monitor

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

Suzanne Aigrain - IoA, Cambridge

Jonathan Irwin, Simon Hodgkin, Estelle Moraux, Mike Irwin, Cathie Clarke, Gerry Gilmore	Institute of Astronomy, University of Cambridge
Leslie Hebb	John Hokpins University, Baltimore
Jerome Bouvier	LAOG, Grenoble
Fabio Favata	ESA / ESTEC
Ettore Flaccomio	Osservatorio Astronomico di Palermo
Mark McCaughrean	University of Exeter
Michael Ashley	University of New South Wales, Sydney

LAM, Marseille, 02/05/2005

outline

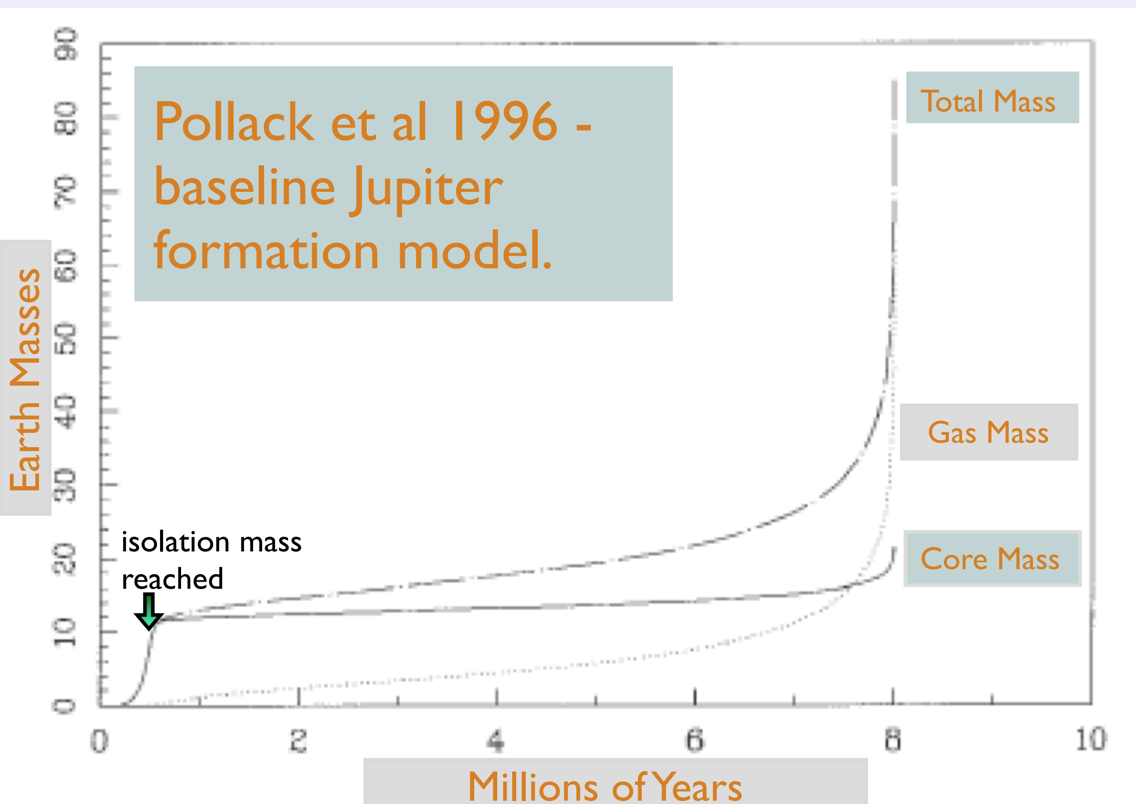
- motivation & background
- targets & observing strategy
- detection rate estimates
- data reduction & light curve production
- early results from the ONC & M34
- outlook

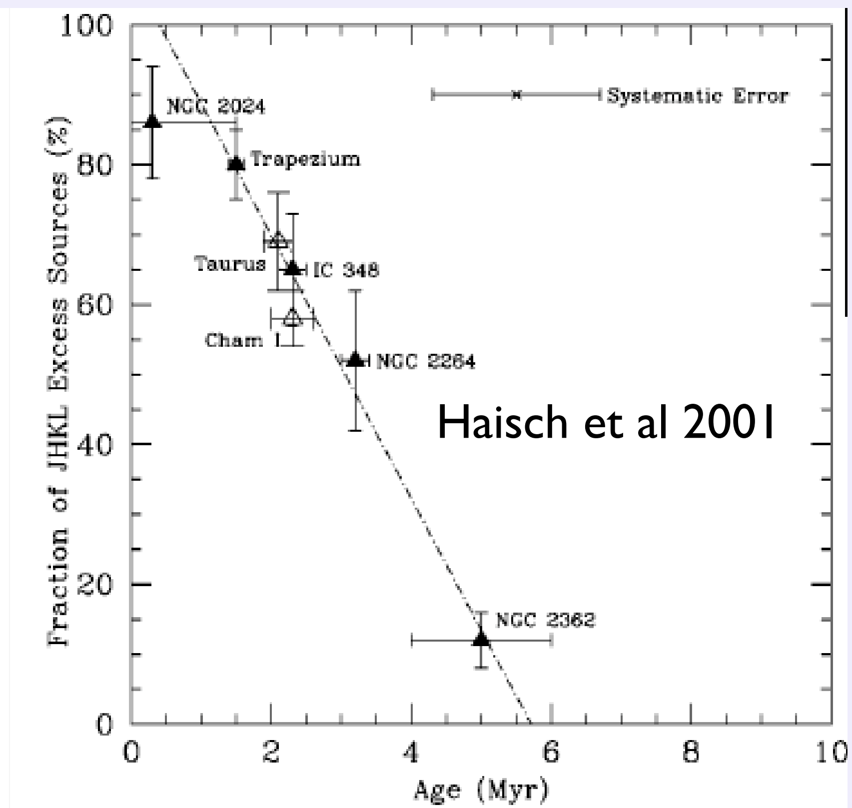
motivation

- 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?



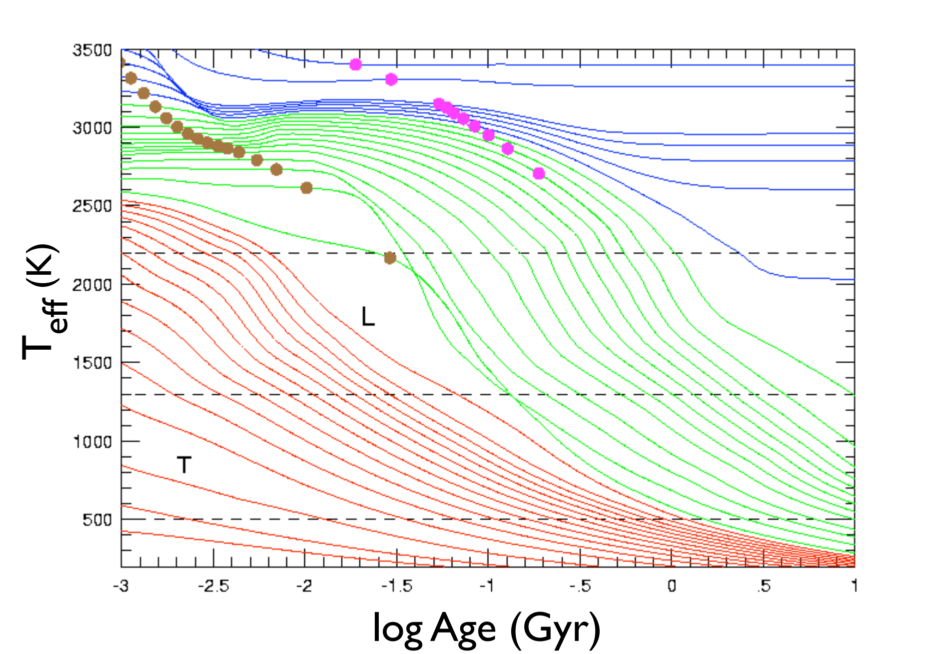


slides from G. Laughlin (2005)

questions

how bright & large are young brown dwarfs and planets?

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



Burrows et al. 1997

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

monitor

questions

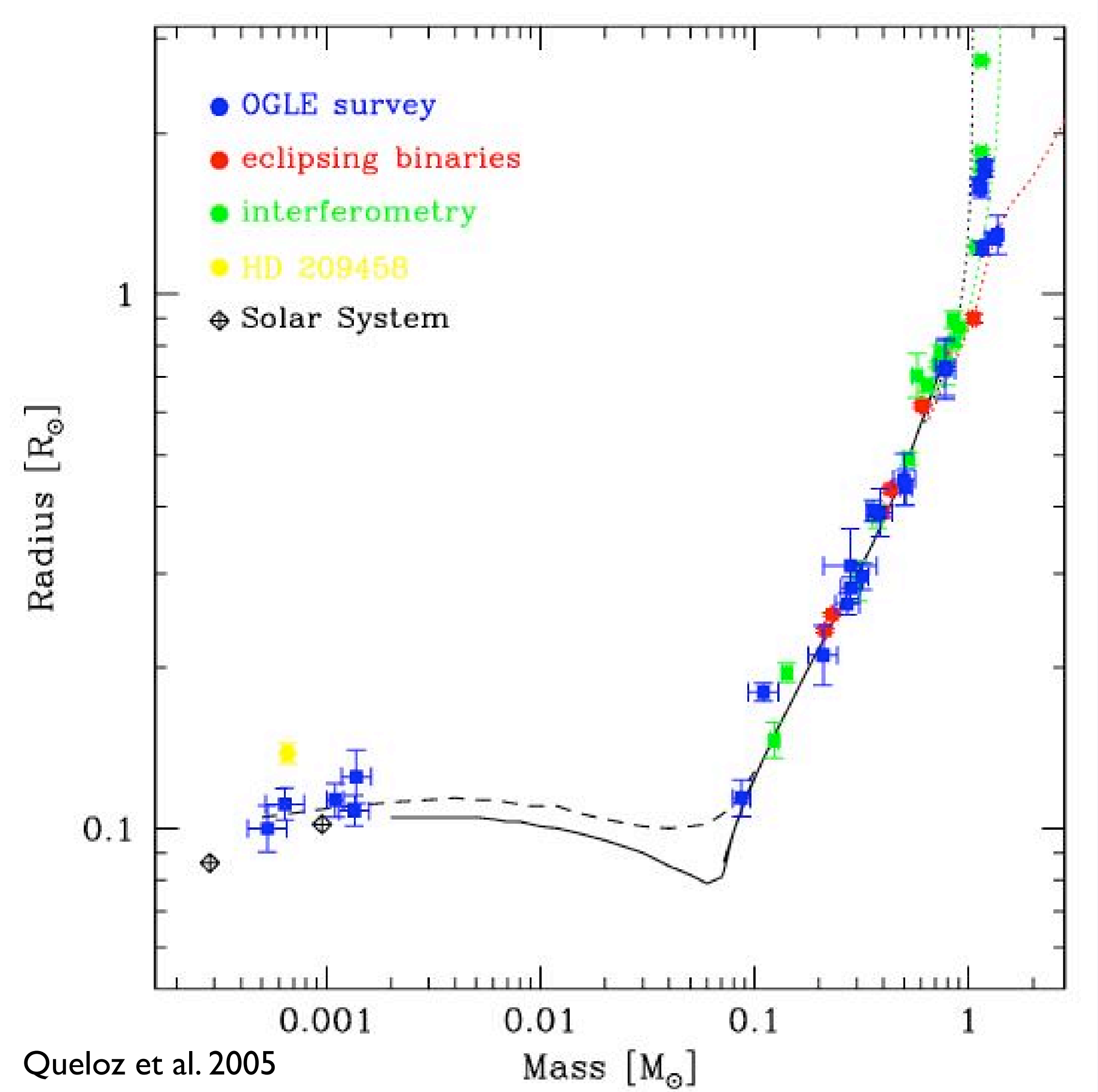
what are the properties (incidence, mass ratio and period distributions) of brown dwarf companions?

