The Monitor project
Transits, eclipses & rotation in young open clusters

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What is Monitor?

- Photometric monitoring survey of young (1-200 Myr), rich, compact and nearby open clusters
- 2-4 m telescopes, 0.25-1 sq.deg. FOV, mainly I-band
- ~100 hours / cluster either in nights or in hourly blocks, 3-15 min sampling
- Goal I: detection of transits by planets, brown dwarfs and very low-mass stars in the light curves of low-mass cluster members
- Goal II: detection of rotation periods
- Additional science: flaring, accretion, pulsation, eclipses / transits in background stars
Motivation - eclipses

Can planets form as fast as disks evaporate?

Pollack et al 1996 - baseline Jupiter formation model.

Core Mass
Gas Mass
Total Mass

Millions of Years

Earth Masses

isolation mass reached

Haisch et al 2001

Observed disk lifetimes tend to be shorter than the ~8 Myr required in the Pollack et al. (1996) standard case model.

slides from G. Laughlin (2005)
Motivation - eclipses

Can planets form as fast as disks evaporate?
How bright & large are young brown dwarfs and planets?

![Diagram](image-url)
Motivation - eclipses

Can planets form as fast as disks evaporate?
How bright & large are young brown dwarfs and planets?

Close et al. 2005

Chauvin et al. 2005a,b
Motivation - eclipses

Can planets form as fast as disks evaporate?
How bright & large are young brown dwarfs and planets?
Motivation - eclipses

Can planets form as fast as disks evaporate?
How bright & large are young brown dwarfs and planets?

![Graph showing the mass-radius relation for M dwarfs. The graph includes data points from various sources such as OGLE survey, eclipsing binaries, interferometry, HD 209458, and ONC EB (Stassun et al. 2006). The graph also shows a comparison with the Solar System.]
Motivation - eclipses

Can planets form as fast as disks evaporate?
How bright & large are young brown dwarfs and planets?
A crucial and unchartered area of parameter space

- ~170 known exoplanets, mostly from RV surveys, 9 that transit
- Few K & M eclipsing binaries
- 1 eclipsing brown dwarf: OGLE-TR-122 (Pont et al. 2005)
- But all orbit main sequence stars with ill-known ages
- 1 M-type EB in M35 (Hebb et al. 2004)
- 1 brown dwarf EB in ONC (Stassun et al. 2006)
- Monitor should detect significant numbers of EBs and several transiting planets
Detection rate estimates
(Aigrain et al. 2006, in prep.)

• Adapted approach of Gaudi et al. 2005 (for surveys of field stars such as OGLE) to young open clusters (see also Pepper et al. 2005, for older clusters).

• Ingredients include
  • cluster mass function, age, distance, extinction
  • mass-radius and mass-radii relations from Baraffe et al. 1998 (stars / BDs) and Burrows et al. 1997 (planets)
  • companion incidence and period / mass distribution from literature
  • real (observed) time distribution of observations and noise properties

• Predicts ~80 EBs and ~8 transiting planets over the Whole of Monitor

• Several refinements need to be made, including accounting for systematics and magnitude limits for RV follow-up
Motivation - rotation

Once disk connection is broken, contraction leads to fast spin-up. Maximum rotation is reached at ZAMS. Angular momentum loss driven by magnetized wind then leads to slow spin-down.

Bouvier et al. (1997)
Motivation - rotation

Monitor target clusters cover the entire evolutionary sequence up to the early MS.

In the TTauri phase, examine link between rotation and presence of disks.

Will also reach down to the BD regime, where the star-disk connection may be altered.

