Astron. Nachr. / AN **327**, No. 1, 9–13 (2006) / **DOI** 10.1002/asna.200510487

Monitor: transiting planets and brown dwarfs in star forming regions and young open clusters[*]

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Received 17 October 2005; accepted 14 November 2005; published online 7 January 2006

Abstract. The *Monitor* project[**] is a large scale photometric monitoring survey of ten star forming regions and open clusters aged between 1 and 200 Myr using wide-field optical cameras on 2–4 m telescopes worldwide. The primary goal of the project is to search for close-in planets and brown dwarfs at young ages through the detection of transit events. Such detections would provide unprecedented constraints on planet formation and migration time-scales, as well as on evolutionary models of planets and brown dwarfs in an age range where such constraints are very scarce. Additional science goals include rotation period measurements and the analysis of flares and accretion-related variability.

Key words: stars: low-mass, brown dwarfs – stars: rotation – binaries: eclipsing – planetary systems – techniques: photometric

1. Motivation

We are undertaking an ambitious programme of high-cadence, high-precision, long-term photometric monitoring of young open clusters (ages < 200 Myr, see Fig. 2 and Table 1). In combination with radial velocity observations, measurements of both the mass and radius of transiting objects can be obtained. Transit surveys are an efficient method of discovering low mass eclipsing binaries and planets, despite low alignment probabilities, because of the large numbers of stars that can be surveyed simultaneously. Over the last few years, several transit surveys (e.g. von Braun et al. 2004; Bramich et al. 2005; Street et al. 2003) have been targetting 'middle aged' (≥ 1 Gyr) open clusters, but no confirmed discoveries have been reported to date. We will use our survey to address some of the following questions:

- What are the timescales for planet formation, migration and contraction?
- In what environments do planets form, and around what kinds of stars?
- What constraints can we place on the mass-radius relationship for young brown dwarfs and planets?
- What governs the evolution of stellar rotation?

Our sample of cluster members is dominated by low-mass stars. Of the plethora of planets detected to date with radial velocity surveys, nearly all the host stars lie in the range 0.7–1.4 $M_{\odot}$[1]. Stars more massive than $1.4\,M_{\odot}$ are simply not amenable to radial velocity studies due to featureless spectra from their hot atmospheres. Stars less massive than $0.7\,M_{\odot}$ rapidly cool and become increasingly faint in the green-visible where the iodine cell provides reference lines. Even with the difficulty of detecting planets around cool stars, some of the most interesting examples have been discovered around M type stars. To date, three radial velocity planets orbit M dwarfs: GJ 876 (Marcy et al. 2001), GJ 436 (Butler et al. 2004) and Gliese 581 (Bonfils et al. 2005).

Models of planet formation based on core accretion (Hubickyj, Bodenheimer & Lissauer 2003, Pollack et al. 1996) predict that it should be possible to form jupiter-mass plan-

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[*] Workshop "Ultralow-mass star formation and evolution", see AN **326**, No. 10
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[1] e.g. http://vo.obspm.fr/exoplanetes/encyclo/encycl.html.