- RV suveys 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



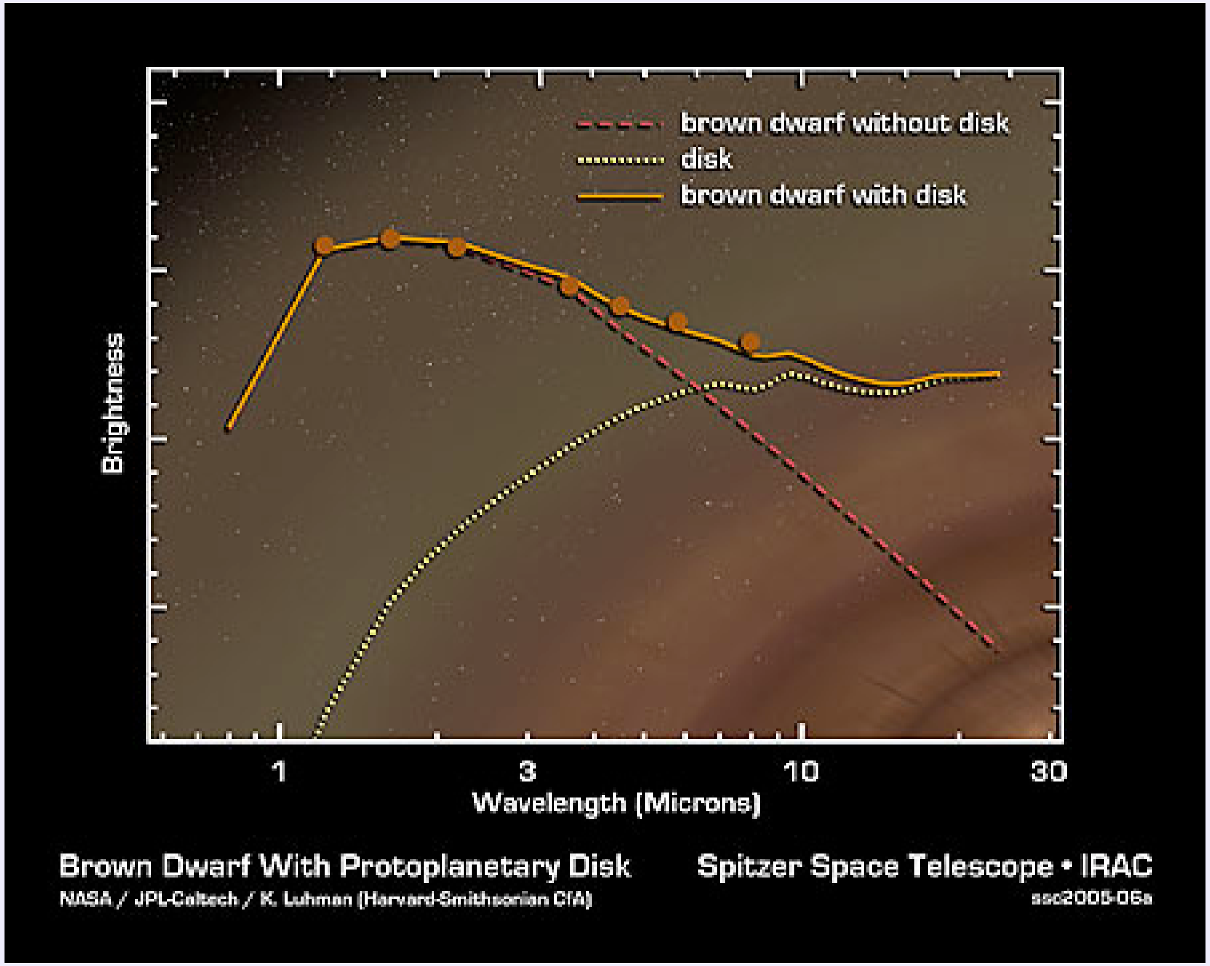
Queloz et al. 2005

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

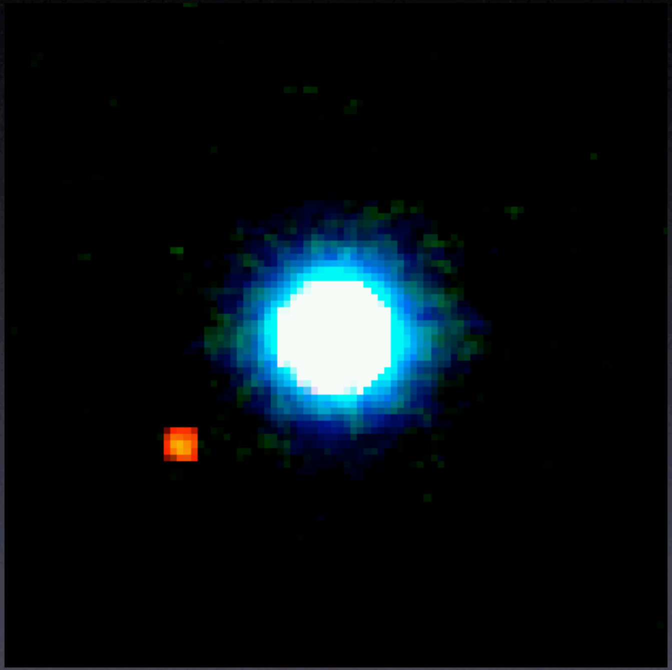
2M1207 Companion

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

red J-K implies late L, T_{eff} ~ 1250 K

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

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

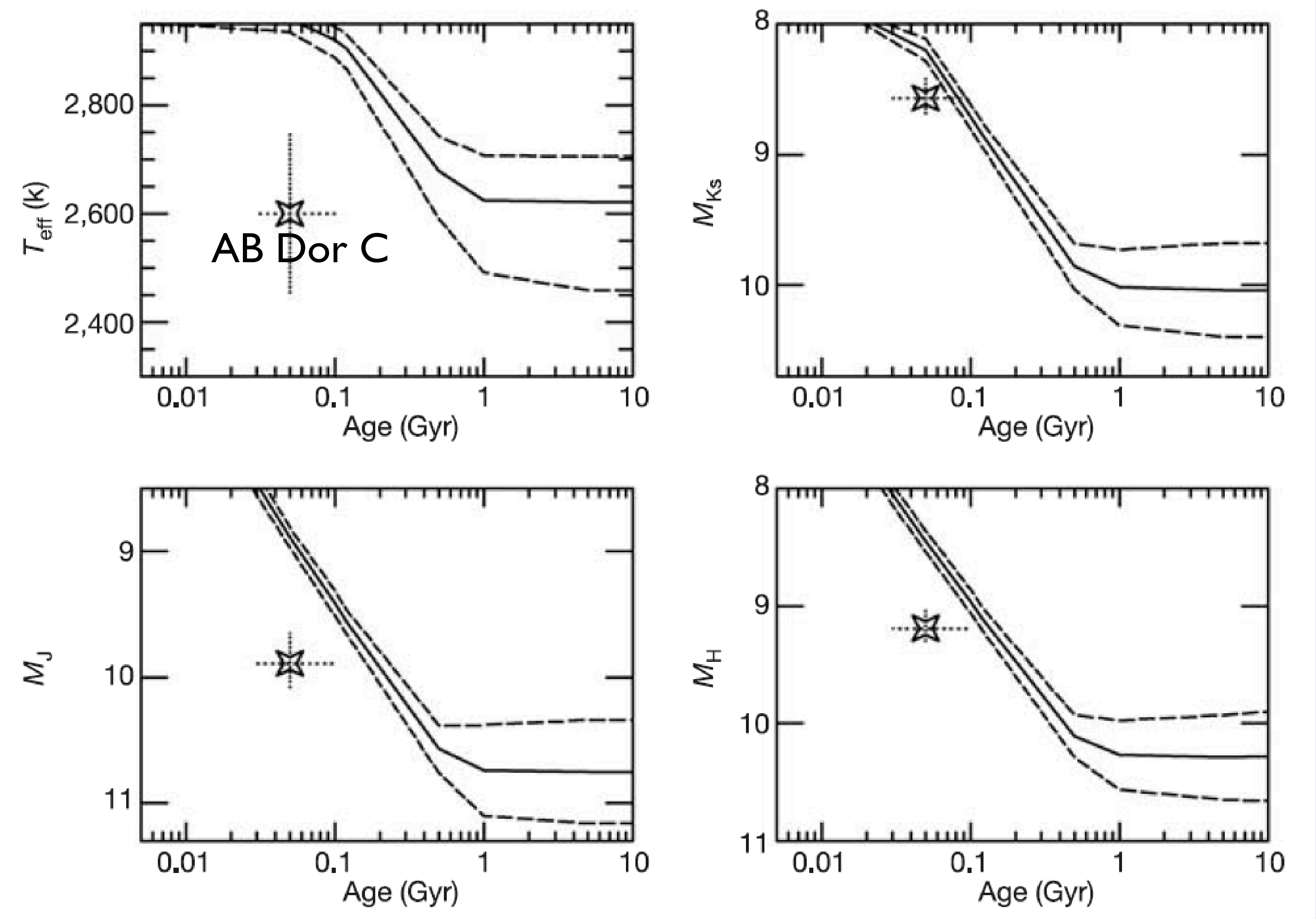


Chauvin et al. (2004)

see also recent announcement by Neuhauser et al.

recent discoveries

Close et al. 2004



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

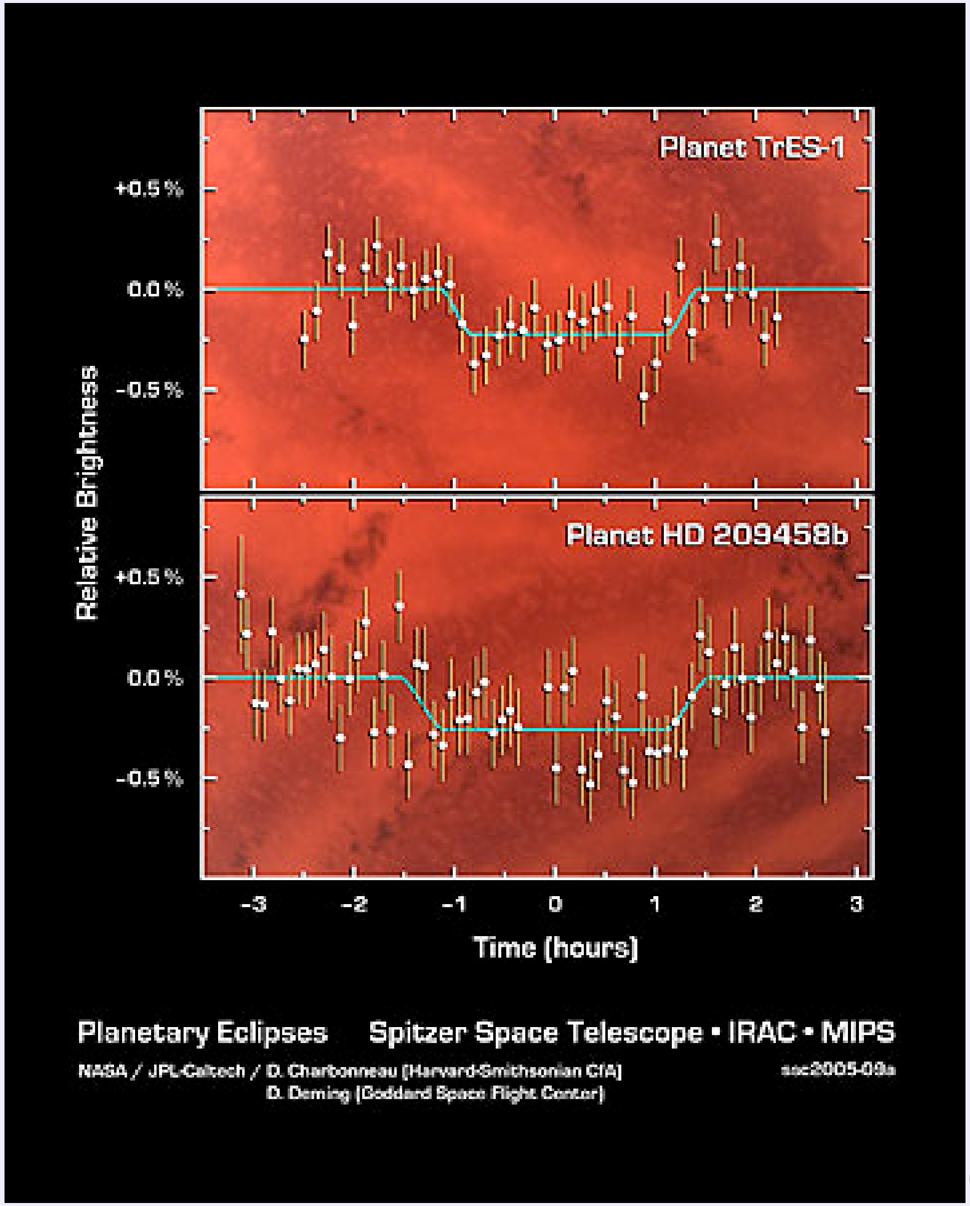
⇒ a few would be very useful

⇒ 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, contrain T_{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...

