monitor
transiting planets and brown dwarfs
in star forming regions and young open clusters

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University of Exeter
University of New South Wales, Sydney

LAM, Marseille, 02/05/2005
outline

• motivation & background
• targets & observing strategy
• detection rate estimates
• data reduction & light curve production
• early results from the ONC & M34
• outlook
motivation

• detect transiting planets & brown dwarfs with known ages
• detect the first very young exoplanets (< 8 Myr)
• other variability
  • rotation - down to brown dwarf masses
  • flaring / short term variations
questions

can planets form as fast as disks evaporate?

Pollack et al 1996 - baseline Jupiter formation model.

Haisch et al 2001

slides from G. Laughlin (2005)

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questions

how bright & large are young brown dwarfs and planets?

- evolutionary models
  - Baraffe et al. 98
  - Chabrier et al. 00
  - Burrows et al. 97

- initial conditions?

- high uncertainties at early ages (Baraffe et al. 2003, Marley et al 2005)
questions

what are the properties (incidence, mass ratio and period distributions) of brown dwarf companions?

- RV surveys probe close, high mass ratio binaries
- AO surveys probe large separation binaries
- We will probe close, near-equal mass ratio binaries
known transiting planets & VLM EBs

- ~154 known exoplanets, mostly from RV surveys, 7 that transit:
  - HD 209458b, OGLE-TR-10, 56, 111, 113, 132, TrES-1
- few K & M eclipsing binaries
- 1 eclipsing brown dwarf: OGLE-TR-122
mass-radius relation

Queloz et al. 2005
known transiting planets & VLM EBs

- ~ 154 known exoplanets, mostly from RV surveys, 7 that transit:
  - HD 209458b, OGLE-TR-10, 56, 111, 113, 132, TrES-1
- few K & M eclipsing binaries
- 1 eclipsing brown dwarf: OGLE-TR-122
- but all orbit main sequence stars with ill-known ages
recent discoveries

- brown dwarfs with proto-planetary disks
recent discoveries

2M1207 Companion

Companion to ~M8 brown dwarf in TW Hydrae (age ~ 8 Myr)

red J-K implies late L, $T_{\text{eff}} \sim 1250$ K

Models give $M = 5 \pm 2 M_{\text{Jup}}$

recent confirmation that the companion is comoving (see astroph yesterday)

Chauvin et al. (2004)

see also recent announcement by Neuhauser et al.

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recent discoveries

Close et al. 2004

AB Dor C
to summarise...

- no young transiting exoplanets are currently known, and no exoplanets at all younger than 8 Myr
- observational constraints on evolutionary models of planets and BDs at early ages are very few
- those that are available have sparked intense discussions

⇒ even one detection would have a large impact
⇒ a few would be very useful
⇒ several (tens?) would be a benchmark
the transit approach...

- simultaneously survey 1000’s of stars
- with RV follow-up, constrain companion radius & mass
  - in EB case, constrain $T_{\text{eff}}$ & luminosity to few %
- potential for follow-up:
  - transit spectroscopy
  - secondary eclipse searches
secondary eclipses

Observed at 4 to 8 microns (Tres-1) and 24 microns (HD 209458 b)

Planet temperature at least 1000K

Shown both orbits are circular
... in young open clusters

- known ages (& metallicities)
- increased alignment probabilities (bloated primaries)
- luminous BDs & planets - enhanced follow-up potential
- observations tailored for low and very low mass primaries
  - unchartered region of parameter space
  - deeper transits
- larger RV amplitude: easier confirmation
but...

