From CM Draconis to the Crowded Field BW3: Aspects of the Search for Extrasolar Planets Around Small Eclipsing Binaries

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Abstract

We review some apsects of the search for extrasolar planets around small-mass short-period eclipsing binaries, including lessons from the extensive search around CM Draconis (over 1,000 hours), and the extention of the search to small eclipsing binaries in the crowded field Baade's Window 3 (BW3) in the Galactic plane. In addition to being of intrinsic interest to planet formation studies, due to a likely more complex angular momentum history than single stars, we outline several aspects of planet detection around eclipsing binaries that also make them attractive targets for ground-based searches.

Advantages of Eclipsing Binary Searches

CM Draconis is the smallest known eclipsing binary system consisting of two M4 main-sequence stars of total mass 0.444 M_s (solar mass), and a total area about 12% that of the solar disc (Lacy 1977). Immediately this made it a prime candidate for extensively testing the photometric transit detection method as its small cross-sectional area allows the highest differential attenuation for a transiting planet of a given size, while the small total binary mass allows the largest offset by a third-body giant planet by the eclipse timing method (Schneider and Doyle 1995, Deeg et. al. 2000).

The advantage of choosing eclipsing binaries for such photometric transit searches include, of course, an expected higher probability of planetary orbital alignment with the observer's line-of-sight, with precessional damping of protoplanetary material—caused by the binary itself—further being expected to constrain the tendency for protoplanetary material to accrete in the binary orbital plane (Schneider and Doyle 1995).

Transit events across eclipsing binaries are quasi-periodic as the planet is not so much crossing in front of a star (as in the single star case) as the binary stars are orbiting behind the planet as it moves through the "transit window" (i.e. across the region of the binary barycenter as seen along the observer's line-of-sight). This quasi-periodicity can have two effects: to generally reduce the duration of individual transits, and to allow such transits to be clearly distinguished from rotational periodicities. Shorter individual transit events (50 minutes is typical for CM Draconis) take place at a lower noise region in the ground-based observational power spectrum than typical single star transits of 5 hours or more—the observational noise at a frequency of 4.8-day^{-1} is almost 4 times the noise power at 28.8-day^{-1} (Doyle et. al. 1996, Deeg et. al. 1998, Jenkins et. al. 2000).

Close binaries (especially highly convective late-type dwarfs) will rapidly become tidally locked in rotation so that short-term periodicities associated with any starspot activity, for example, should be easily separable from planetary transit events (without the need for multiple-filter bandpass observations ; see Rosenblatt 1971; Borucki and Summers 1984). In addition, this quasi-periodicity lends itself to a modeling of possible transits that can be "matched" with the differential light curve (Jenkins et. al. 1996, Doyle et. al. 2000). By comparing (correlation matching) models of virtually all possible transit events that could have occurred within the light curve, transit events of individual candidates may be isolated and their detection confidence may be quantified, which we will discuss further below. (We note that such detections do not take place in frequency space as the total amplitude attenuations expected by infrequent transits would not have sufficient power in the spctrum to be detected.)

Finally, in addition to transit detection, eclipsing binaries are a sort of "clock" in themselves—the binary pair, when offset around a second barycenter (caused by the giant planet), show a periodic delay or advance in the time of occurance of their eclipse minima. Such a second barycenter offset would have to result from a third massive body being in orbit around the binary pair (Doyle et. al. 1998). Thus a precise timing of eclipses can also allow the detection of jovian-mass planets around the stellar system provided the giant planets have sufficiently large semi-major axes (i.e. a few light seconds).

The CM Draconis Search

Observations and Modeling

In order to detect extrasolar planetary transit events at or below the photometric observational noise level (the signal or intrinsic detectability, p_i), as well as to approach the likelihood of a transit event actually being in the data (the coverage or observational detectability, p_o) a great deal of data must be obtained. To this end we (the Transit of Extrasolar Planets, or TEP Network; Deeg et. al. 1998) observed CM Draconis over the observing seasons from 1994 to 1999. Requring the photometric precision to be better than 0.7% we obtained a total of 1,014 hours of (mostly R-band) photometry on the system. These observations resulted in a light curve (differential magnitude—CM Draconis minus the standard stars in the field—plotted agains Heliocentric Julian Day) with 26,042 points, including 82 eclipse events (Doyle et. al. 2000, Deeg et. al. 2000, Deeg and Doyle 2000).