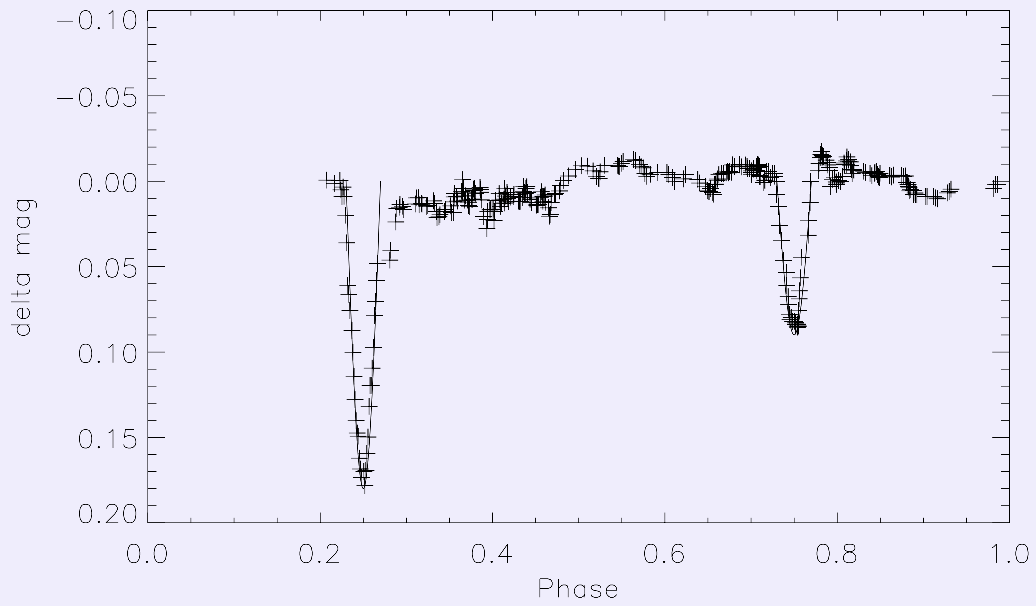
- strong bias towards short periods (Queloz et al. 2005, Gaudi et al 2005)
  - partly mitigated by our observing strategy: more later
- activity and accretion related variability may impede transit detection
  - variability filters
  - simultaneous V & i monitoring for the youngest targets
- activity induced jitter may impede RV follow-up?
  - expect jitter ~ 60 m/s at 3 Myr
  - $0.03M_{\odot}$ BD in 3d orbit around $1M_{\odot}$ star: RV amplitude 3 km/s
  - $1\ M_{Jup}$ 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)
- PISCES (Mochejska et al 2002, 2004, 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

Name	RA	Dec	Age	(M-m)_0	E(B-V)	I(HBL)	M(I=20)	N (c)	Area
	(hh~mm)	(dd~mm)	(Myr)	(mag)	(mag)	(mag,a)	(M_Sun,b)		(°,d)
Blanco~1	00 04	-29 56	100	7.1	0.01	19.2	0.06	300 (0.03,0.6)	2.3
h/χ~Per	02 20	+57 08	12.8	11.85	0.56	22.0	0.22	230 (4,10)	1.0
M34	02 42	+42 47	180	8.7	0.07	21.7	0.11	89 (0.9,2.5)	0.55
IC~348	03 44	+32 17	~3	8.0	??	16.9	0.02	150 (0.08,1.25)	0.35 (g)
ONC	05 35	-05 23	~1	8.16	0.05	16.6	0.02	500 (0.02,0.5)	0.07
M50	07 02	-08 23	130	10.5	??	22.6	0.25	1100 (0.15,0.55)	0.35
NGC~2362	07 19	-24 57	7	11.0	??	20.5	0.09	500 (0.11,0.65)	0.11
NGC~2516	07 58	-60 52	150	7.7	??	20.0	0.08	1200 (0.02,0.2)	2.0
NGC~2547	08 10	-49 10	30	8.4	??	19.2	0.05	500 (0.035,0.9)	0.855
IC~4665	17 46	+05 43	50	8.3	??	19.6	0.06	150 (0.02,0.2)	4.0

monitor

monitor targets

Name	RA (hh~mm)	Dec (dd~mm)	Age (Myr)	(M-m)_0 (mag)	E(B-V) (mag)	I(HBL) (mag,a)	M(I=20) (M_Sun,b)	N (c)	Area (º,d)
Blanco~1	00 04	-29 56	100	7.1	0.01	19.2	0.06	300 (0.03,0.6)	2.3
h/χ~Per	02 20	+57 08	12.8	11.85	0.56	22.0	0.22	230 (4,10)	1.0
M34	02 42	+42 47	180	8.7	0.07	21.7	0.11	89 (0.9,2.5)	0.55
IC~348	03 44	+32 17	~3	8.0	??	16.9	0.02	150 (0.08,1.25)	0.35 (g)
ONC	05 35	-05 23	~1	8.16	0.05	16.6	0.02	500 (0.02,0.5)	0.07
M50	07 02	-08 23	130	10.5	??	22.6	0.25	1100 (0.15,0.55)	0.35
NGC~2362	07 19	-24 57	7	11.0	??	20.5	0.09	500 (0.11,0.65)	0.11
NGC~2516	07 58	-60 52	150	7.7	??	20.0	0.08	1200 (0.02,0.2)	2.0
NGC~2547	08 10	-49 10	30	8.4	??	19.2	0.05	500 (0.035,0.9)	0.855
IC~4665	17 46	+05 43	50	8.3	??	19.6	0.06	150 (0.02,0.2)	4.0

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

potential targets under investigation

NGC~2631	16 54	-41 49	??	??	??	??	??	??	??
Trumpler~24	16 57	-40 40	??	??	??	??	??	??	??

observations to date

semester	telescope	instrument	time	targets	strategy	status
2004B	INT 2.5m	WFC	20 nights	ONC M34	nights	reduced, under analysis
2005A	CTIO 4m	Mosaic	6 nights	NGC 2632 M50 NGC 2516	nights	under reduction
	CFHT 3.6m	MegaCAM	40 hours	IC4665	blocks	awaiting data
	ESO 2.2m	WFI	50 hours	Blanco 1	blocks	awaiting data
2005B	ESO 2.2m	WFI	150 hours	Blanco1 NGC 2457	blocks	awaiting data

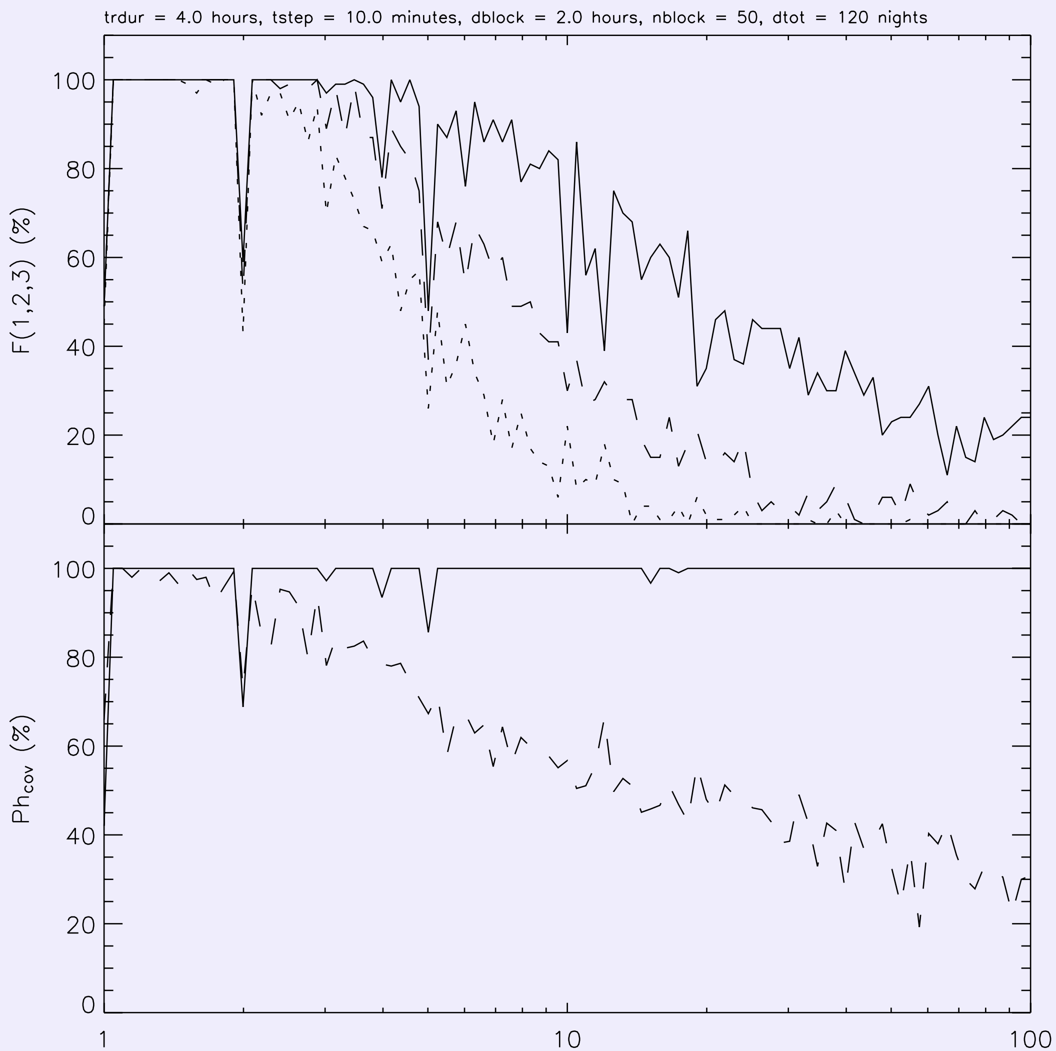
monitor

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

monitor

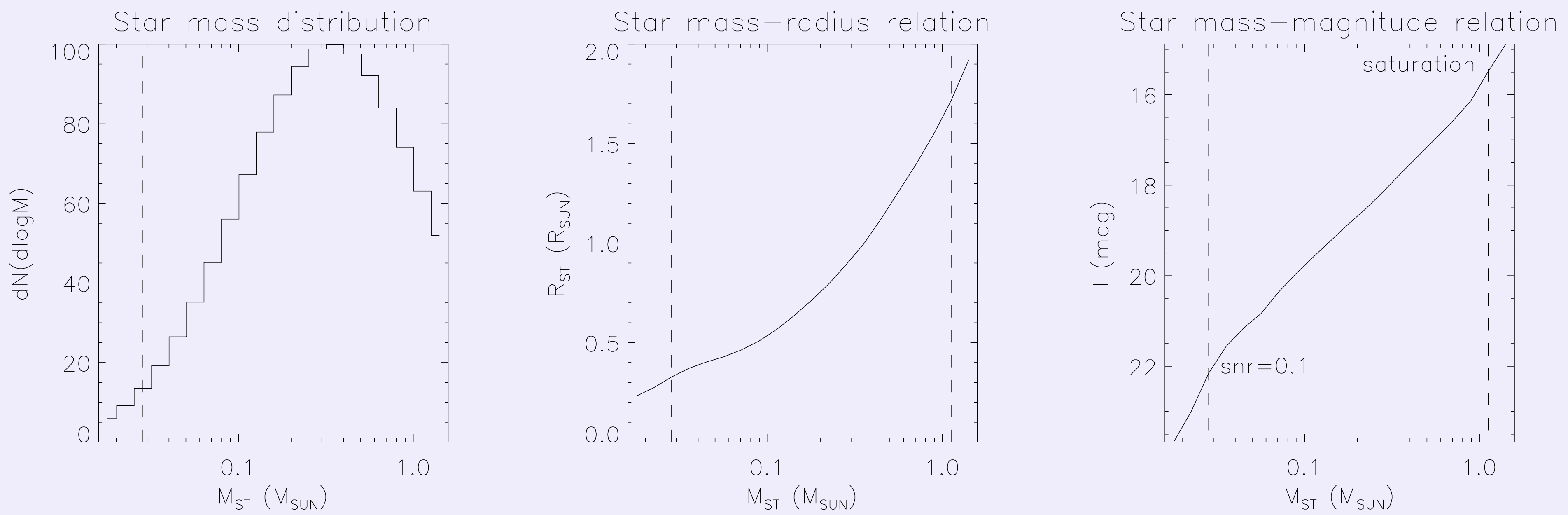
observing strategy



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, $\langle M \rangle = 0.34\ M_\odot$, $\sigma = 0.54$)
    - 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