- strong bias towards short periods (Queloz et al. 2005, Gaudi et al 2005)
  - partly mitigated by our observing strategy: more later

- activity and accretion related variability may impede transit detection
  - variability filters
  - simultaneous V & i monitoring for the youngest targets

- activity induced jitter may impede RV follow-up?
  - expect jitter $\sim 60$ m/s at 3 Myr
  - $0.03M_\odot$ BD in 3d orbit around $1M_\odot$ star: RV amplitude 3 km/s
  - $1M_{\text{Jup}}$ planet in 3 d orbit around $1M_\odot$ star: RV amplitude 140 m/s
related studies

- EXPLORE-OC (von Braun et al. 2004)
- St Andrews Open Cluster Planet Search (Street et al. 2003, Bramich et al. 2005)
- older open clusters (1 to a few Gyr)
- no detections so far (some candidates not yet excluded)
- early detection rate estimates were over-optimistic: more careful estimates (Pepper et al 2005) show absence of detections consistent with results of RV searches
related studies

- survey of middle aged open clusters to search for VLM EBs (Hebb et al. 2004)
- candidate in M35
  - secondary eclipse detected during main survey from INT & KPNO
  - primary eclipse detected during a Monitor INT run in Jan 2005
monitor targets

targets need to be young, nearby, rich and compact
# Monitor Targets

<table>
<thead>
<tr>
<th>Name</th>
<th>RA</th>
<th>Dec</th>
<th>Age</th>
<th>(M-m)_0</th>
<th>E(B-V)</th>
<th>I(HBL)</th>
<th>M(I=20)</th>
<th>N (c)</th>
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<td>(hh~mm)</td>
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<td>(mag)</td>
<td>(mag,a)</td>
<td>(mag,a)</td>
<td>(c)</td>
<td>(º,d)</td>
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<td>0.02</td>
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<td>-08 23</td>
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<td>0.06</td>
<td>150</td>
<td>4.0</td>
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</table>

Many already have deep CMDs (from e.g. CFHT key project).

### Potential Targets Under Investigation

<table>
<thead>
<tr>
<th>Name</th>
<th>RA</th>
<th>Dec</th>
<th>Age</th>
<th>(M-m)_0</th>
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<th>I(HBL)</th>
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<td>??</td>
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<td>??</td>
<td>??</td>
<td>??</td>
<td>??</td>
<td>??</td>
<td>??</td>
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**observations to date**

<table>
<thead>
<tr>
<th>semester</th>
<th>telescope</th>
<th>instrument</th>
<th>time</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>reduced, under analysis</td>
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<tr>
<td>2005A</td>
<td>CTIO 4m</td>
<td>Mosaic</td>
<td>6 nights</td>
<td>NGC 2632 M50 NGC 2516</td>
<td>nights</td>
<td>under reduction</td>
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<tr>
<td></td>
<td>CFHT 3.6m</td>
<td>MegaCAM</td>
<td>40 hours</td>
<td>IC4665</td>
<td>blocks</td>
<td>awaiting data</td>
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<td></td>
<td>ESO 2.2m</td>
<td>WFI</td>
<td>50 hours</td>
<td>Blanco 1</td>
<td>blocks</td>
<td>awaiting data</td>
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<tr>
<td>2005B</td>
<td>ESO 2.2m</td>
<td>WFI</td>
<td>150 hours</td>
<td>Blanco 1 NGC 2457</td>
<td>blocks</td>
<td>awaiting data</td>
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</table>
observing strategy

- 2 distinct requirements:
  - (a) need to monitor enough targets with sufficient photometric precision to have a good chance of detecting transits / eclipses
  - (b) need to characterise eclipse shape well enough to fit the parameters of the system

- (b) implies sampling time shorter than ingress / egress and blocks of observations longer than 2/3 of a typical eclipse
  - typical BD eclipse: duration (P = 2d): 1.5h, ingress / egress 30 min
  - need 1-2 hour blocks with 1 point every 15 min

- (a) implies many observations over time scale >> periods of interest
  - when possible, request service mode, blocks of ~ 2 hours scheduled randomly throughout observability window
  - lax observing conditions requirements - ease of scheduling
observing strategy

trdur = 4.0 hours, tstep = 10.0 minutes, dblock = 2.0 hours, nblock = 50, dtol = 120 nights
detection rate estimates

• 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).