Will cover in detail the ZAMS phase, which is crucial for constraining spin-down models.
## Observations

<table>
<thead>
<tr>
<th>semester</th>
<th>telescope</th>
<th>instrument</th>
<th>time awarded</th>
<th>targets</th>
<th>strategy</th>
<th>status</th>
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<tbody>
<tr>
<td>2004B</td>
<td>INT 2.5m</td>
<td>WFC</td>
<td>20 nights</td>
<td>ONC M34</td>
<td>nights</td>
<td>analysed</td>
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<tr>
<td></td>
<td>CTIO 4m</td>
<td>Mosaic II</td>
<td>6 nights</td>
<td>NGC 2632 M50</td>
<td>nights</td>
<td>analysed</td>
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<tr>
<td>2005A</td>
<td>CFHT 3.6m</td>
<td>MegaCAM</td>
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<td>WFI</td>
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<td>Blanco 1 NGC 2457</td>
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<td>2005B</td>
<td>CFHT 3.6m</td>
<td>MegaCAM</td>
<td>40 hours</td>
<td>M34 h &amp; X Per</td>
<td>blocks</td>
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<tr>
<td></td>
<td>WIRCAM (IR)</td>
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<td>40 hours</td>
<td>ONC</td>
<td>blocks</td>
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<td>WFC</td>
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<td>NGC 2362 M50</td>
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<tr>
<td>2006A</td>
<td>CTIO 4m</td>
<td>Mosaic II</td>
<td>8 nights</td>
<td>NGC 2516</td>
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</tbody>
</table>

*Note: WFC - Wide Field Camera, CTIO - Cerro Tololo Inter-American Observatory, ESO - European Southern Observatory, CFHT - Canada-France-Hawaii Telescope.*
ONC (1 Myr)
fake colour V, Hα, i image
INT + WFC (33’x33’)
~ 2000 sources (almost all likely members)

M50 (130 Myr)
greyscale i-band image
CTIO 4m + Mosaic (40’x40’)
~ 80000 sources (~8000 likely members)
Data reduction & light curves

(J. Irwin et al. 2006a, in prep.)

• All basic reduction and calibration steps carried out using standard INT Wide Field Survey (WFS) pipeline developed by the Cambridge Astronomy Survey Unit (Irwin & Lewis 2001)

• Co-located aperture photometry:
  • Refine astrometric solution to 0.1” accuracy
  • Generate master catalogue ‘noise free’ stacked master frame, flagging likely blends and non-stellar objects
  • Perform aperture photometry at master catalogue position on each frame, choosing from a range of aperture sizes to maximise SNR in aperture
  • Background estimated by interpolating across grid of 64x64 pixel bins

• Fit 2-D polynomial surface to map of light curve residuals versus x-y position to remove systematics that vary temporally as a function of position
Photometric accuracy

M50 (6 nights, all objects flagged as stellar and unblended)
Photometric accuracy

rms over transit timescale

Selected non-variable light curves
Transit / eclipse detection strategy

- Systematics removal (PCA-like algorithm of Tamuz et al. 2005)
- Membership selection from V, V-I CMD using empirical sequence
- In young clusters with active stars, high pass filter or sine fit to remove rotational modulation
- Transit search algorithm (Aigrain & Irwin 2005) for box-shaped transits (good enough approximation for most eclipses)
- Currently, correlated noise implies we have to set relatively high detection threshold - all our candidates were independently identified by eye
- Modification of algorithm to account for correlated noise under implementation
Eclipse candidates from 2004-2005

Candidates - original set
• Used for the last round of spectroscopy proposals
M34, M50, NGC 2362 ONC

3% - planet?
0.7 + 0.2 Msun from flux ratio
eccentricity?

M34, M50, NGC 2362

ONC
• $I = 13.82$, $V = 16.92$, $P = 2.65$ days, $d = 0.2$ days, $\Delta F/F = 0.06$
• Grazing?; Hillenbrand (1997) membership probability 99%
• $M_1 \sim 0.50\, M_\odot$, $R_1 \sim 2.08\, R_\odot$ (1 Myr NextGen models)
• $R_1, \Delta F/F \Rightarrow R_2 > 0.51\, R_\odot$
• $M_2 \sim M_{\text{Jup}} \rightarrow K \sim 0.4\, \text{km s}^{-1}$, $M_2 \sim 0.1\, M_\odot \rightarrow K \sim 42\, \text{km s}^{-1}$
Spectroscopy to date

