Monitor: transiting planets and brown dwarfs in star forming regions and young open clusters.

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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: planets, brown dwarfs, very low mass stars, transits, rotation

1. Motivation

We are undertaking an ambitious programme of high-cadence, high-precision, long-term photometric monitoring of young open clusters (ages<200Myr). 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) have been targetting 'middle aged' ($\geq$1Gyr) 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 are the masses and radii of young brown dwarfs?
- 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 to 1.4 $M_\odot$. 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. Only two radial velocity planets orbit low mass, M type stars: GJ 876 (Marcy et al. 2001) is a multiple planet system exhibiting resonant interactions and GJ 436 (Butler et al. 2004) is the lowest mass planet to be yet detected.

Models of planet formation based on core accretion (Hubickyj et al. 2003, Pollack et al. 1996) predict that it should be possible to form Jupiter mass planets around Solar mass stars within ∼1Myr. Laughlin et al. (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 et al. (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 con-

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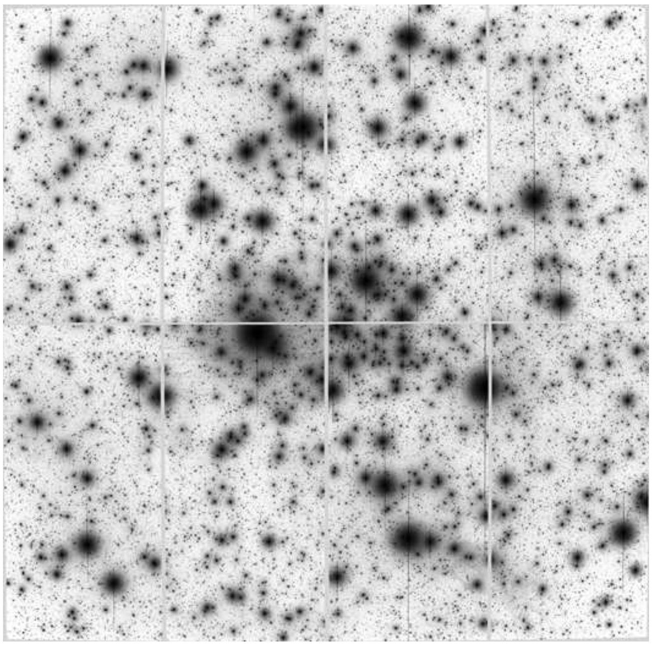

Fig. 1. An image of the open cluster M50 taken with the Mosaic2 on the 4m telescope at the Cerro Tololo Inter-American Observatory. The camera comprises 8 2k×4k CCDs and covers a field-of-view of 36×36 arcmins.

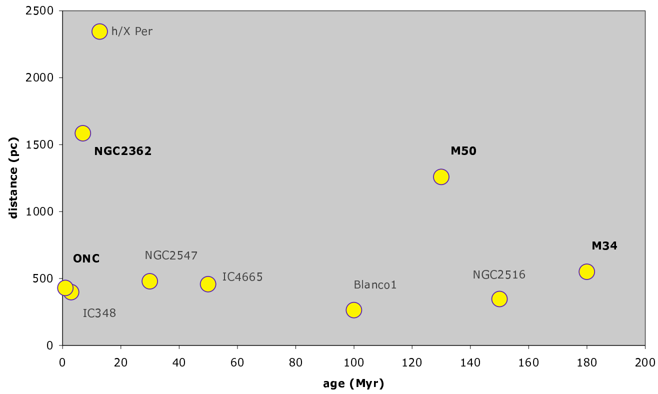

Fig. 2. The distribution in distance and age of our 10 target clusters

clude 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 brown dwarfs (e.g. Bouy et al. 2004, Close et al. 2005 and Zapatero-Osorio et al. 2005) 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, where uncertainties in the initial conditions are dominant (Baraffe et al. 2002, Marley et al. 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 somehwat larger), however the probability of alignment increases. Objects with masses in the range 1MJup 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 $0.1M_\odot$ star by a $2M_{\rm Earth}$ 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 colledted 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 PMS population (see Figure 2. We have observed or are scheduled to observe 8 of those by the end of 2005 (see the *Monitor* webpage for a list), and will apply 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 (for the ONC and M34) V & i' are obtained for each cluster, with exposure times ensuring SNRs > 30 down to the Hydrogen burning limit. We are monitoring around 10,000 cluster members over >10 square degrees of sky.