• Primaries:
  • cluster age and distance (literature or WEBDA)
  • number of known members in a given area and mass range (literature)
  • log-normal IMF (Moraux et al. 2005, $<M> = 0.34 \, M_\odot$, $\sigma = 0.54$)
  • area we plan to survey
  • → number of primaries versus mass
  • evolutionary models (Baraffe et al. 1998) → magnitude, radii versus mass
  • exposure times we plan to use
  • resulting SNR versus magnitude (source & sky photon + readout noise)
  • saturation and source detection limits
  • → photometric precision versus mass from saturation to detection limit
detection rate estimates

NGC 2362, 7 Myr, 1 CTIO4m/Mosaic field, 540 observations
detection rate estimates

- Adapted approach of Gaudi et al. 2005 to young open clusters.
- Secondaries:
  - planets - masses $1 \, M_{\text{Nep}}$ to $5 \, M_{\text{Jup}}$
    - models (Burrows et al. 1997) → radii versus mass
    - 1% of F,G,K primaries have a Hot Jupiter (Marcy et al. 2004)
    - very Hot Jupiters 3 times as rare (Gaudi et al. 2005)
    - Jupiter-mass planets twice as rare around lower mass stars (RV surveys)
    - More low mass planets around low mass stars? (Laughlin et al. 2004)
    - $P_{\text{companion}}(M_\star, M_p, P)$

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detection rate estimates

- Adapted approach of Gaudi et al. 2005 to young open clusters.
- Secondaries:
  - stars and brown dwarfs - masses above $13 \ M_{\text{Jup}}$
  - models (Baraffe et al. 1998) $\rightarrow$ radii versus mass
  - F,G,K primaries:
    - log normal period distribution $<P> = 170 \ \text{yrs}$ (Duquennoy & Mayor 1991)
    - multiplicity rate 13.5% for $P < 10 \ \text{yrs}$ (Halbwachs et al 2003)
    - 45% of binaries have mass ratio $q > 0.75$ (Halbwachs et al 2003)
  - lower mass primaries - closer, high mass ratio?
    - same overall multiplicity rate but
    - $<P> = 17 \ \text{yrs}, \ q > 0.7 \ \text{always}$
  - $\rightarrow P_{\text{companion}}(M_1, M_2, P)$
NGC 2362, 7 Myr, 1 CTIO4m/Mosaic field, 540 observations
detection rate estimates

- Adapted approach of Gaudi et al. 2005 to young open clusters.
- For each primary & secondary mass and period, compute
  - expected number of systems $N$
  - alignment probability
  - transit depth
  - number of in-transit points (assume random sampling)
  - required photometric precision (require transit SNR > 10)
  - if primaries in that mass range will be monitored precisely enough, add $N$ to the expected number of detections
NGC 2362, 7 Myr, 1 CTIO4m/Mosaic field, 540 observations

→ 1.3 planets, 7 EBs

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### detection rate estimates

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<thead>
<tr>
<th>Cluster</th>
<th>Ref</th>
<th>$N_L$</th>
<th>$M_{1,a}$</th>
<th>$M_{2,a}$</th>
<th>$\Omega_L$</th>
<th>Detector</th>
<th>$\Omega_O$</th>
<th>$N_O$</th>
<th>$N_P$</th>
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<td>1684</td>
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<tr>
<td>h/χ ~Per</td>
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<td>230</td>
<td>4</td>
<td>10</td>
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<td>230</td>
<td>8676!</td>
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<td>3 or 4 pointings?</td>
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<td>300</td>
<td>318</td>
<td>500</td>
<td>0.3</td>
<td>0.9</td>
<td>4 pointings include most members</td>
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<td>1100</td>
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<td></td>
<td>MegaCAM</td>
<td>1.0</td>
<td>100</td>
<td>409</td>
<td>400</td>
<td>0.2</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>11.3</strong></td>
<td><strong>16112</strong></td>
<td></td>
<td><strong>8.4</strong></td>
<td><strong>86.8</strong></td>
<td><strong>1</strong></td>
<td><strong>dataset only per cluster</strong></td>
</tr>
</tbody>
</table>