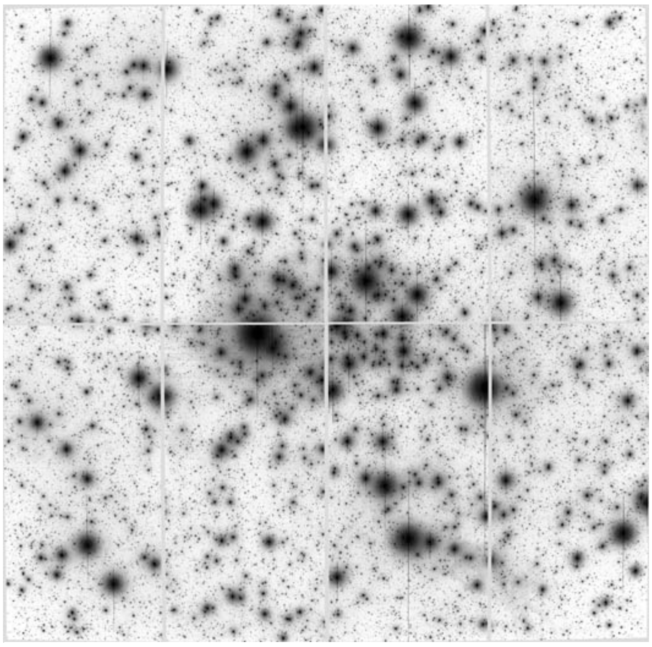

Fig. 1. An i'-band image of the open cluster M50 generated by stacking our short exposures taken with the Mosaic2 on the Blanco 4m telescope at the Cerro Tololo Inter-American Observatory. The camera comprises 8 2k×4k CCDs and covers a field-of-view of 36×36 arcmins.

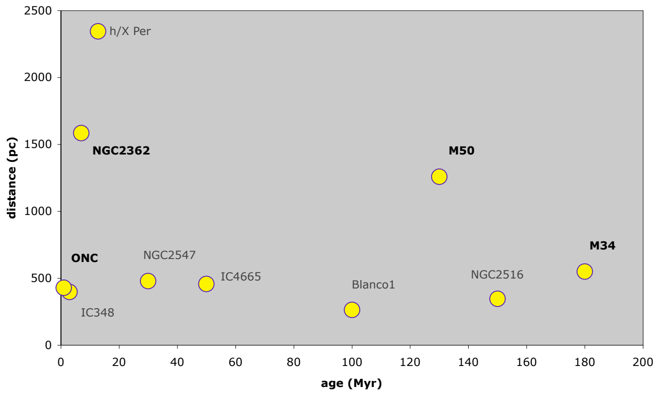

Fig. 2. The distribution in distance and age of our 10 target clusters.

ets around solar-mass stars within ~ 1 Myr. Laughlin, Bodenheimer & Adams (2004) suggest it is hard to form planets around low mass stars via this route, and that Jupiters should consequently be scarce around M dwarfs. Lodato, Delgado-Donate & Clarke (2005) investigate the low-mass ratio binary 2MASS J1207334–393254 in TW Hydrae (a 5 $M_{\rm Jup}$ companion to a 25 $M_{\rm Jup}$ primary, Chauvin et al. 2004, 2005), and conclude that it would take too long to form via core-accretion; they suggest that formation via gravitational instability is a viable alternative.

Some recent dynamical mass measurements for VLM stars and brown dwarfs (e.g. Bouy et al. 2004 [2MASSW J0746425+2000321], Close et al. 2005 [AB Dor C] and Zapatero Osorio et al. 2005 [GJ 569Bab]) are, for the first time, providing us with constraints on the theoretical models of substellar objects (Burrows et al. 1997; Baraffe et al. 1998). Our goal is to find eclipsing binaries containing brown dwarfs of known age and metallicity to provide even stronger constraints on their masses and radii, especially at young ages (few Myr), where uncertainties in the initial conditions are dominant (Baraffe et al. 2002; Marley, Fortney & Hubickyij 2004).

2. Transit method

For a Jupiter around a solar mass star, a transit event dims the primary by 1 %. When the primary star is young and has a larger radius, then the eclipse depth is slightly shallower (the planet is also somewhat larger), however the probability of alignment increases. Objects with masses in the range 1 $M_{\rm Jup}$ to 0.1 $M_\odot$ at the age of the Sun, all have essentially the same radius of about $0.1R_\odot$ (e.g. Pont et al. 2005), thus the eclipse depths around low mass primaries can be very large. Note that a transit of a 0.1 $M_\odot$ star by a 2 $M_{\rm Earth}$ planet results in a dimming of 1 % – easily in reach of a ground based transit survey, given enough photons from the primary (which are probably best collected in the near-infrared).

Transit surveys are the most efficient way to discover objects for which we can measure dynamical masses and radii. If secondary eclipses are detected then we can also measure the luminosities of both components. Transiting systems also enable us to attempt transmission specroscopy if the object is bright enough and hence to attempt an analysis of the structure of the companion's atmosphere.