- Spectroscopy is needed to confirm cluster membership and measure companion mass
- Membership: youth indicators (Lithium, Halpha emission), gravity sensitive lines
- Spectral type: e.g. using Kirkpatrick (1991) relative flux indices
- Companion mass: radial velocities, e.g. using cross-correlation with standards over Call infrared triplet region at 8500 A
- Not much luck with 2006A proposal round
- WHT/ISIS
  - Red arm 8085-8075 A, R~5000, get RV accuracy ~ 4 km/s for SNR~10
  - Blue arm 5950-7350 A, R~2000
- 1 night in Dec 2005, few hours in Feb 2006, poor seeing in both... 2 epochs of two objects, 1 of a few others
ISIS blue arm
ISIS red arm

Wavelength (Å)
• $I = 13.82$, $V = 16.92$, $P = 2.65$ days, $d = 0.2$ days, $\Delta F/F = 0.06$

• Grazing?; Hillenbrand (1997) membership probability 99%

• $M_1 \sim 0.50$ M$_\odot$, $R_1 \sim 2.08$ R$_\odot$ (1 Myr NextGen models)

• $R_1$, $\Delta F/F \Rightarrow R_2 > 0.51$ R$_\odot$

• $M_2 \sim M_{\text{Jup}} \rightarrow K \sim 0.4$ km s$^{-1}$, $M_2 \sim 0.1$ M$_\odot \rightarrow K \sim 42$ km s$^{-1}$

• 2 spectra with ISIS
  – RV measurements $17.1 \pm 6.3$, $21.1 \pm 12.4$ km s$^{-1}$ → inconclusive
  – Preliminary Feb 2006 RV $27.2 \pm 4.2$ km s$^{-1}$
  – Broad lines in ISIS spectrum, maybe double-lined in Keck spectrum
  – LiI 6708 Å in absorption, SpT M4-M5V
Some new candidates in M50
Rotation periods

- sine-fitting \( m(t) = m_{dc}(t) + a \sin(2\pi t/P + \phi) \)

- goodness of fit estimated by subtracting smoothed phase-folded light curve at best period \( \Delta \chi^2 = \chi^2_{\text{red (after)}} - \chi^2_{\text{red (before)}} \geq 0.4 \)

- no a priori variability test to ensure sensitive to low-amplitudes

- check quality of detection and of period determination by eye (process can be fully automated, but at the cost of loss of sensitivity at faint / long period end)

- combine multiple filters when available, forcing period and phase to be the same but allowing for different amplitudes (use multiple bandpasses to minimise alias pollution)

- insert fake signals into non-variable light curves to test completeness and contamination as a function of magnitude, period and amplitude
Rotation in M34

(J. Irwin et al. 2006b, in prep.)

Monitor’s age makes it ideal to constrain ZAMS spin-down relative to alpha Per and Pleiades

Rotation (both v sin i and periods) has only been explored down to mid-K (Soderblom et al. 2001, Barnes 2003)

107 periods identified

Simultaneous V- and i-band monitoring allows us to explore spot properties
Mass dependence

Masses from I-mag & Baraffe et al. (1998) isochrone
Mass dependence

Mass dependence of rapid rotator envelope

Clustering around 7-8 days for M>0.4M\textsubscript{sun}

Lack of low mass slow rotators

Masses from I-mag & Baraffe et al. (1998) isochrone
Sentivity limits

Masses from I-mag & Baraffe et al. (1998) isochrone

clustering around 7-8 days for M>0.4M\text{sun}

clear mass dependence of rapid rotator envelope
Comparison to Pleiades

Comparison to Pleiades
Summary

• About 1/3 of the Monitor photometric observations are complete and reduced

• We have 25 eclipse candidates so far. Based on current trends, should rise to ~40 from completing the first pass analysis on the currently available data.

• Taking estimated contamination into account, the current candidate set is already expected to represent an increase of several 100% on the currently known set of PMS eclipsing binaries

• Rotation period analysis in M34 already is showing interesting trends:
  • Above 0.5 Msun, cluster of slow rotators superimposed on uniform background of faster rotators, indicative of different disk-locking timescales
  • Below 0.5 Msun, tentative evidence for faster fast rotators, and lack of slow rotators (TBC), indicative of less efficient / less long-lasting disk locking

• Comparison to published periods in other clusters is hampered by (ill-known) sensitivity limits of previous surveys. The complete, uniformly analysed Monitor sample should help circumvent this problem.