3.1. Predictions

We have adapted the calculations of Gaudi et al. 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 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.

4. Data reduction

Data processing for Mointor is a challenge. In a typical night we obtain 25-50 Gbytes (instrument dependent). Observing

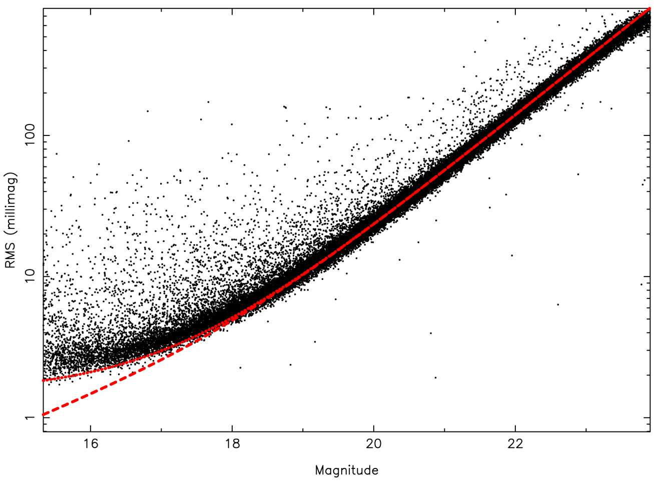

Fig. 3. Photometric precision achieved over 6 n of CTIO+Mosaic i-band observations in the direction of M50. The dashed line shows the theoretical noise estimate including source and sky photon and readout noise. The dotted line shows the same with a 1.5 mmag constant component added to account for residual systematics. Accuracy better than 1% is achieved over >4 magnitudes.

10 clusters for >10 nights each therefore makes thisa multi-terabye 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. We then perform co-located list-driven aperture photometry and 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 ~ 4 magnitudes (Figure 3.

5. Early results

5.1. Transits

13 eclipse candidates with colours consistent with cluster membership have been identified in the 4 clusters observed and analysed so far (see Fig. **??** 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 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 at 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.

5.2. Rotation

Photometric monitoring data of the open cluster M34 (180Myr) were obtained for ~4.5 hours per night over 8 nights in November 2004 with the Wide Field Camera on the

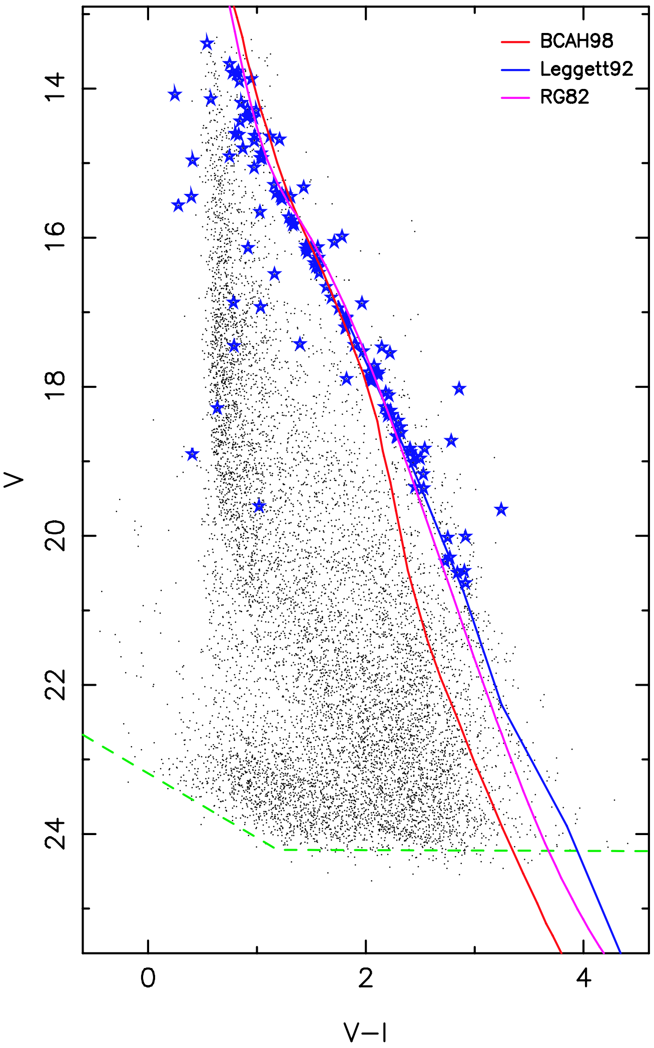

Fig. 5. The V versus $V-I$ colour-magnitude diagram of M34 for all objects with stellar morphological classification (made from a deep stack of our best images). Objects with detected periods are shown as stars. The solid lines from left to right are (1: red) a model cluster sequence from Baraffe et al. (1998), (2: pink) the empirical fiducial main sequence of Reid & Gilmore (1982) and (3: blue) 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). The limits correspond to the 5σ limiting magnitude (completeness ~50%) in the stacked image.

