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The Monitor Project: Searching for Occultations in Young Open Clusters

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Abstract. The Monitor project is a photometric monitoring survey of nine relatively rich, compact and nearby open clusters in the age range 1–200 Myr, whose primary goal is to detect young low mass eclipsing binaries and transiting planets, in order to provide observational constraints on the formation and evolution of very low mass stars, brown dwarfs and planets at early ages. The present contribution gives an overview of the motivation, design and expected performance of the survey, and presents some preliminary results.

1. Motivation

The primary motivation behind the Monitor project is to gather robust observational constraints on the early evolution of low mass stellar, substellar and planetary objects, through the detection of eclipsing binaries and transits in the members of young open clusters. Once the original photometric observations are complemented by radial velocity follow-up, the systems we hope to detect should act as anchoring points for theoretical evolutionary models. Additionally, the detection of young planets and the characterisation of the binarity properties of low mass stars and brown dwarfs should provide important insights into the relevant formation mechanisms.

Eclipsing binary systems that are also double-lined spectroscopic binaries provide very detailed contraints on the fundamental parameters of stars, as they enable direct (model-independent) measurements of the masses, radii, and surface brightness of both components. In the case of single-lined systems, including transiting planets, only some of the orbital elements can be solved, but the occulting configuration constrains the inclination of the system and one therefore derive the mass and radius of the companion relative to that of the primary.

There has been a significant increase in recent years in the number of field K and M stars and planets with reliable masses and radii, through large photometric monitoring surveys and interferometric programmes (see references in Aigrain et al. 2007). However, contraints on the main sequence mass-radius relation remain scarce in the entire low mass regime, and non-existent in the brown dwarf domain, as illustrated by the black symbols in Figure 1. This scarcity is even more acute for pre main-sequence systems: only 3 sub-solar binaries are known in young open clusters (see Stassun et al. 2004; Hebb et al. 2006; Stassun, Mathieu & Valenti 2006, coloured symbols in Figure 1).

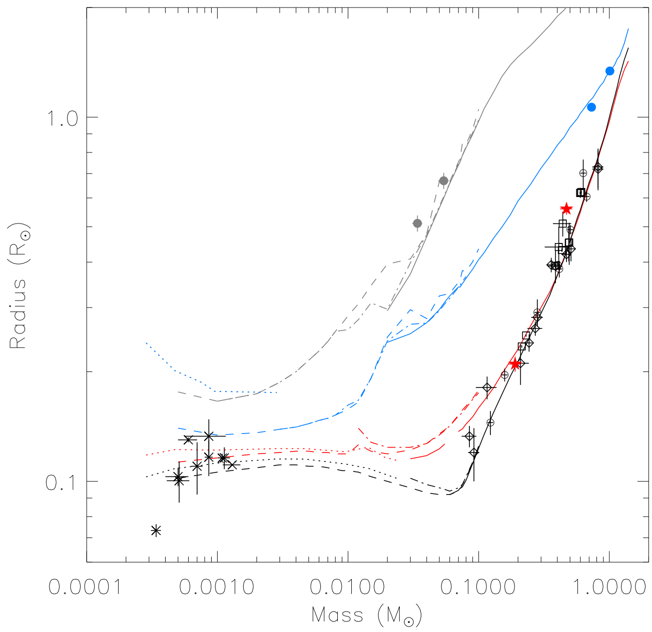

Figure 1.: : Observational constraints on the mass-radius relation. Hollow black circles show interferometric measurements of field stars; hollow black diamonds the secondaries of field F-M or G-M systems; hollow black squares field M-M systems; and black crosses transiting planets around field stars (see Aigrain et al. 2007, for a full reference list). Filled symbols show the components of PMS EBs in NGC 1647 (150 yr, Hebb et al. 2006, red stars); Ori 1c (10 Myr, Stassun et al. 2004, blue circles); and the Orion Nebula cluster (1 Myr, Stassun, Mathieu & Valenti 2006, grey circles). The solid, dashed, dot-dash and dotted lines respectively show the NEXTGEN (Baraffe et al. 1998), DUSTY (Chabrier et al. 2000) and COND (Baraffe et al. 2003) models of the Lyon group and the non-grey models of Burrows et al. (1997); from top to bottom: 1 Gyr (black), 150 Myr (red), 10 Myr (blue) and 1 Myr (grey).