We then generated models for virtually all possible planetary transits that could have occurred across the discs of CM Draconis A and B using a program we call the transit detection algorithm (TDA). Due to the extensive coverage, over 570 million individual models of possible planets were required, each one with a different period and starting phase (the phase of CM Draconis already being known at each observation time). Optimizing the detection limit for the smallest possible planet size we reached a 90% detection confidence for planets of size 3 R_e (Earth radii) with periods of 60 days or less (the confidence was

99% for 30 day periods), and a confidence of 50% for planets of size 2.5 R_e (80% for periods of 10 days or less). Thus this was the confidence (in the signal detection sense) with which we would have expected to have seen such planet transits at the noise level in our observatons (see Doyle et. al. 2000, for full details).

While no outstanding candidates appeared in this search, it is clear that when performing such a search near the observational noise (0.45% photometry translates to a single transit of a planet of size 2.6 R_e around CM Draconis) predicted transit events with follow-up observational confirmations are essential. Of the nine top candidates we isolated with the TDA, only one has presently “survived” the follow-up observational tests. In addition, we have precisely determined times of minima of the 82 binary eclipses from 1994 through 1999 and a sub-set of the best of these should allow strong constraints to be placed on jovian-mass planets in orbit around CM Dracoins (essentially regardless of orbital inclination) for periods from about 100 days to over a decade (see Deeg et. al. 2000, for full details).

Conclusions From CM Draconis of Bioastronomial Interest

CM Draconis may be the first main-sequence system searched for, what may essentially be considered, terrestrial-sized planets. The significant transiting planet detection limit achieved was in the range 2.5 to 3 R_e, or about 1% to 2% the size (volume) of Jupiter. The region essentially searched—from 7 to 60 days—was dictated by the nearest possible stable planet orbit (a binary-to-planet semimajor axis ratio of about 1 to 3 being required; Holman and Wiegert 1999) as well as our total data coverage (for multiple transits to be in the light curve). As the CM Draconis system itself has only about 1.03% the total luminosity of the Sun, this region—from 7 to about 35 days—constitutes the region that receives an equivalent amount of stellar energy as the terrestrial planets in our Solar System. (Interestingly enough, the surviving candidate from our 1999 observations has a period of about 22.6-days, giving it an equivalanet insolation about that of Earth. This will be observationally confirmed or ruled out next year.)

The circumstellar habitable zone (CHZ) is defined as the region around a star that receives enough stellar flux to accommodate liquid water on the surface of a roughtly Earth-like planet. The inner boundary is conservatively limited by the locale where a moist runaway greenhouse would occur (water is photodissociated in the upper atmosphere) , while the outer boundary of the CHZ can be defined as the locale where CO_2 condensation begins—i.e., not only losing its greenhouse warming properties but increasing the planetary albedo by snowing out of the atmosphere (Kasting et. al. 1993). By these criteria, the CHZ around virtually all M-dwarf stars is well within the tidal rotational locking limit for a planet (this is because the luminosity increases with the inverse square of the planet’s orbital semi-major axis while the tidal force increases as the inverse cube of this distance).

What then, one may ask, would be the interest in main-sequence M-stars from the viewpoint of possible exobiology, as any planets within the CHZ would be synchronous locked to the orbital period and the atmosphere might be expected to boil off on the stellar side and freeze out on the dark side? Interestingly, however, recent 3-D modeling of synchonously rotating planets have revealed that only about 100 millibars of CO_2 would be sufficient to lower the thermal gradient so that liquid water could exist on an Earth-like planet’s surface within the habitable zone of such a synchronously rotating planet (Haberle et. al. 1996). Further, M-stars might allow a proportionately extended inner boundary to their CHZ (perhaps as high as three times the solar inner CHZ flux) as there is essentially no UV radiation from M-stars to initiate the photodissociative escape of water in the upper atmosphere, and therefore no moist runaway greenhouse effect (Joshi et. al. 1998). Finally, as the result of a recent in-depth study of infrared photosynthesizing bacteria as the base of an M-star planetary ecosystem, it would appear that higher-plant habitability might be possible (Heath et. al. 1999). Given that such M-stars (at least in the solar neighborhood) constitute about three-quarters of all stars, such results could be rather encouraging for exobiological studies, as well as allowing CM Draconis itself to remain of relevant interest to the bioastronomical community.