3. Observing strategy

Discoveries in the field always throw up the issue of age. We are attempting to sidestep this by aiming for transits around stars of known age. Ten target clusters were selected on the basis of youth, richness, proximity and compactness, as well as the existence of a known low-mass pre-main sequence population (see Fig. 2). We have observed or are scheduled to observe 8 of those by the end of 2005 (see Table 1, or the *Monitor* webpage for a list), and have applied to survey the remainder over the next few semesters. Sampling times are 3.5–15 min to ensure appropriate sampling of eclipse ingress/egress. 300–1000 frames in i', or V and i' (for the ONC and M34), are obtained for each cluster, with exposure times ensuring signal-to-noise ratios > 30 down to the hydrogen burning limit. We are monitoring a total of around 10 000 cluster members over > 10 square degrees of sky.

3.1. Predictions

We have adapted the calculations of Gaudi, Seager & Mallén-Ornelas (2005) to estimate the expected number of detections from *Monitor*, using assumptions specific to our young cluster targets. Taking into account cluster (age, distance, size, richness) and obervational (magnitude range, precision, sampling) characteristics and using suitable assumptions for companion incidence and theoretical mass-radius-luminosity relations, we calculate that *Monitor* as a whole should detect several planets and several tens of VLMSs / BDs that transit

Table 1. This table lists the coordinates, ages, distances, and metallicities (where available) for our target clusters. We also list the area (in square degrees) we are surveying for each cluster and the number of cluster members we expect to monitor within this area (based on published mass functions where available, and corrected to the magnitude limits of our survey).

Cluster name	α_{J2000} (h m)	δ_{J2000} (° ′)	Age (Myr)	Distance (pc)	[Fe/H]	Area (sq deg)	N_{survey}	Ref
Blanco1	00 04	-29 56	100	260	+0.23	1.0	320	1
h/χPer	02 20	+57 08	13	2300	0.00	1.0	8000	2
M 34	02 42	+42 47	200	550	-0.30	0.25	250	3
IC 348	03 44	+32 17	~ 3	400	-	1.0	110	4
ONC	05 35	-05 23	~ 1	430	-0.02	0.25	1700	5
M 50	07 02	-08 23	130	1000	-	0.36	1700	6
NGC 2362	07 19	-24 57	7	1585	-	0.36	1000	7
NGC 2516	07 58	-60 52	150	350	+0.06	1.0	1400	8
NGC 2547	08 10	-49 10	30	480	-0.16	1.0	400	9
IC 4665	17 46	+05 43	50	460	-	4.0	300	10

References for each cluster: (1) Moraux priv. comm.; (2) Slesnick, Hillenbrand & Massey (2002); (3) Ianna & Schlemner (1993); (4) Luhman et al. (2003); (5) Slesnick, Hillenbrand & Carpenter (2004); (6) Kalirai et al. (2003); (7) Alves et al. in prep; (8) Moraux priv. comm.; (9) Jeffries et al. (2004); (10) de Wit et al. (2005).

their primaries (see the *Monitor* webpage for more details). Our target sample is large enough that, if no bona-fide companions are discovered, we will be able to place meaningful constraints on the incidence of planets and brown dwarfs as close companions to low-mass star and brown dwarf primaries. Our observing strategy is designed such that the numbers of detections should be limited by close companion frequency and alignment probability rather than sensitivity and time sampling.

4. Data reduction

Data processing for *Monitor* is a challenge. In a typical night we obtain 25–50 Gbytes (instrument dependent). Observing 10 clusters for more than 10 nights each therefore makes this a multi-Terabyte project. Standard data reduction steps are done automatically using our in-house pipeline (Irwin & Lewis 2001), including: bias correction, overscan trimming, non-linearity correction, flatfield and gain correction, defringing, catalogue generation and astrometric and photometric calibration. Our best quality images are stacked to form a *master* frame. This master frame is then searched for sources to generate a reference list of objects. We have found that when measuring photometry of an object, then the centroiding error ($\sim$0.1 pixel) for a bright star is a significant source of noise (neighbouring objects contribute different amounts of flux in each exposure as the aperture moves around). To minimize this error, we transform the coordinates of the stars in our reference list using the accurately derived astrometric solution for each frame. We can thus place our apertures to a precision of $\sim$0.01 pixel, and practically halve the error in the photometry for our brightest stars. We remove temporal and spatial systematics by fitting and subtracting a 2-D polynomial surface to light curve residuals in each frame. Typical relative precisions reach 2–3 mmag at the bright end, and remain < 1 % over $\sim$4 magnitudes (Fig. 3).