Isaac Newton Telescope. We alternated between 60s $V-$band and 30s $i'-$band exposures, and took a total of ~270 images in each filter. Lightcurves were extracted from the data for ~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 ¡=10 days). We fitted sine curves to each $i'-$band lightcurve in order to detect variability. We found 118 stars with lightcurves which could be well-described as periodic sinusoidal variation. Of these, the vast majority (100 or 85%) are on the photometric cluster sequence (Figure 5). The faintest objects for which we can detect rotation (with amplitudes around 1%) have $i'-$band magnitudes around 18.0.

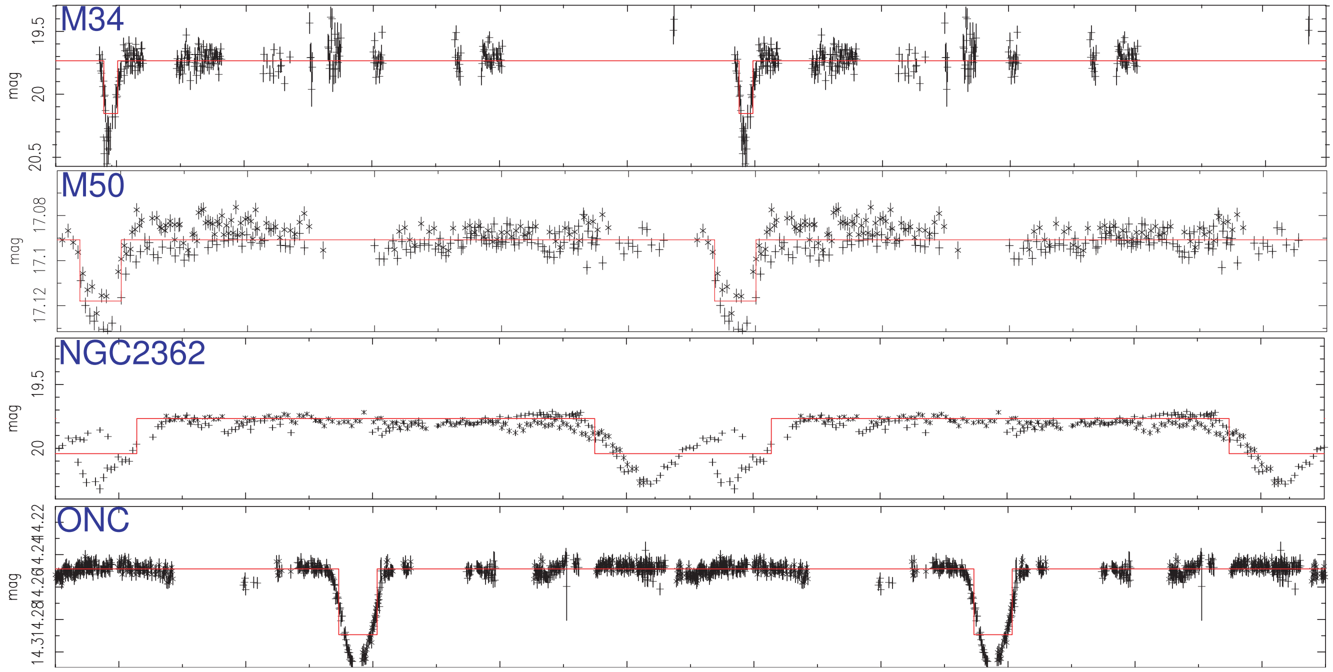

Fig. 4. Phase-folded i'−band light-curves of 4 of our eclipse candidates (M34, M50, NGC 2362 and ONC from top to bottom). Cluster ages are 180, 130, 7 and 1 Myr respecitvely, periods range from 0.5 to 2 d and likely primary masses are between 0.1 and $0.6\,M_{\odot}$.

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 M34, M50, ONC and NGC2362 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 6-8m class telescopes with higher dispersion spectrographs to follow-up any surviving candidates.

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