Extention to Larger Telescopes and Crowded Stellar Fields

We conclude, from the work outlined above, that a successful search for both inner terrestrial-sized and outer jovian-mass planets around small eclipsing binaries may be undertaken with existing technology using the photometric transit method. For stars with larger disc areas, and also of larger masses, the photometric precision must be improved,and this can best be accomplished by going to larger telescopes. Figure 1 shows the improvments in detection one might expect, scaling from results on CM Draconis using the Crossley 0.9-meter.

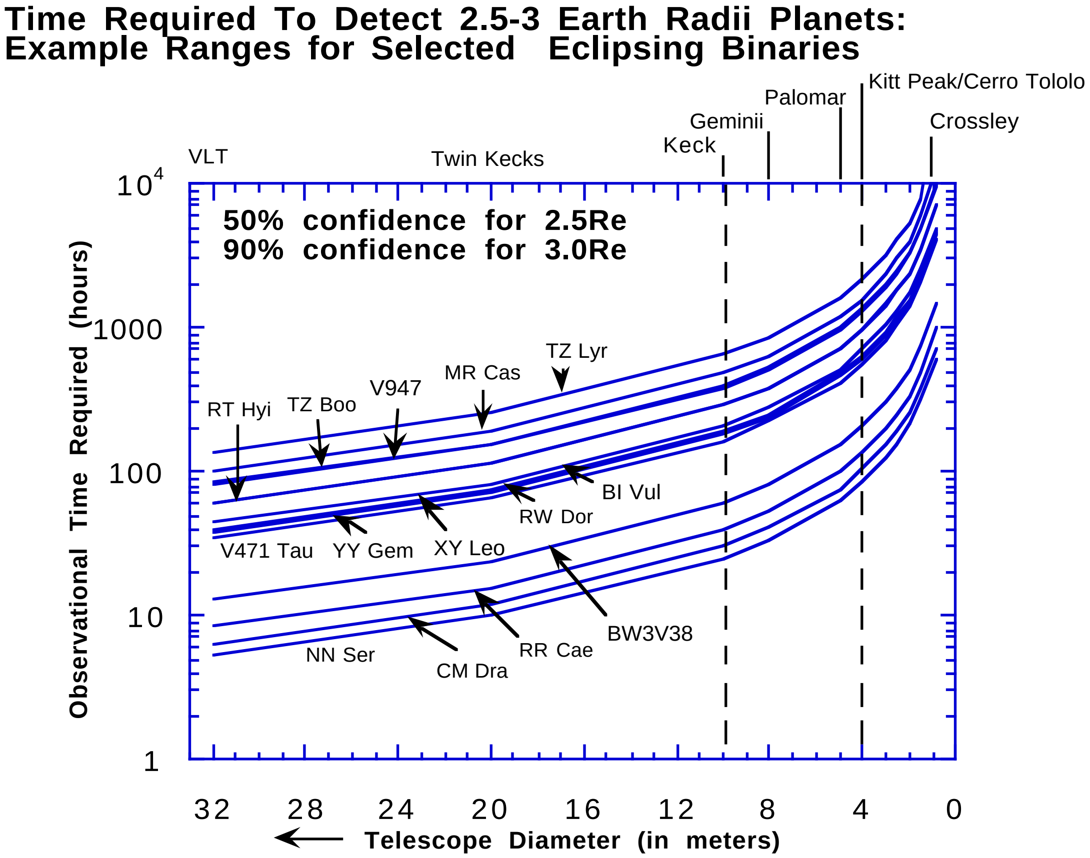

Figure 1. A comparison of times required to reach the stated detection confidence for 2.5 and 3.0 Earth radii transiting planets (p_i), scaled for telescope aperature size from the Crossley results for CM Draconis. Scaling includes both Poisson statistics and improvement over scintillation with (telescope aperture)$^{-2/3}$ (see Dravins et. al. 1998, Eq. 10). Telescope size cannot, of course, mitigate the necessity for thorough period-phase observational coverage (p_o).