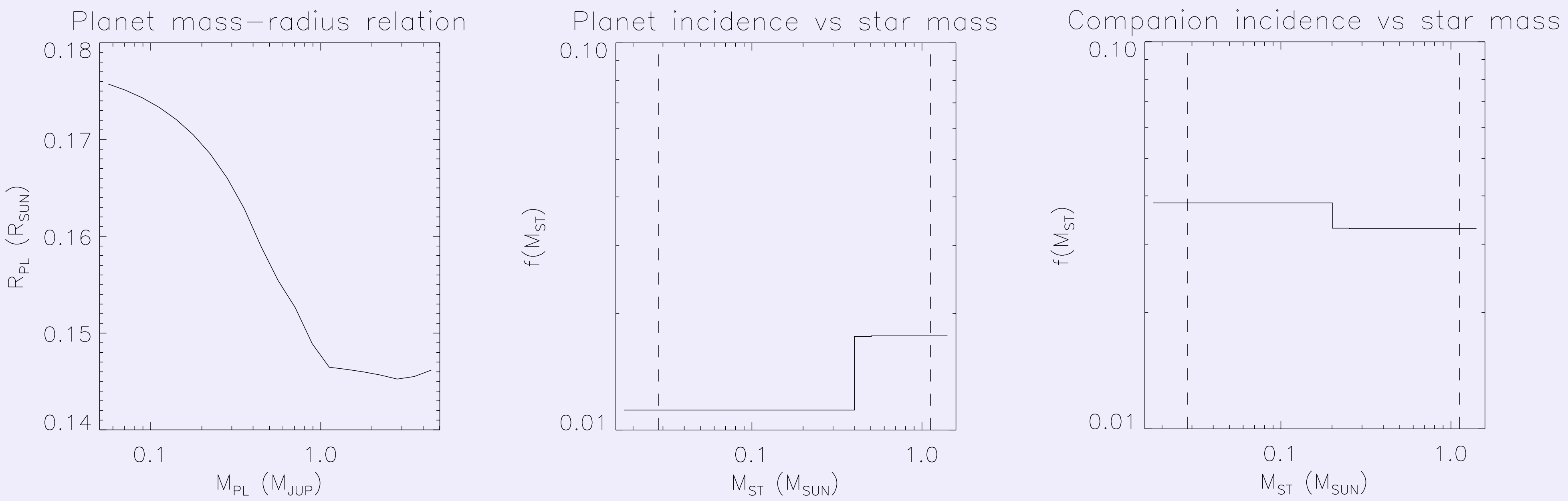
detection rate estimates

- Adapted approach of Gaudi et al. 2005 to young open clusters.
- Secondaries:
  - planets - masses 1 M_{Nep} to 5 M_{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)
    - → $P_{companion}(M_{\bigstar}, M_P, P)$

detection rate estimates

- Adapted approach of Gaudi et al. 2005 to young open clusters.
- Secondaries:
  - stars and brown dwarfs - masses above 13 M_{Jup}
    - models (Baraffe et al. 1998) → radii versus mass
    - F,G,K primaries:
      - log normal period distribution <P> = 170 yrs (Duquennoy & Mayor 1991)
      - multiplicity rate 13.5% for P < 10 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 yrs, q > 0.7 always
    - → $P_{companion}(M_1, M_2, P)$

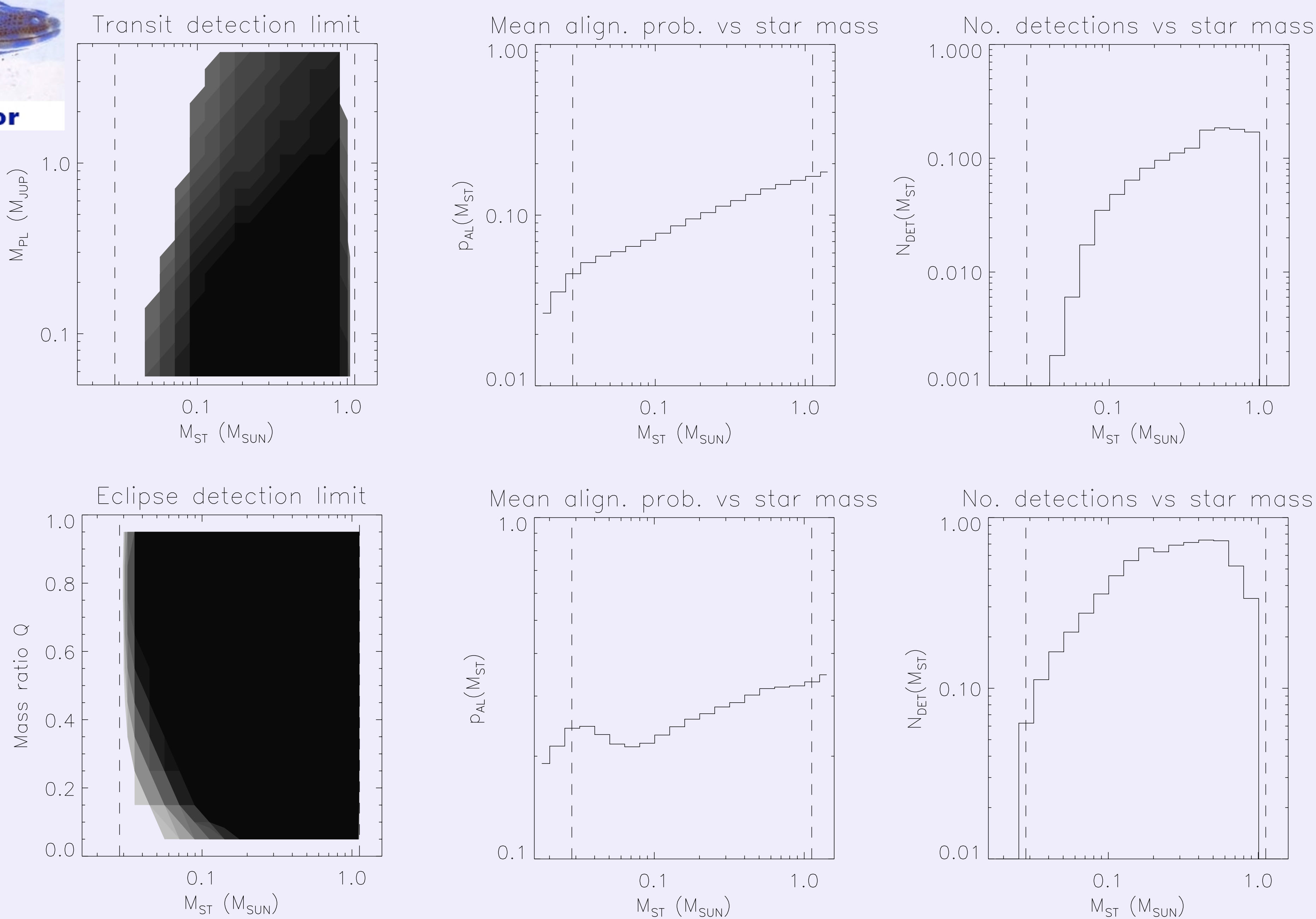
detection rate estimates



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

detection rate estimates

- Adapted approach of Gaudi et al. 2005 to young open clusters.
- For each primary & secondary mass and period, comput
  - 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

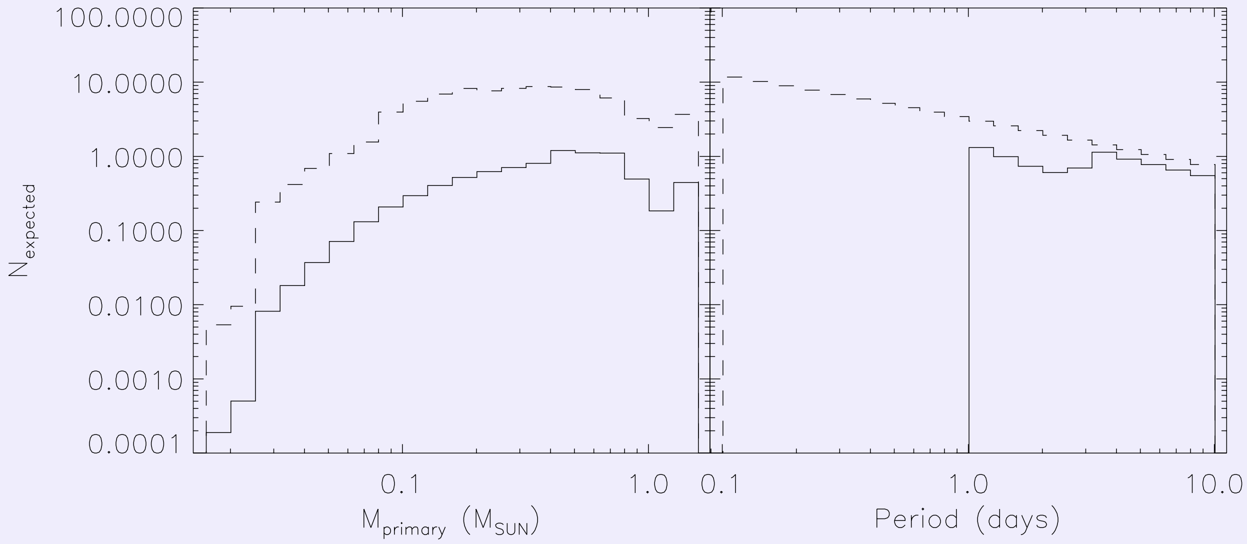
detection rate estimates

Cluster	Ref	N_L	$M_{1,a}$	$M_{2,a}$	Ω_L	Detector	Ω_O	N_O	N_P	N_{obs}	N_{PL}	N_{EB}	Comment
ONC	1	500	0.02	0.5	0.007	WFC	0.25	1400	1684	700	3.8	21.5	N_O from 2MASS, 2004B data only
						WIRCAM	0.11	2000	1539	1500	2.5	20.4	N_O from N_L, r^{-1} profile
IC~348	2	150	0.08	1.25	0.35	MegaCAM	1.0	150	112	400	0.3	0.9	Cluster extent < 0.35 sq.deg.
NGC~2362	3	500	0.11	0.65	0.11	Mosaic	0.36	700	1055	540	1.3	7.2	Cluster extent < 0.35 sq.deg.
h/χ ~Per	4	230	4	10	1.0	MegaCAM	1.0	230	8676!	400	1.0	44.8	S/N limited for planets
NGC~2457	5	400	0.035	0.9	0.855	WFI	1.0?	400	408	500	0.3	1.5	3 or 4 pointings?
IC~4665	6	150	0.02	0.2	4.0	MegaCAM	4.0	150	329	400	0.2	1	4 pointings
Blanco~1	7	300	0.03	0.6	2.3	WFI	1.0	300	318	500	0.3	0.9	4 pointings include most members
M50	8	1100	0.15	0.55	0.35	Mosaic	0.36	1100	1734	540	1.0	4.0	θ=30'
NGC~2516	9	1200	0.02	0.2	2	Mosaic	1.08	900	1387	216	0.4	3.2	3 pointings
M34	10	89	0.9	2.5	0.55	WFC	0.25	70	256	250	0.1	0.7	
						MegaCAM	1.0	100	409	400	0.2	1.1	cluster extent < 1 sq.deg.
Total							**11.3**		**16112**		**8.4**	**86.8**	1 dataset only per cluster