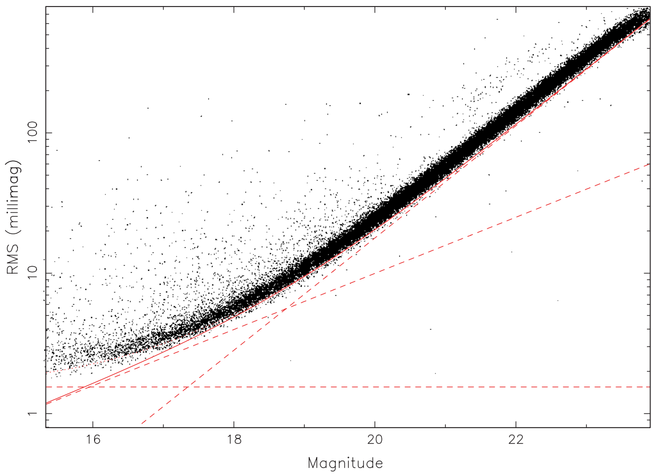

Fig. 3. Photometric precision achieved over 6 nights of CTIO + Mosaic i'-band observations in the direction of M 50. The dashed lines shows the individual theoretical noise estimate including source and sky photon and readout noise as well as a systematic contribution of 1.5 mmag. The solid line shows the sum of the object and sky noise contributions. Accuracy better than 1 % is achieved over >4 mag.

5. Early results

5.1. Rotation

Photometric monitoring data of the open cluster M 34 (200 Myr, Meynet, Mermillod & Maeder 1993) were obtained for $\sim$4.5 hours per night over 8 nights in November 2004 with the Wide Field Camera on the Isaac Newton Telescope. We alternated between 60s V-band and 30s i'-band exposures, and took a total of $\sim$270 images in each filter. Light curves were extracted from the data for $\sim$8500 stellar objects. The baseline of 10 nights is insufficient for a detailed study of stellar rotation periods, but we can investigate the faster rotators (periods $\leq$ 10 days). We fitted sine curves to each i'-band light curve in order to detect variability. We found 118 stars with light curves which could be well-described as peri-