Observing times are long but reasonable. For example, an approximate 90% confidence is given for a 3 R_e planet to be detected with a mean period of about 30 days in about 700 hours using the Crossley, while about 100 hours on the VLT would be required to constrain the presence of a 2.5 R_e planet at the 50% level around MR Cas, for example. It is important to note that these times refer only to the intrinsic detection probability, (p_i), *and do not abviate the necessity of full period-phase coverage* (p_o). The total detection probability is: $p_d = p_i p_o$ (see Doyle et. al. 2000).

In addition to larger telescopes one would like to obtain as substantial a statistical result as possible for many stars, indicating that going to a crowded field (clusters, or in the Galactic plane) is in order. We have begun a search in Baade's Third Window in the Galactic plane using the OGLE cataloge as a beginning guide (Udalski et. al. 1995). In Figure 2 we have plotted 103 eclipsing binary in our field of data taken with the 0.9-meter telescope at Cerro Tololo Inter-American Observatory (we have obtained only a bit more than 21 hours on this field to date). V-I colors (with un-reddening-corrected spectral types indicated) are plotted against binary period. Short-period, red systems would certainly have to be small star systems. Clearly indicated are a statistically well-sampled number of small-mass eclipsing binaries for extention of our search. (A study of BW3-V38 has already been done by Maceroni and Rucynski 1997, references therein.)

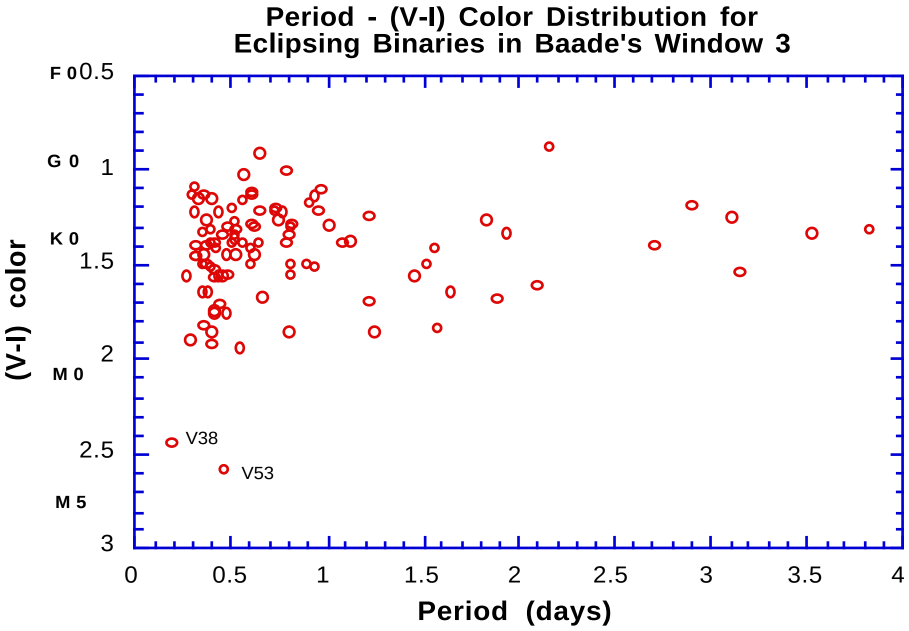

Figure 2. Plot of 103 (of the 108) eclipsing binaries in the Baade's Window 3 field observed by us at the Cerro Tololo Inter-American Observatory (identified from the OGLE catalogue; Udalski et. al. 1995). V-I colors are scaled to spectral type after Allen (1976) with no reddening corrections. Short periods (less than 4 days as plotted here) coupled with red colors indicate small-mass systems suitable for the smallest planet transit detections. Twenty-three are Algol-type binaries with the rest being identified as contact W Ursa-Majoris systems.