Monitor has been designed to fill out the mass-radius relation throughout the age range 1–200 Myr, from the K-dwarf to the planetary regime. As an occultation survey, it takes advantage of two properies of this relation apparent on Figure 1: the bloated radii of young systems, which lead to increased alignment probabilities, and the flattenting of the relation at low masses, which leads to deeper occultations, which are easier to detect.

2. Observations & data analysis

Target clusters were selected on the basis of age (< 200 Myr), richness, compactness and proximity, and are listed in Table 1.

Photometric monitoring started in November 2004, and is complete for 6 of the 9 targets at the time of writing. We use 2 to 4 m telescopes equipped

Table 1.: The Monitor target clusters. Basic properties are taken from the literature. Wherever possible, the approximate number N of cluster members monitored is estimated membership counts based on deep CMDs constructed from Monitor data. Ω is the total area monitored in each cluster, and the mass range $M_{\rm L}$–$M_{\rm H}$ refers to the unsaturated stars monitored with precision $< 5\%$.

Name	RA hh mm	Dec dd mm	Age Myr	Dmod mag	N	Ω sq.°	$M_{\rm L}$–$M_{\rm H}$ $M_\odot$
ONC	05 35	−05 23	1	8.36	2143	0.28	0.04–0.75
NGC 2362	07 19	−24 57	5	10.85	587	0.38	0.07–1.14
h & χ Per	02 20	+57 08	13	11.85	7756	1.00	0.33–1.49
IC 4665	17 46	+05 43	28	7.72	216	1.00	0.04–0.45
NGC 2547	08 10	−49 10	30	8.14	334	0.56	0.06–0.88
Blanco 1	00 04	−29 56	90	7.07	148	0.50	0.06–0.80
M50	07 02	−08 23	130	10.00	1942	0.38	0.18–0.88
NGC 2516	07 58	−60 52	150	8.44	1214	1.13	0.08–0.56
M34	02 42	+42 47	200	8.98	845	1.00	0.11–0.99

with wide field imagers in la Palam (INT 2.4 m with WFC), Chile (ESO/MPI 2.2 m with WFI at la Silla, Blanco 4 m with Mosaic II at CTIO), Hawaii (CFHT 3.6 m with MegaCAM) and Arizona (Mayall 4 m with Mosaic at CTIO). The observations are carried out in I, with intervals between consecutive data points ranging from 3.5 to 15 min. In each cluster, we aim to accumulate at least 100 h of observations to ensure a relatively high likelihood of observing at least 2–3 eclipses for short-period systems. Practical considerations have meant that the observations were taken in visitor mode in some cases, and in service mode in others, resulting in widely different temporal distributions, and our light curves span 2 weeks in some clusters and more than 2 years in others.

We have implemented a fully automated data processing pipeline, described in detail in Irwin et al. (2007). We use co-located aperture photometry combined with a refined astrometric solution to minimise aperture placement shifts from one frame to the next. The light curves are corrected for temporal systematic effects smoothly varying with position on the detector using an inverse variance weighted 2–D polynomial fit to the light curve residuals on each frame. When preparing light curves specifically for eclipse/transit finding, we also apply additional steps intended to minimise the correlated noise on transit timecales, namely decorrelation of the light curves agains seeing variations followed by application of the SysRem algorithm of Tamuz, Mazeh & Zucker (2005). The light curves are then searched for occultations using the transit search algorithm of Aigrain & Irwin (2004), in some cases after filtering them to remove the intrinsic variability exhibited by many of our young, active target stars.

