding problem.

## 5. Summary

The TEP network has embarked on obtaining extended observational coverage of the eclipsing M star binary CM Dra with the goal of detecting transits of planets which are orbiting in the plane of the binary components. Reported here are the data from the first three years of this project, covering the years 1994 through 1996. Time series of about 200 hours coverage were obtained in each year of observations, containing a total of 17176 data points. This gives the most thorough coverage of any binary eclipsing star observed to date. In this coverage we observed six events in which the brightness of CM Dra dropped between 0.004 mag and 0.01 mag over a time scale of an hour. These events are compatible with planetary transits, but their true nature can only be ascertained by further observational coverage. The absence of any light drops larger than 0.01 mag allows us to rule out the presence of close planets with radii of larger than 2.5 $R_E$ (corresponding to about 1.1% the volume of Jupiter), with a confidence of 80% for orbital periods of less than 60 days. The confidence is 98% that such planets are absent with periods of less than 20 days. The light-loss events listed in Table 5 are examples of what lightcurves from the transits of extrasolar planets with sizes between 1.5 and 2.5 $R_E$ should look like. But again, their true nature can only be confirmed by observations of repeated transits from the same planet.

Furthermore, the light-loss events in Table 5 only contain events that are *visible* in the lightcurve. The typical noise in the lightcurve is 2-3 mmag, and events from planets smaller than about 2 $R_E$ could be hidden in the lightcurve. Such small planets, although their transits are visually undetectable in the lightcurve, may be found by the application of a matched filter algorithm - i.e. cross-correlations with the quasi periodic signals caused by planetary transits (Jenkins et al. 1996). Detection statistical calculations show, that the confidence that planets with $2R_E$ could be detected in the current data - *if* they are present - is about 50%. In conclusion, it is therefore definitively possible to use the photometric transit method with ground based 1 meter class telescopes to obtain results about the presence of extrasolar terrestrial-sized planets within a star's habitable zone. With larger telescopes and longer observing times, this method may be extended to the detection of terrestrial-like planets around many other eclipsing binary systems, as well.

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