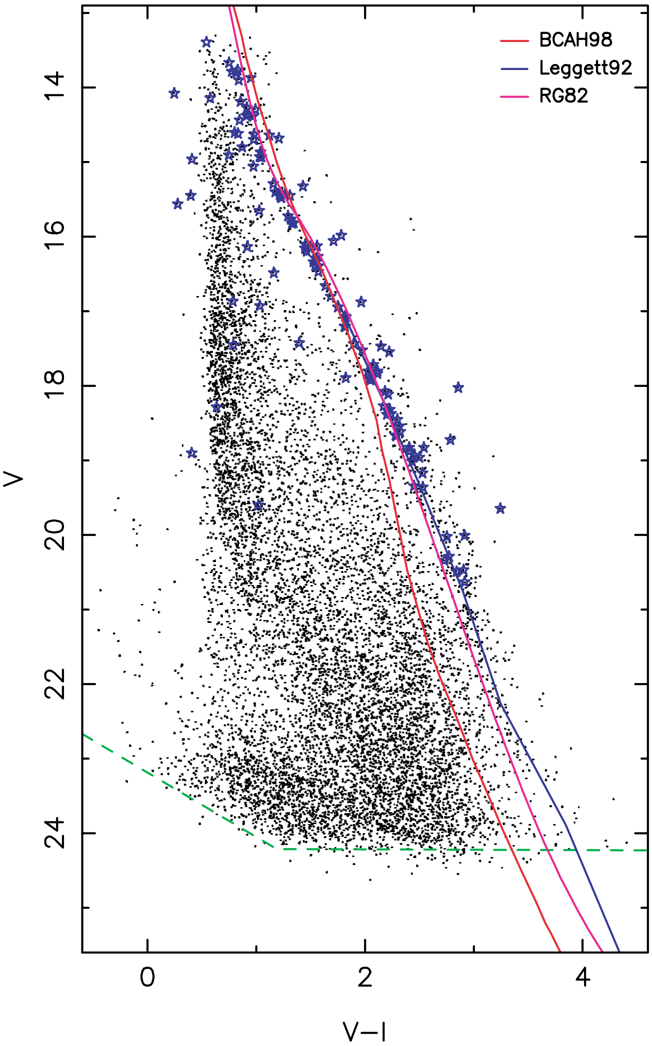

Fig. 4. The V versus $V-I$ colour-magnitude diagram of M 34 for all objects with stellar morphological classification (made from a deep stack of our best images). Objects with detected periods are shown as stars. The solid lines from left to right are (1) a model cluster sequence from Baraffe et al. (1998) for an age of 200 Myr, (2) the empirical fiducial main sequence of Reid & Gilmore (1982) and (3) the empirical track for young disk stars from Leggett (1992). We assume a cluster distance modulus of 8.60 and reddening $E(B-V) = 0.07$ (Jones & Prosser 1996). As a rough guide to masses, from Baraffe et al., objects on the sequence with $V = 23$ correspond to a mass of about $0.13\,M_{\odot}$, while $V = 20.5$ corresponds to $\sim 0.3\,M_{\odot}$.

odic sinusoidal variation. Of these, the vast majority (100 or 85 %) are on the photometric cluster sequence (Fig. 4). The faintest objects for which we can detect rotation (with amplitudes around 1 %) have i'-band magnitudes around 18.0 (mass $\sim 0.2\,M_{\odot}$).

5.2. Transits

13 eclipse candidates with colours consistent with cluster membership have been identified in the 4 clusters observed and analysed so far (see Fig. 5 for examples), using the algorithm of Aigrain & Irwin (2004) plus visual light curve examination. We can make a preliminary guesstimate of the nature of the companions. For each primary, we derive a mass and radius from the NextGen models of Chabrier & Baraffe (1997). The minimum radius of the secondary is then derived from the assumption that the eclipse is full (i.e. not grazing) and that $\Delta F/F = (R_2/R_1)^2$. All these candidates have radii which place them near or below the BD limit. Half could be planets, as we see no evidence for secondary eclipses. We have started follow-up with medium-resolution spectrographs on 4 m telescopes.

6. Outlook

Our monitoring campaign for the remaining clusters will continue for the next several years. We have also been allocated additional time to monitor M 34, M 50, ONC and NGC 2362 in December 2005 to recover eclipses from our existing detections. This will really help us to tie down the eclipse durations, periods and phase information. We will also begin spectroscopy in December 2005, initially on 4-m class telescopes with intermediate resolution to eliminate contaminating high mass stellar binaries (e.g. from blends within the photometric aperture). We have requested time on 6–8 m class telescopes with higher dispersion spectrographs to follow-up any surviving candidates.

Acknowledgements. The *Monitor* Collaboration includes J. Irwin, S. Aigrain, S. Hodgkin, E. Moraux, M. Irwin, C. Clarke and G. Gilmore (IoA, Cambridge), L. Hebb (JHU, Baltimore), J. Bouvier (LAOG, Grenoble), F. Favata (ESA/ESTEC), E. Flaccomio (Palermo), M. McCaughrean (Exeter) and M. Ashley (UNSW, Sydney). We acknowledge the SIMBAD data base operated at CDS, Strasbourg, France and the WEBDA data base operated at University of Lausanne, Switzerland. The results presented here are based on observations made with the Isaac Newton Telescope (operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias) and the Blanco 4 m Telecope (CTIO is operated by the Association of Universities for Research in Astronomy Inc. (AURA), under a cooperative agreement with the National Science Foundation as part of the National Optical Astronomy Observatories).