Conclusions

Small eclipsing binaries hold great promise for the detection of extrasolar planets for many reasons, as we have demonstrated for the CM Draconis system using 1-meterclass telescopes. With the possible exception of the gravitatonal lense method, close double stars are entirely complimentary to other detection methods since, for example, radial velocity methods might generally want to avoid the confusion intrinsic in short-period spectroscopic binaries. Yet, if planets do form around close binaries (and there is reason to suspect such to be the case from binarity in circumstellar discs; see, for example, Jensen et. al. 1996, Kalas and Jewett 1998), such configurations would be of great interest as another important example of the planet formation process. In the BW3 field, most of the eclipsing binaries identified (almost 78%) are contact binaries (of course there is a large observational selection effect). This indicates that one would get more transits per planetary transit window passage (see Brandmeier and Doyle 1996). Another advantage of detecting transits at or near stellar eclipse events is that, while the absolute magnitude attenuation due to a planetary transit would not change, during eclipse the differential magnitude drop is doubled (for equal-sized stars) as the stellar area halves during this time, (i.e., the planetary transit signal is twice its out-of-eclipse strength). Also, for such close binaries, precession of non-planar planets across the line-of-sight becomes slightly more likely (see Schneider 1994). Finally, the precision with which eclipse minima can be determined increases with decreasing period (equal-size stellar components also giving sharper eclipse minima). One must, of course, address the possibility of mass transfer, and other effects causing period changes for such systems (see Doyle et. al. 1998). In conclusion we feel that the search for extrasolar planets around small eclipsing binaries holds significant promise for success and is essentially complimentary to other extrasolar planetary detection methods, an understanding of outer planets orbiting an inner binary system being an essential component to our understanding of star and planet formation in general.

References

Allen, C.W., 1976, *Astrophysical Quantities*, Athlone Press, London, p. 208.

Brandmeier, S. and L.R. Doyle, 1996, “Simulation of Planetary Transits in Eclipsing Binary Systems,” in *Circumstellar Habitable Zones*, L.R. Doyle (ed), Travis House Publications, Menlo Park, CA, 251-266.

Borucki, W.J. and A.L. Summers, 1984, "The Photometric Method of Detecting Other Planetary Systems,” Icarus **58,** 121–134.

Deeg, H.-J., and L.R. Doyle, “VAPHOT – A Package for Precision Differential Aperature Photometry,” in *Proceedings of the Photometric Extrasolar Planets Detection Workshop*, SETI Institute, Mountain View, CA, W. Borucki and D. Koch (eds).

Deeg, H.J., L.R. Doyle, J.E. Blue, E. Martin, and J. Schneider, 2000, " A Search for Jovian-Mass Planets Around CM Draconis Using the Eclipse Timing Method," submitted to *Astronomy and Astrophysics Letters.*

Deeg, H.J., L.R. Doyle, V. P. Kozhevnikov, E. Martin, E. Palaiologou, J. Schneider, C. Afonso, E.T. Dunham, J.M. Jenkins, Z. Ninkov, R. Stone, and P.E. Zakharova, 1998, "A Photometric Search for Transits of Extrasolar Planets: Observations and Photometric Analysis of CM Draconis," *Astronomy and Astrophysics,* **338**, 479-490.

Doyle, L.R., H.-J. Deeg, V.P. Kozhevnikov, B. Oeitiker, E. Martin, J.E. Blue, L. Rottler, R.P.S. Stone, Z. Ninkov, J. Jenkins, J. Schneider, E.W. Dunham, M. Doyle, E. Paleologou, 2000, "Observational Limits on Terrestrial-Sized Inner Planets Around the CM Draconis System Using the Photometric Transit Method With a Matched-Filter Algorithm, “*Astrophysical Journal*, in press.

Doyle, L.R., H.J. Deeg, J.M. Jenkins, J. Schneider, Z. Ninkov, R. P.S. Stone, J.E. Blue, H. Götzger, B, Friedman, and M.F. Doyle, 1998a, "Detectability of Jupiter-to-Brown-Dwarf-Mass Companions Around Small Eclipsing Binary Systems," in *Brown Dwarfs and Extrasolar Planets,* R. Rebolo, E. L. Martin, and M.R.Z. Osorio (eds.), A.S.P. Conference Series **134**, San Francisco, California, 224-231.