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

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

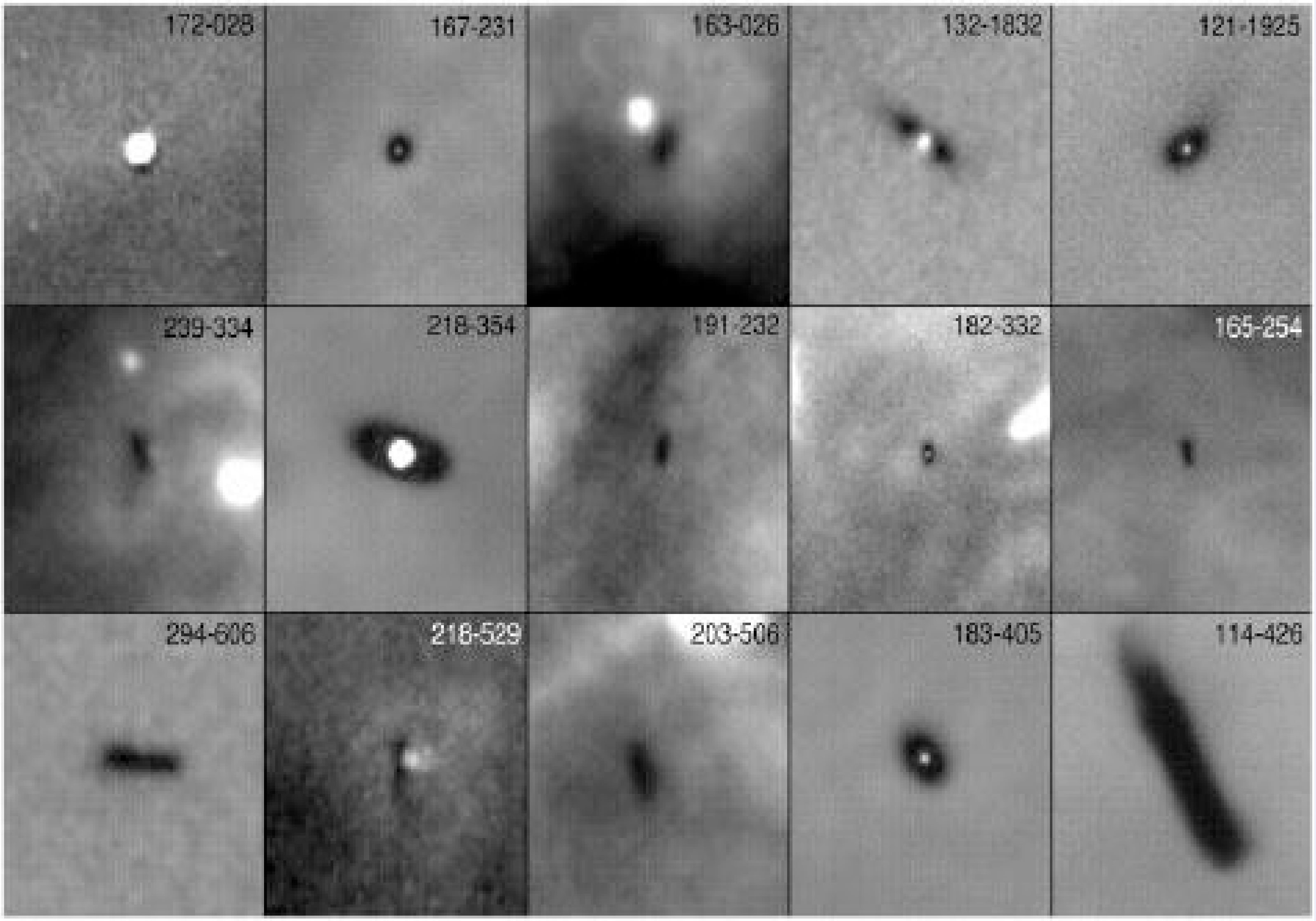
by far the richest nearby open cluster with an angular size matched by wide-field optical detectors

monitor

ONC - membership & disks

- Hillenbrand 1997, 1998
  - optical (I) and near-IR (JHK) surveys + spectroscopy
  - 1600 PMS members in central sq.deg.
  - 60% disk fraction
- Slesnick et 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 a;. 2005
  - Gemini JHK survey, 26 sq. arcmin
  - 138 BD candidates, 33 of planetary mass

ONC - membership & disks



Bally et al. 2000

ONC - previous monitoring

- 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 ϵ & σ Ori rather than the ONC):
    - ~10 min time sampling but only 4 consecutive nights

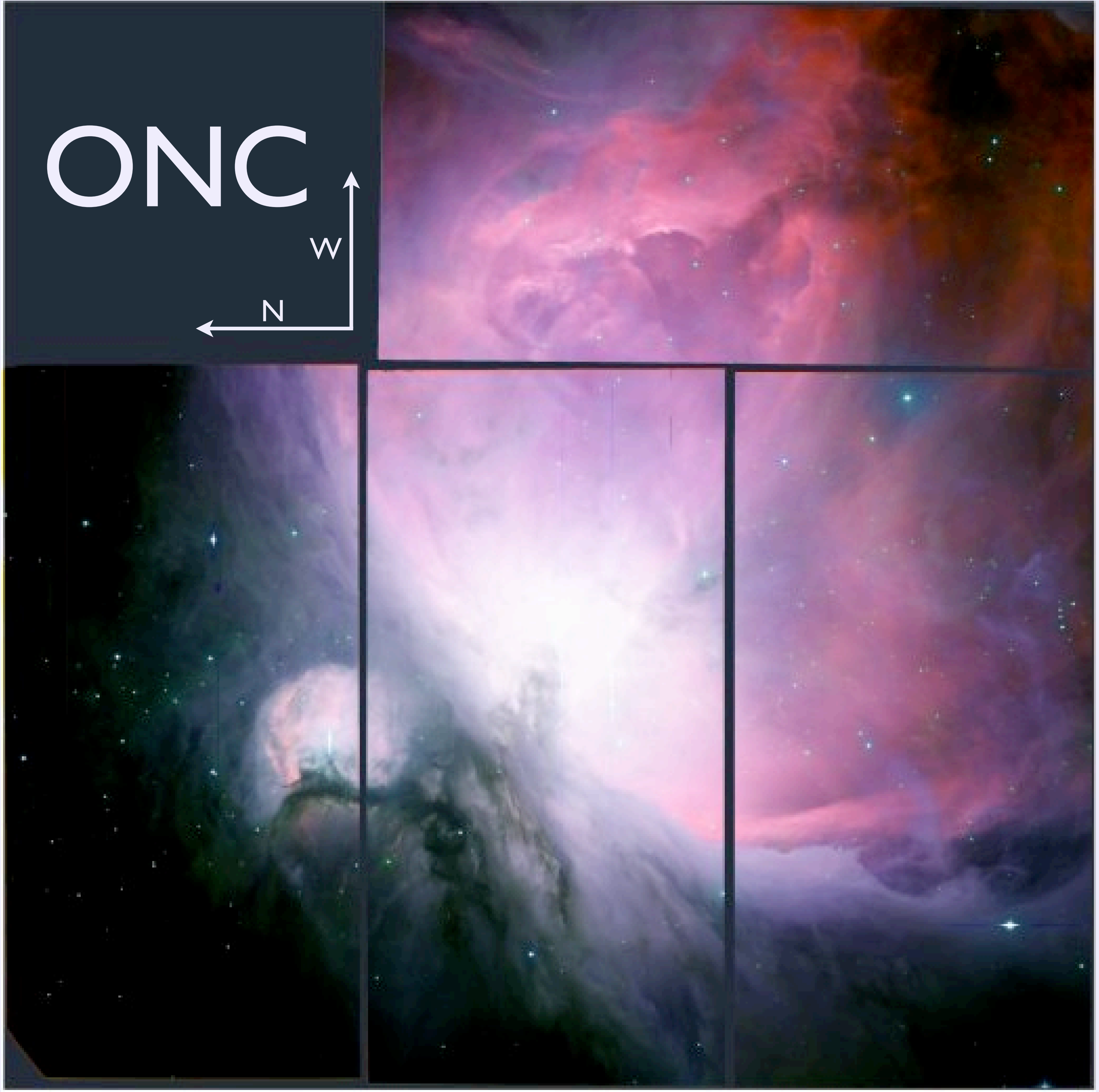
monitor

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 $M_\odot$
- had to use 2MASS as input source catalog



red - Hα
green - i’
blue - V

monitor

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 & Schlemner (1993):
  89 members with $0.9 < M/M_{\odot} < 2.5$ in 0.55 sq.deg.

monitor

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 $M_{\odot}$

monitor

red - i’
blue - V
green - (i’+V)/2

data reduction

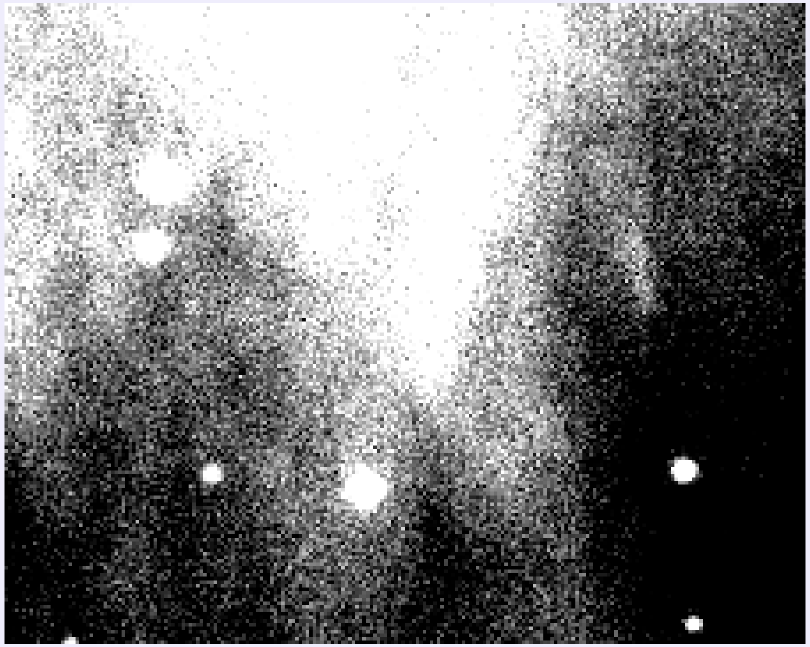
- used standard INT Wide Field Survey (WFS) pipeline developed by the Cambridge Astronomy Survey Unit (Irwin & Lewis 2001)
  - cross-talk correction
  - bias correction
  - flatfielding
  - defringing (i’ only)
  - astrometric & photometric calibration using observations of Landolt 1999 standard star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