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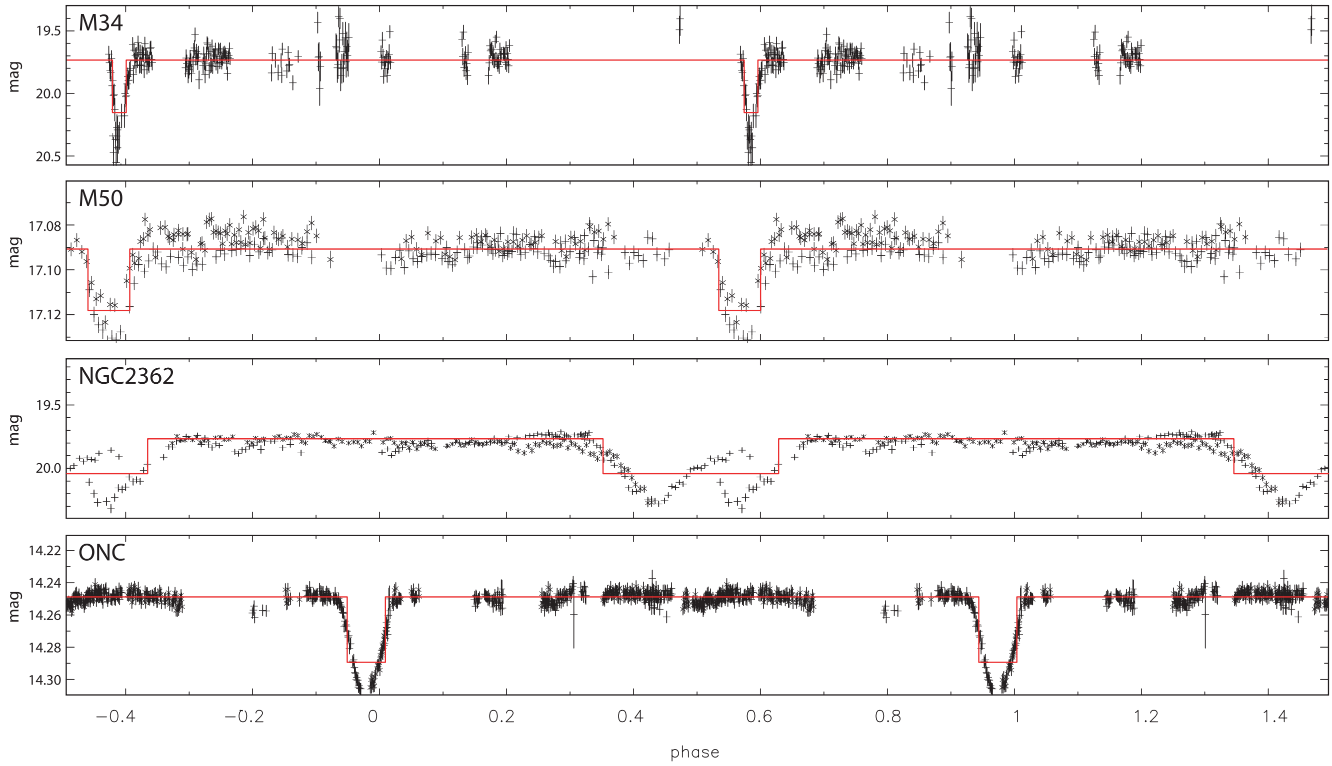

Fig. 5. Phase-folded i'-band light curves of 4 of our eclipse candidates (M 34, M 50, NGC 2362 and ONC from top to bottom). Long term variability has been removed from the ONC and NGC 2362 light curves shown here. Cluster ages are 200, 130, 7 and 1 Myr respectively, periods range from 0.5 to 2 d and likely primary masses are between 0.1 and 0.6 $M_{\odot}$. The primary in M 34 is of very low mass with $M \sim 0.1\,M_{\odot}$. The misalignment of the eclipses in the NGC 2362 example is suggestive of a small eccentricity. The ONC candidate is consistant with a planet around a 0.3 $M_{\odot}$ primary.

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