Doyle, L.R., E.T. Dunham, H.-J. Deeg, J.E. Blue, and J.M. Jenkins, 1996, "Ground-Based Detection of Terrestrial-Sized Extrasolar Planets: U.C. Lick Observations of CM Draconis," *J.Geophy.Res Planets* **101**, 14823–14829.

Dravins, D., L. Lindegren, E. Mezey, and A.T. Young, 1998, "Atmospheric Intensity Scintillation of Stars. III. Effect for Different Telescope Apertures," *P.A.S.P.* **110**, 610-633.

Haberle, R.M., C.P. McKay, D. Tyler, and R.T. Reynolds, 1996, "Can Synchronously Rotating Planets Support an Atmosphere?" in *Circumstellar Habitable Zones: Proceedings of the First International Conference*, L.R. Doyle (ed.), Travis House, Menlo Park, Calif., 29–33.

Heath, M., L.R. Doyle, M. Joshi, and R.M. Haberle, 1999, "Habitable Zones Around M-Dwarf Stars," *Origins of Life and Evolution of the Biosphere*, **29**, 405-424 .

Holman, M.J. and P.A. Wiegert, 1999, "Long-Term Stability of Planets in Binary Systems," *Astronomical Journal* **117**, 621-628.

Jenkins, J.M., L.R. Doyle, H.-J. Deeg, 2000, “Ground-Based Photometric Detection of Extrasolar Planets,” *Acta Astronautica*, in press.

Jenkins, J.M., L.R. Doyle, and D.K. Cullers, 1996, "A Matched-Filter Method for Ground-Based Sub-Noise Detection of Extrasolar Planets in Eclipsing Binaries: Application to CM Draconis," *Icarus* **119**, 244–260.

Jensen, E.L.N., D.W. Koerner, and R.D.Mathieu, 1996, “High-Resolution Imaging og Circumstellar Gas and Dus in UX Tauri: Comparing Binary and Single-Star Disk Properties,” *Astronomical Journal* **111**, 23431-2438.

Joshi, M.M., R. Haberle, and R.T. Reynolds, 1997, "Simulations of the Atmospheres of Synchronously Rotating Terrestrial Planets Orbiting M Dwarfs: Conditions for Atmospheric Collapse and the Implications for Habitability," *Icarus* **129**, 450–465.

Kalas, P. and D. Jewitt, 1997, “A Candidate Dust Disk Surrounding the Binary Stellar System BD +31˚643,” *Nature* **386**, 52-54.

Kasting, J. F., D.P. Whitmire, and R.T. Reynolds, 1993, “Habitable Zones Around Main-Sequence Stars,” *Icarus* **101**, 108-128.

Lacy, C.H., 1977, "Absolute Dimensions and Masses of the Remarkable Spotted dM4e Eclipsing Binary Flare Star CM Draconis," *Astrophy.J.* **218**, 444–460.

Maceroni, C. and S.M. Rucinski, 1997, "The Shortest-Period M-Dwarf Eclipsing System: BW3 V38,"*Pub. Astron. Soc. Pac.* **109**, 782–788.

Rosenblatt, F., 1971, "A Two-Color Photometric Method for Detection of Extra-Solar Planetary Systems," *Icarus* **14,** 71–93.

Schneider, J. and L.R. Doyle, 1995, "Ground-Based Detection of Terrestrial-Sized Extrasolar Planets: The Case for CM Draconis,"*Earth Moon Planets* **71**, 153–173.

Udalski, A., M. Szymanski, J. Kaluzny, M. Kubiak, M. Mateo, and W. Krzeminski, 1995, “The Optical Gravitational Lensing Experiment. The Catalog of Periodic Variable Stars in the Galactic Buldge. II. Periodic Variables in Four Baade’s Window Fields: BW1, BW2, BW3 and BW4,” *Acta Astronomica* **45**, 1-25.