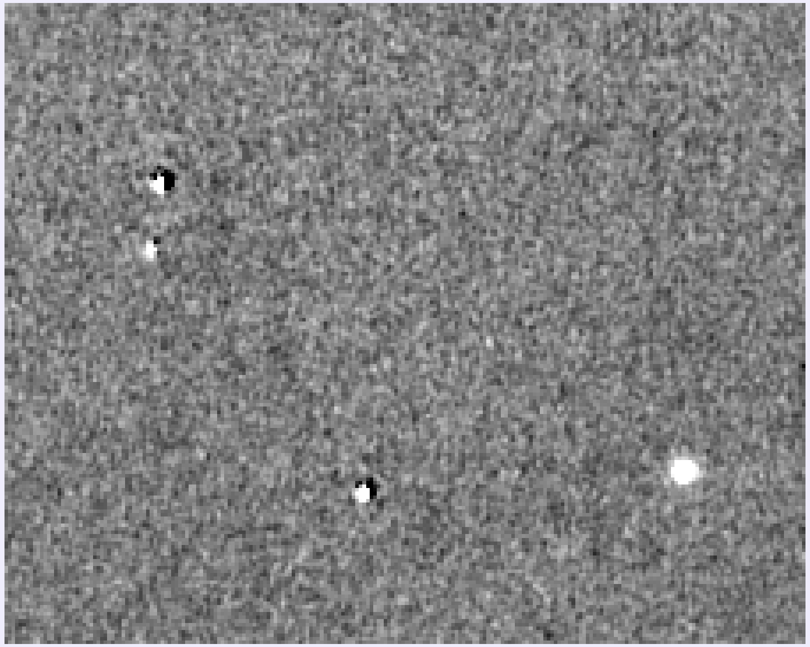
monitor

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

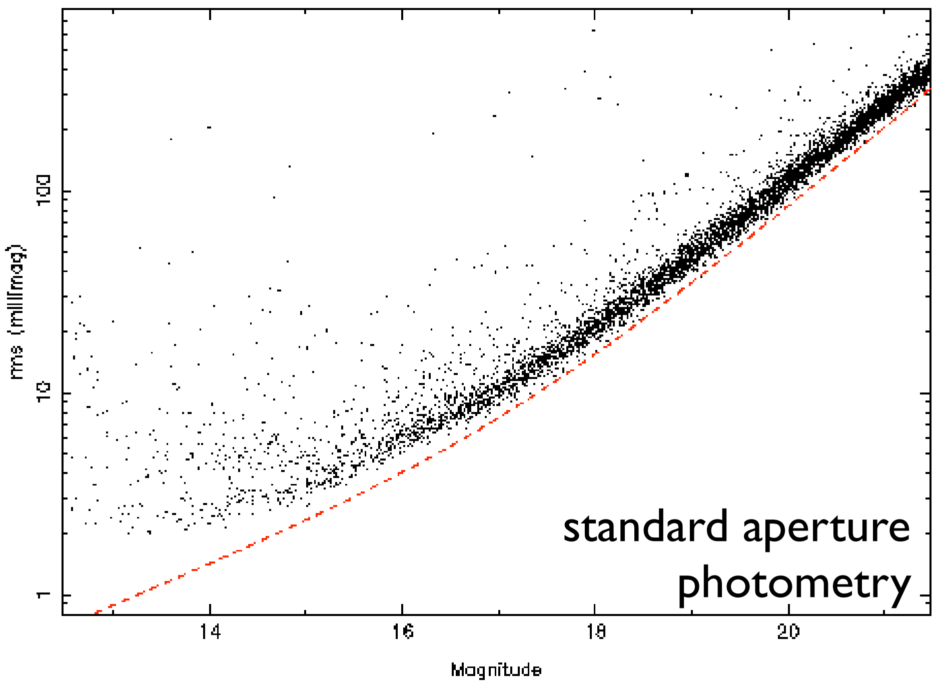
difference image analysis

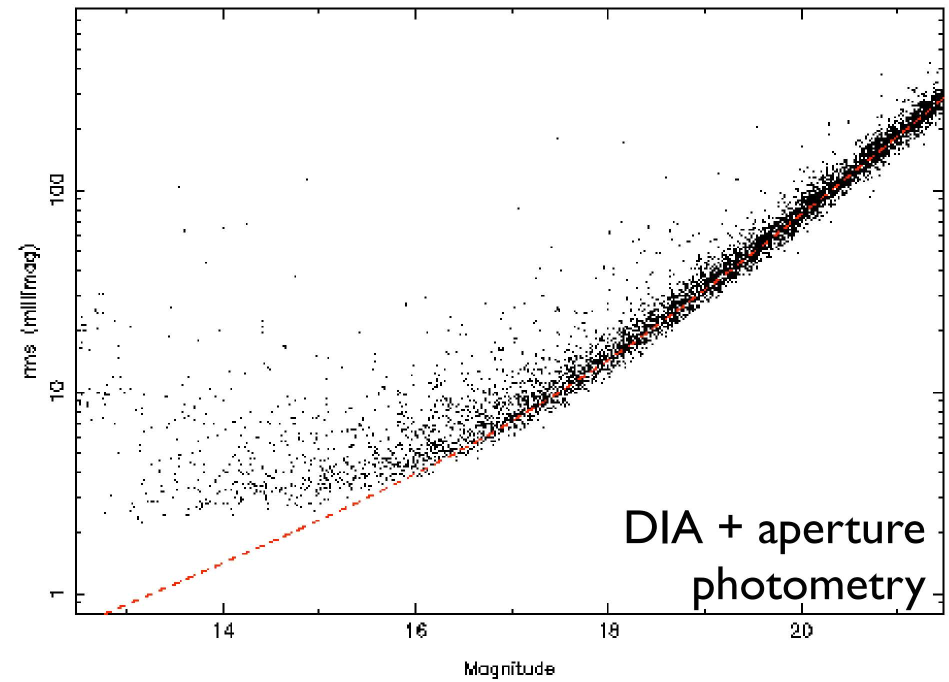




difference image analysis

M34, all frames, all objects classified as stellar





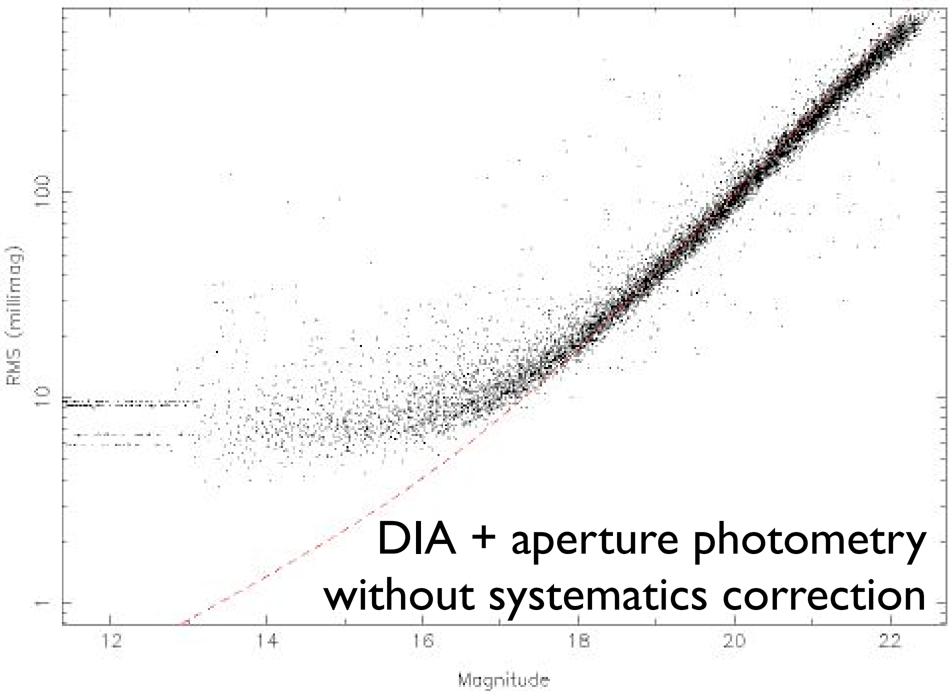
monitor

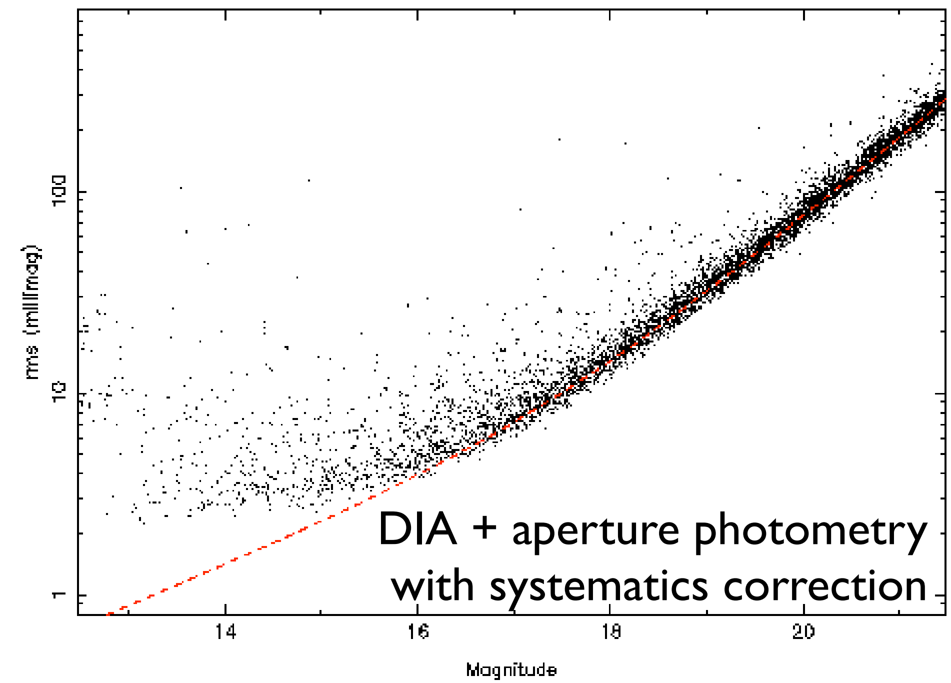
systematics correction

- differential extinction, PSF variations accross 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

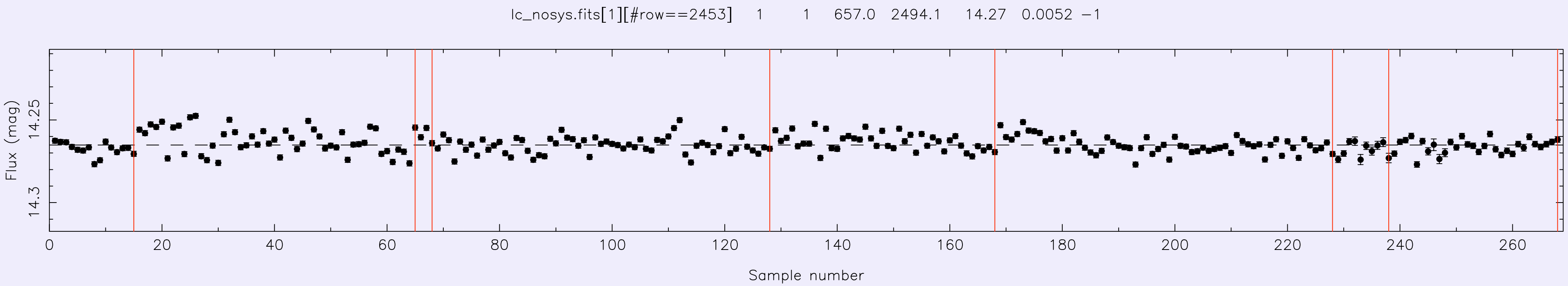
systematics correction

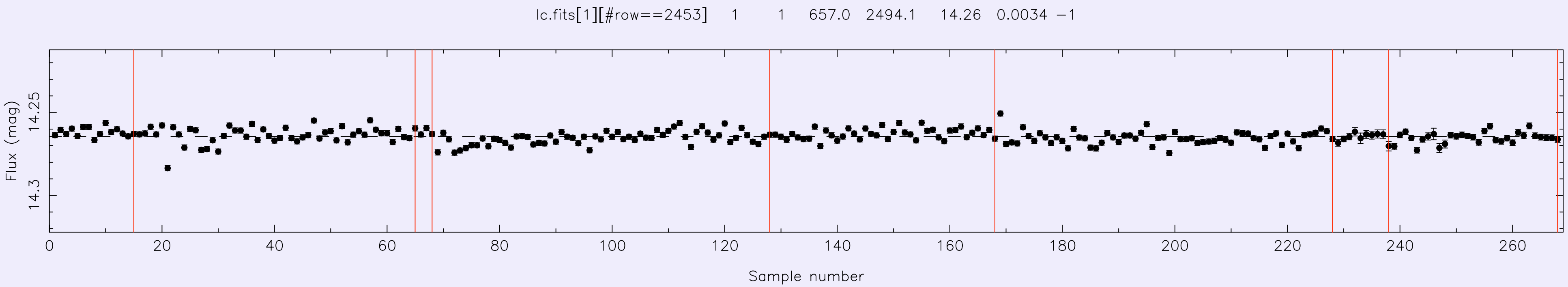
M34, all frames, all objects classified as stellar