3. Detection estimates

Aigrain et al. (2007) carried out detailed simulations of the number of detections expected from the survey as a whole based on the noise properties and time sampling of the data obtained to date. The results depend strongly on the assumptions made regarding companion incidence, but we estimate that Monitor should detect over 100 eclipsing binaries and about 10 transit planets. The distribution of the expected detections in terms of primary mass, mass ratio (or, for the planets, companion radius) and orbital period are shown in Figure 2.

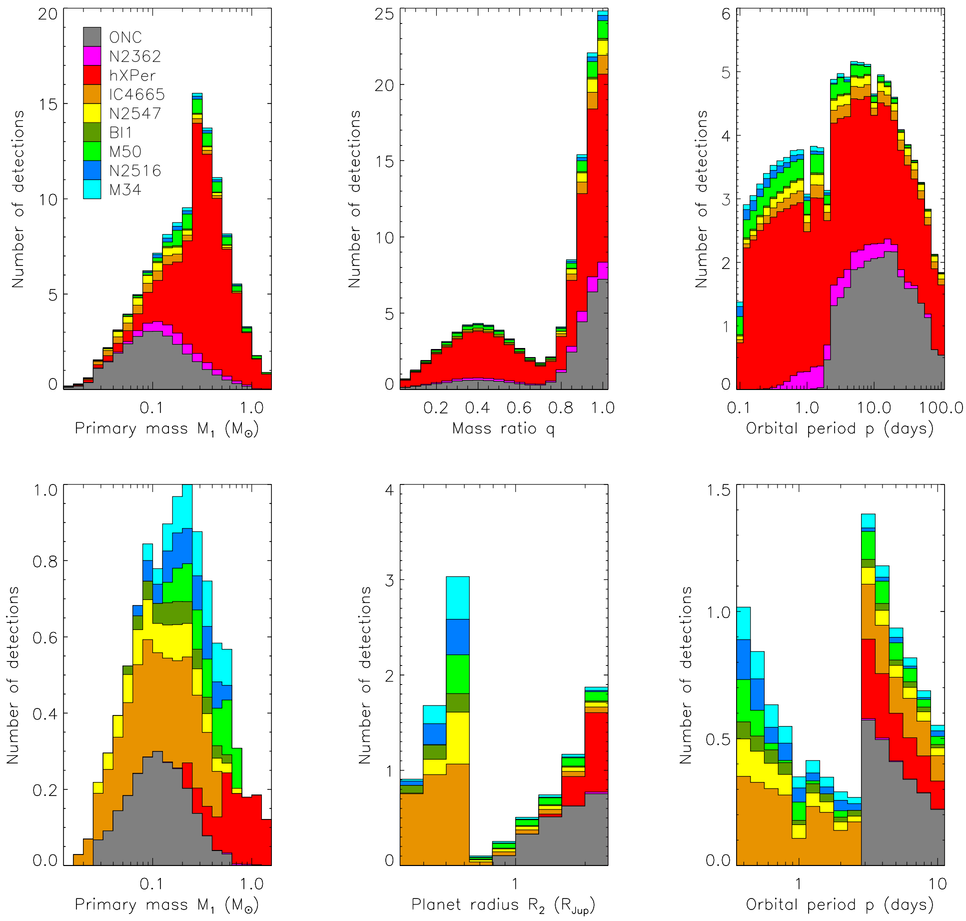

Figure 2.: : Number of expected detections for binaries (top) as a function of primary mass (left), mass ratio (centre) and orbital period (right), and for planets (bottom) as a function of primary mass (left), planet radius (centre) and orbital period (right). The histograms are summed, each of the cluster being represented by a different colour, starting with the youngest (the ONC, in grey) at the bottom and ending with the oldest (M34, in light blue) at the top. The overall filled area corresponds to the total number of detections, all clusters combined.