**caveout: need more realistic assessment of number of in-transit points in some cases**

LAM, Marseille, 02/05/2005
detection rate estimates

Monitor as a whole
early (VERY preliminary) results

INT+WFC observations of M34 and the ONC in 2004B
ONC - the cluster

- 05h 35m -05° 23’
- age 0.8 - 3 Myr
- distance 400 pc
- E(B-V) = 0.05
- Hydrogen-burning limit at I = 16.9

by far the richest nearby open cluster with an angular size matched by wide-field optical detectors
Hillenbrand 1997, 1998
- optical (I) and near-IR (JHK) surveys + spectroscopy
- 1600 PMS members in central sq.deg.
- 60% disk fraction

Slesnick et al. 2004
- J & K spectra of candidate brown dwarf members
- 500 members with $0.02 < M/M_\odot < 0.5$ in 0.07 sq.deg.

Lucas et al. 2005
- Gemini JHK survey, 26 sq. arcmin
- 138 BD candidates, 33 of planetary mass
FIGURE 4. 
'Images showing 15 circumstellar disks that are seen only in silhouette (see Table 1), obtained through the F656N filter, which transmits the H line. All frames are shown at the same image scale, with north toward the top and east toward the left, and they are arranged to reflect their relative locations in the nebula. The intensities have been adjusted so that all objects can be displayed in the same frame. The field of view in each frame is 2.73'.

Along with these objects, there are many bright proplyds that have dark disks silhouetted against both the background nebula as well as the ionization fronts of the proplyd. Theory suggests that all proplyds should have such disks, and the HST images which Bally, et al. (2000) examined support this. Detection of the disks in many bright proplyds becomes difficult, however, because, if not edge on, they can be overwhelmed by the brightness of the ionized fronts (cusp).

Bally et al. 2000
Hasn’t it been done before? The ONC is an intensively monitored piece of sky!

- Herbst et al. 2002: (ESO2.2m + WFI, 45 nights, 1-2 points / night):
  - bimodal distribution peaking at 2 & 8 d for $M>0.3M$
  - unimodal distribution peaking at 2 d for $M<0.3M$
  - stars with no near-IR excess rotate faster - disk locking
  - 1% precision at $I = 16$

- Stassun et al. 1999 (1m telescopes, 17 nights, 1 point / hour)
  - periods close to break up (0.5 d)
  - no evidence for bimodality
  - 1-2% precision at $I = 16.5$

- Scholz & Eisloffel 2004 (concerns $\epsilon$ & $\sigma$ Ori rather than the ONC):
  - ~10 min time sampling but only 4 consecutive nights
ONC - previous monitoring

- Other ONC studies of interest:
  - X-ray monitoring: COUP project (PI Feigelson)
    - megasecond integration with Chandra
    - plan to compare our rotation and flaring results
  - near-IR monitoring: Carpenter et al.
    - 1 point / night, very short exposures
    - many forms of short term variability detected
ONC - observations

- 10 nights in Nov. 2004 & 10 in Jan 2005
- ~10 half-nights clear & ~5 poor
- alternate 30s i' & 60s V, cycle time time 3.5 min
- ~ 2 x 370 frames in each band
- pairs of 30s and 100s Hα exposures every ~ 2 hours
- i' magnitude range 12.8 - 21.5
- mass range 0.85 - 0.008 M☉
- had to use 2MASS as input source catalog
M34 - the cluster