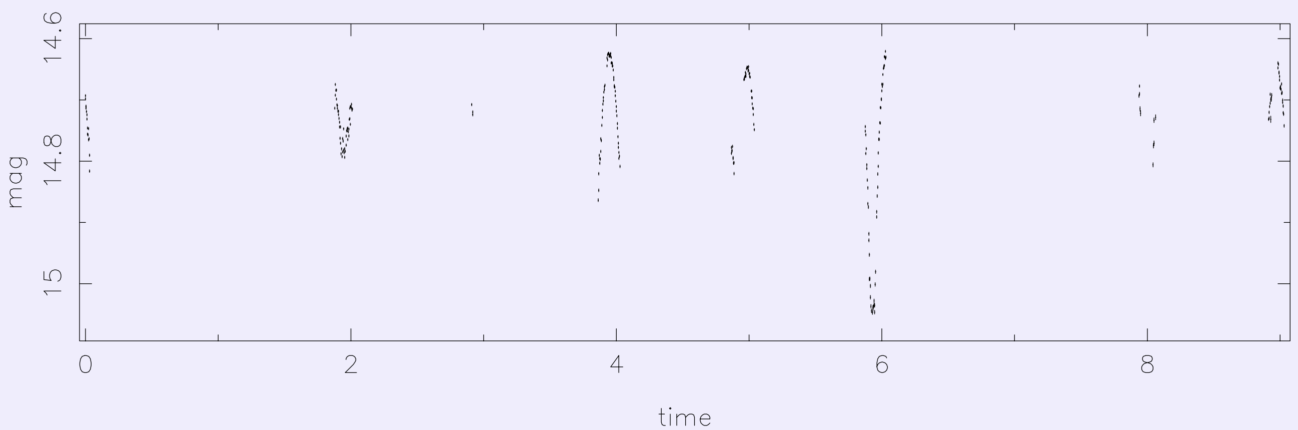


systematics correction



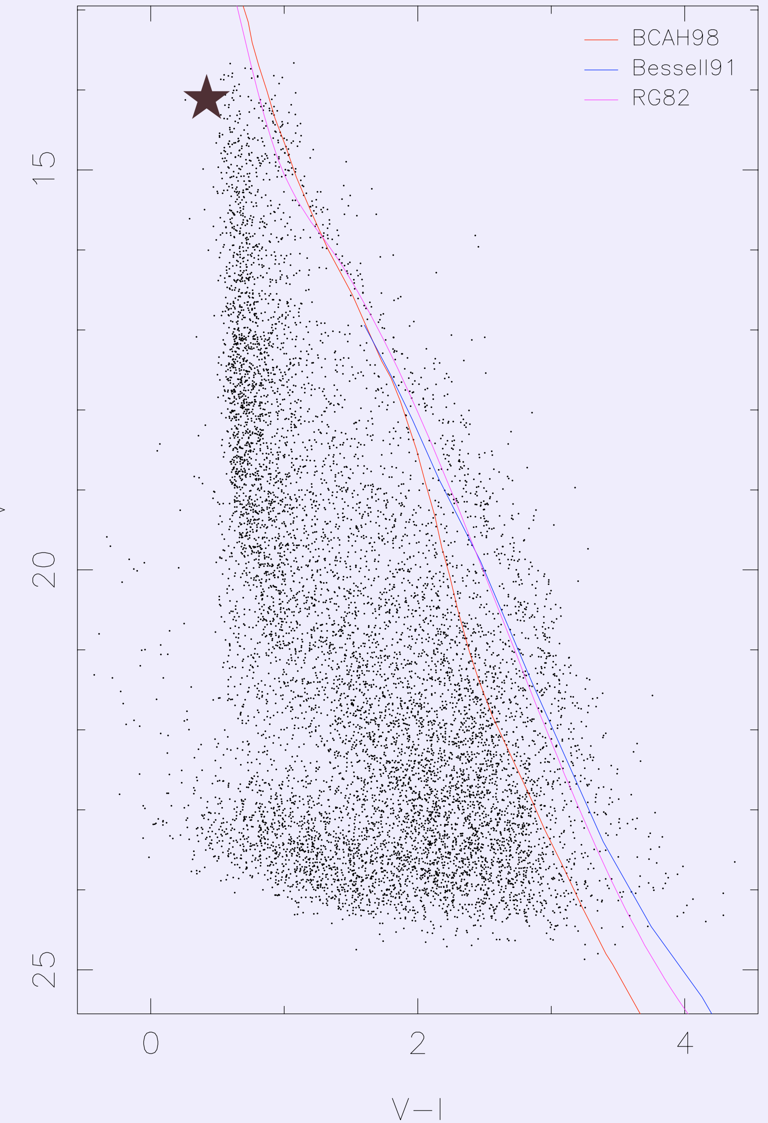


example light curves - M34 - I

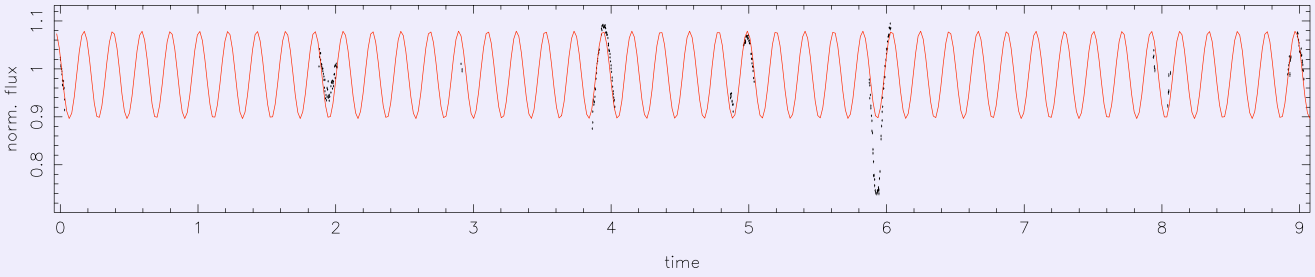


V = 14.95, I = 14.56

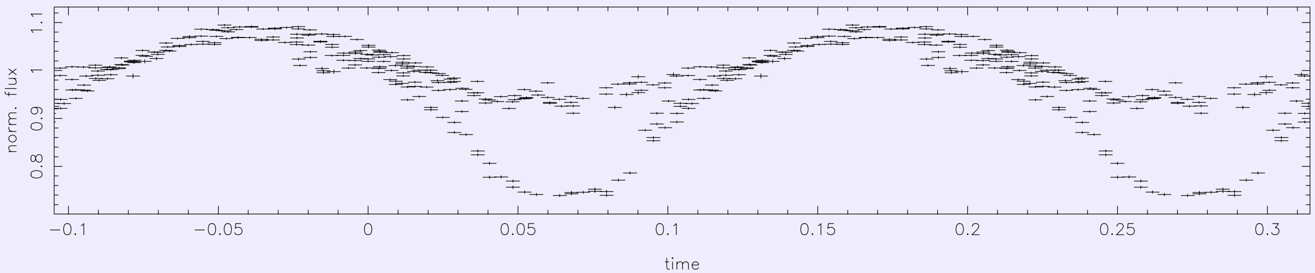
J = 14.44, K = 14.21 (2MASS)