We also evaluated the limits imposed by radial velocity follow-up of the candidates, which is mandatory to determine the nature of the companions and evaluate at least the relative masses of the components. About half of the binaries causing detectable eclipses should also be detectable in radial velocity using medium resolution spectrographs on 4 m-class telescopes such as EMMI on the NTT and ISIS on the WHT, and such observations are underway for our first set of candidates. In a second phase of follow up, using 8 m class telescopes with higher resolution instruments such as GIRAFFE and UVES on the VLT, it should be possible to detect radial velocity modulations for all the binaries and approximately 30% of the planets (the most massive planets in the nearest clusters). Although the radial velocity precision achievable in the near-IR is more uncertain, this spectral region improves the likehood of separating the lines from both components and obtaiing a double lined orbital solution for binaries. We have thus also started observing our best candidates with Phoenix on Gemini South, and will apply for time on CRIRES on the VLT.

4. Preliminary results

At the time of writing, we have carried out a partial analysis of light curves from the ONC, NGC 2362, NGC 2516, M50 and M34. We have identified 48 candidates to date, 24 of which fulfill our criteria for follow-up observations (at least 3 eclipses observed). These numbers are roughly consistent with the estimates mentioned in the previous section.

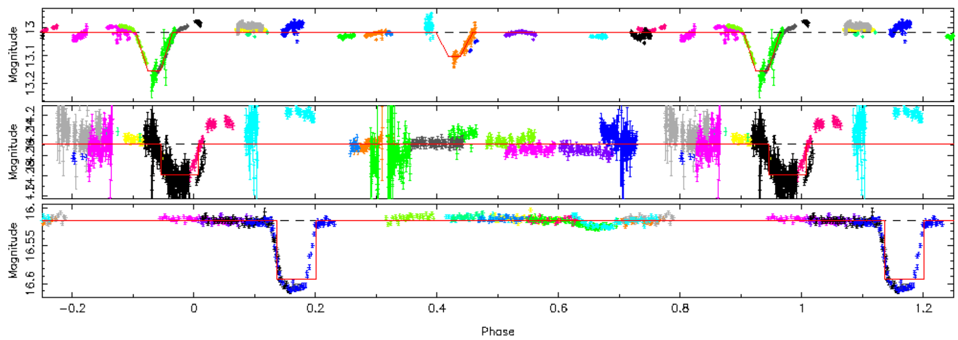

Figure 3.: Phase-folded light curves of three eclipse candidates in the ONC (top two panels) and M50 (bottom panel).

Light curves for three of the candidates are shown on Figure 3. The first two, in the ONC, have likely primary masses below 0.5 $M_{\odot}$ (from the objects' optical and near-IR colours), periods of 4.6 and 2.5 d and primary eclipse depths of 6 and 10%. Preliminary spctroscopy of these objects indicates a mass ratio of $q \sim 0.5$ for the first, and a lower mass ratio for the second. For the third, in the direction of M50, we estimate component masses of 0.7 and 0.2 $M_{\odot}$ based on the optical colour and primary and secondary eclipse depths, assuming the system is indeed a member of the cluster. More data is needed to solve for individual component masses and radii in these systems, but so far the systems appear roughly consistent with the evolutionary models shown in Figure 1.

An important secondary science goal of the Monitor project is the study of the angular momentum evolution of young low-mass star through the measurement of photometric rotation periods. We have so far detected $\sim$ 1000 new rotation periods in Monitor data – a $\sim$ 100% increase in the number of stars with photometric periods (see Irwin et al. 2006, for M34, Irwin et al. in prep. for

NGC 2516, Hodgkin et al. in prep. for NGC 2362). Colour magnitude diagrams built up from our data also confirm the extremely rich nature of twin clusters h & χ Per, where a study of the high-mass population by Slesnick, Hillenbrand & Massey (2002) had indicated a total mass 8–10 times that of the ONC.

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