- 02h 42m +42° 47’
- 180 Myr (Meynet et al. 1993)
- 550 pc
- E(B-V) = 0.07
- Hydrogen-burning limit at I = 21.7
- Most recent survey: Ianna & Schlemmer (1993): 89 members with $0.9 < M/M_\odot < 2.5$ in 0.55 sq.deg.
M34 - observations

- 10 nights in Nov. 2004
- 5 half-nights clear + 3 poor
- alternate 30s i’ & 60s V, cycle time time 3.5 min
- ~ 280 frames in each band
- i’ magnitude range 12.8 - 21.5
- mass range 1.05 - 0.06 M☉
red - i'
blue - V
green - (i'+V)/2
data reduction

- used standard INT Wide Field Survey (WFS) pipeline developed by the Cambridge Astronomy Survey Unit (Irwin & Lewis 2001)
  - cross-talk correction
  - bias correction
  - flatfielding
  - defringing (i’ only)
- astrometric & photometric calibration using observations of Landolt 1999 standard star fields
difference image analysis

• master image constructed by staing 20 best frames

• master transformed to each frame’s exact position and image quality using adaptive kernel technique (Allard & Lupton 1998, Allard 2000) & subtracted off

• adapted the standard DIA routines to fit a varying background

• performed standard list-driven aperture photometry on the difference images
difference image analysis
difference image analysis

M34, all frames, all objects classified as stellar

standard aperture photometry

DIA + aperture photometry
systematics correction

• differential extinction, PSF variations across the field cause systematic trends common to many light curves

• these can induce false transit detections

• several recently published correction techniques
  • Kovacs et al. 2004: linear decomposition on template LCs
  • Tamuz et al. 2004: iterative PCA-like approach

• ours differs slightly:
  • fit & subtract 2-D polynomial to light curve residuals versus x-y position, image by image
systematics correction

M34, all frames, all objects classified as stellar

DIA + aperture photometry without systematics correction

DIA + aperture photometry with systematics correction
systematics correction
example light curves - M34 - I

$V = 14.95, I = 14.56$

$J = 14.44, K = 14.21$ (2MASS)
example light curves - M34 - I

Beta Lyrae type

P = 0.419 d
example light curves - M34 - 3

\[ V = 19.41, I = 17.57 \]
\[ J = 16.71, K = 15.54 \text{ (2MASS)} \]
\[ M_{\text{MS}} = 0.57 \, M_{\odot} \text{ (Baraffe et al. 1998)} \]
\[ R_{\text{MS}} = 0.49 \, R_{\odot} \text{ (Siess et al. 2000)} \]
example light curves - M34 - 3

$V = 19.41, I = 17.57$

$J = 16.71, K = 15.54$ (2MASS)

$M_{MS} = 0.57 \, M_\odot$ (Baraffe et al. 1998)

$R_{MS} = 0.49 \, R_\odot$ (Siess et al. 2000)
example light curves - M34 - 3

\[ P = 1.4342 \text{ d}, \quad R_C = 0.87 \pm 0.1 \text{R}_{\text{Jup}}, \quad i = 90 \pm 2^\circ \]

consistent with planet, but...
need more data to really constrain parameters
giant or MS?

LAM, Marseille, 02/05/2005
Example light curves - ONC - 1

$i' = 16.6, \text{first run only}$

$P = 0.09 \text{ d, amplitude 0.1 to 0.3 mag}$
example light curves - ONC - 2

i' = 16.05, first run

second run
ongoing work on ONC data

- we are currently investigating issues with the photometry in the ONC we believe may be inducing short timescale spurious variations
- once that is resolved, we will derive rotation periods and compare ours to published distributions
- then we will start searching for transits
  - after removal of sine-like periodic components
  - after filtering in Fourier domain
outlook

- The initial 1 or 2 band photometric observations of all our target clusters should be completed by the end of 2006
- Time has been applied for on WHT+ISIS for spectroscopic follow-up of the first candidates
- more information...

http://www.ast.cam.ac.uk/~suz/monitor/monitor.php