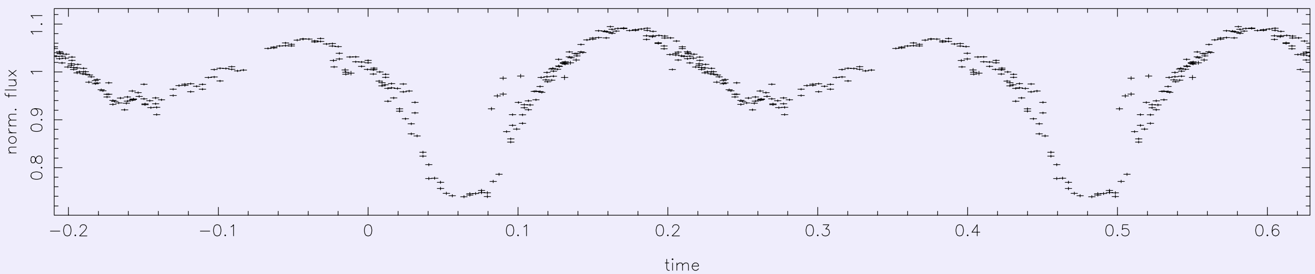
example light curves - M34 - 1



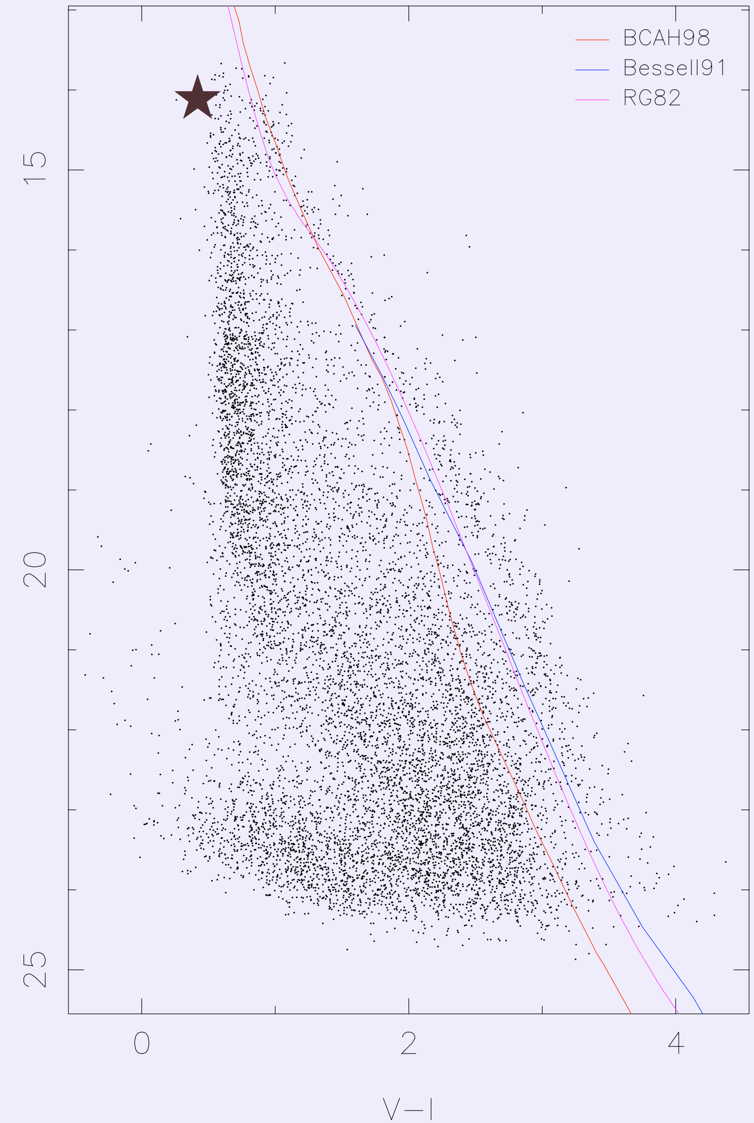
phase−folded



phase−folded at 2 x per

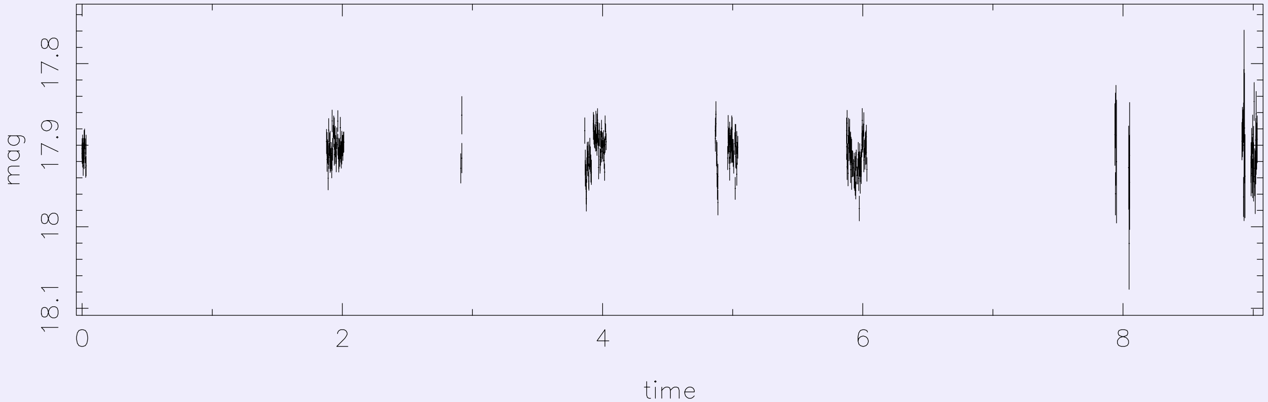


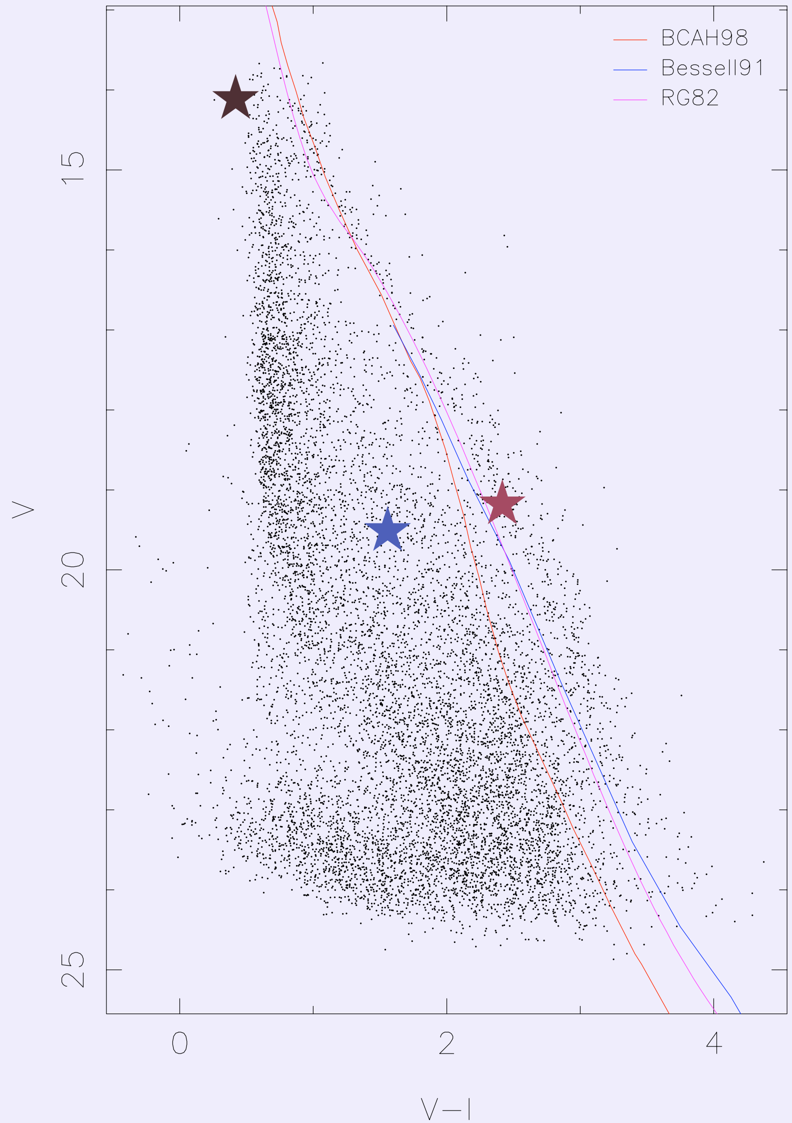
P = 0.419 d



Beta Lyrae type

example light curves - M34 - 3





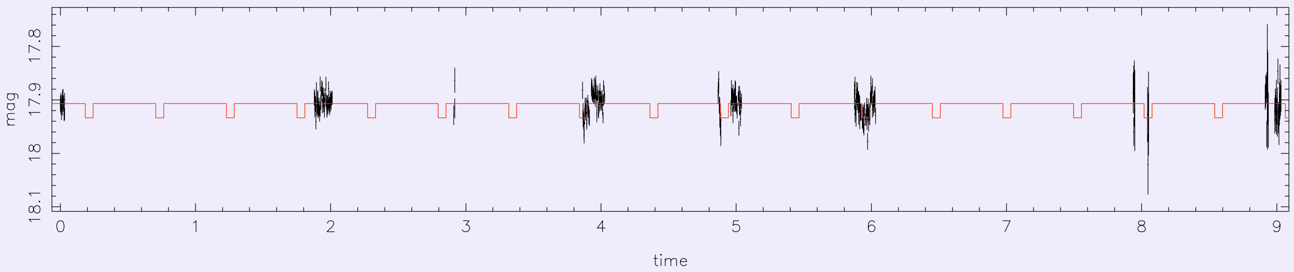
V = 19.41, I = 17.57

J = 16.71, K = 15.54 (2MASS)

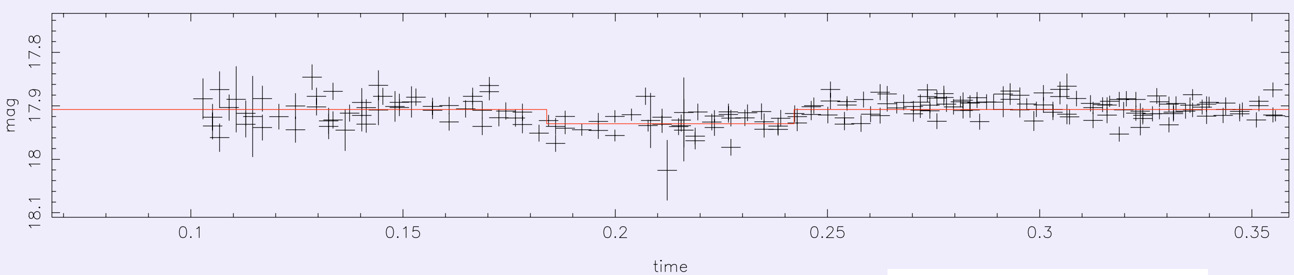
$M_{MS} = 0.57\ M_{\odot}$ (Baraffe et al 1998)

$R_{MS} = 0.49\ R_{\odot}$ (Siess et al. 2000)

example light curves - M34 - 3



phase–folded, transit vicinity

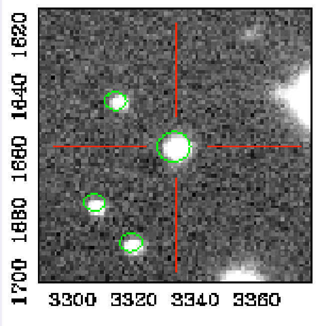


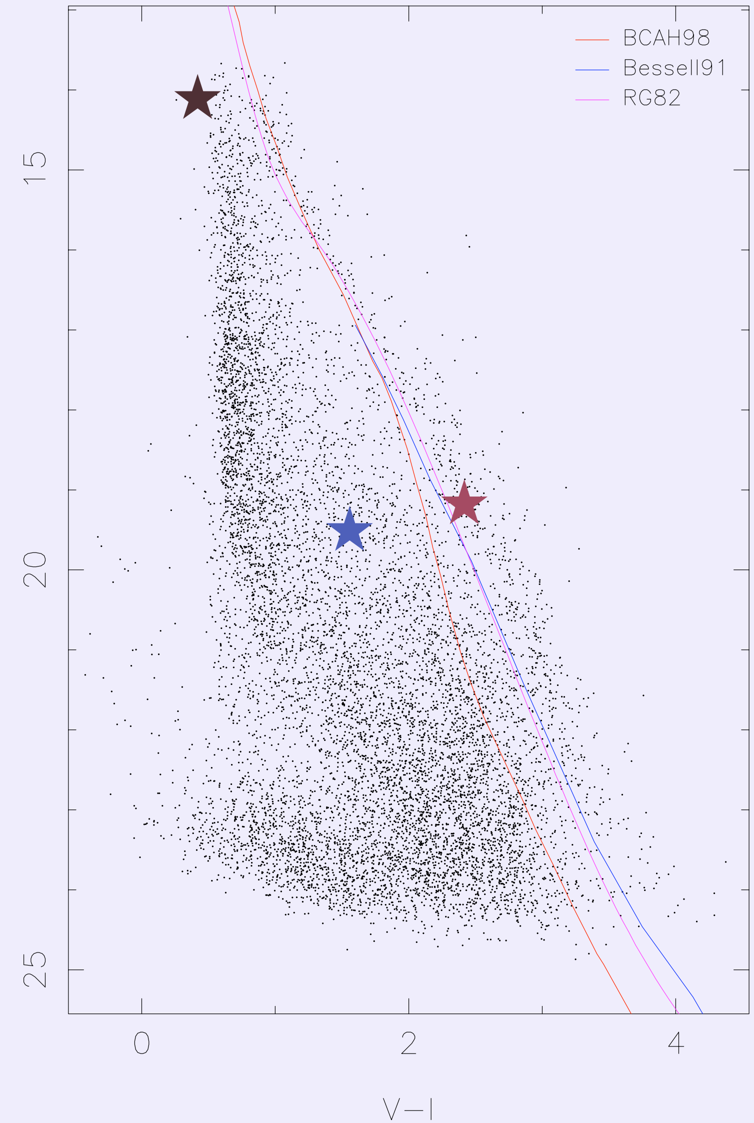
V = 19.41, I = 17.57

J = 16.71, K = 15.54 (2MASS)

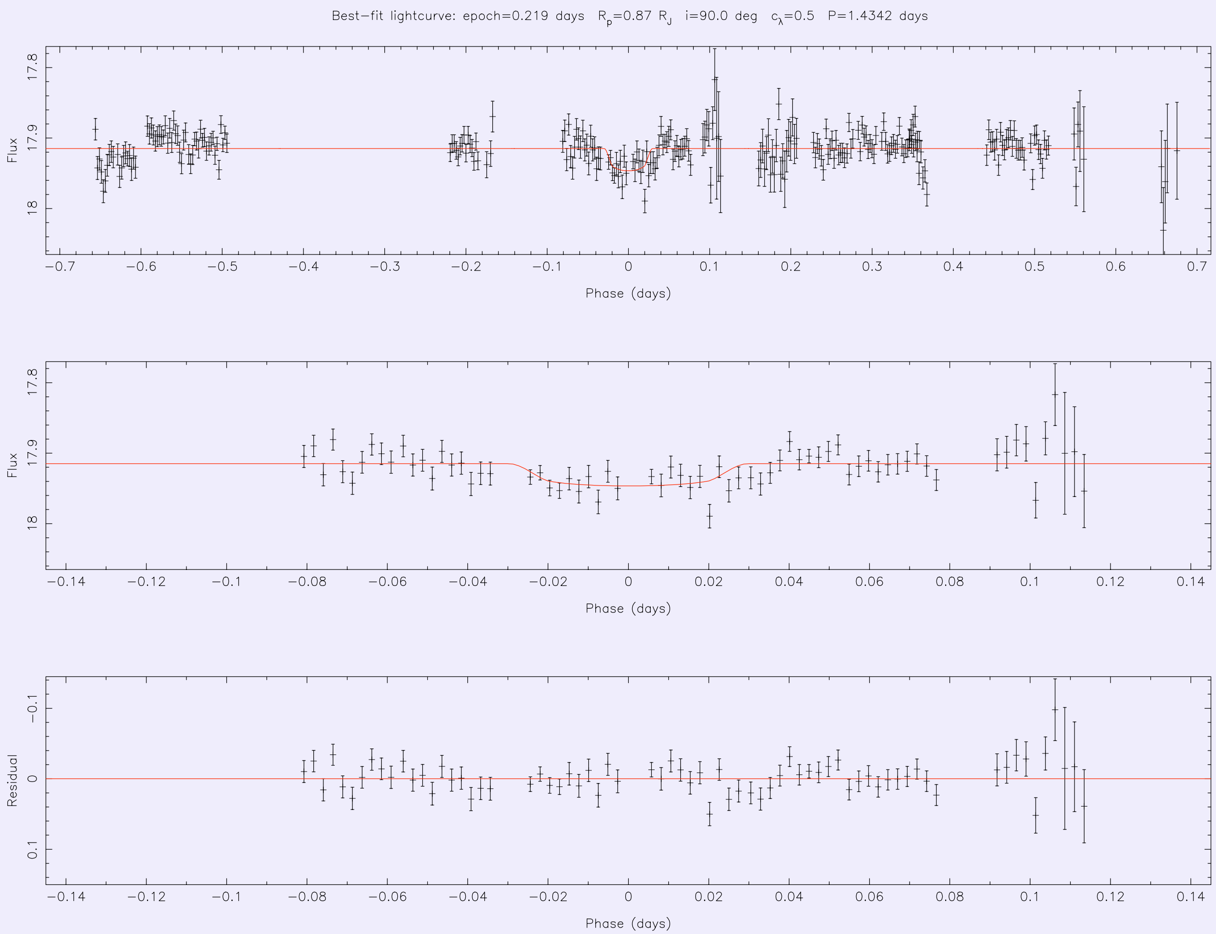
M_{MS} = 0.57 $M_{\odot}$ (Baraffe et al 1998)

R_{MS} = 0.49 $R_{\odot}$ (Siess et al. 2000)

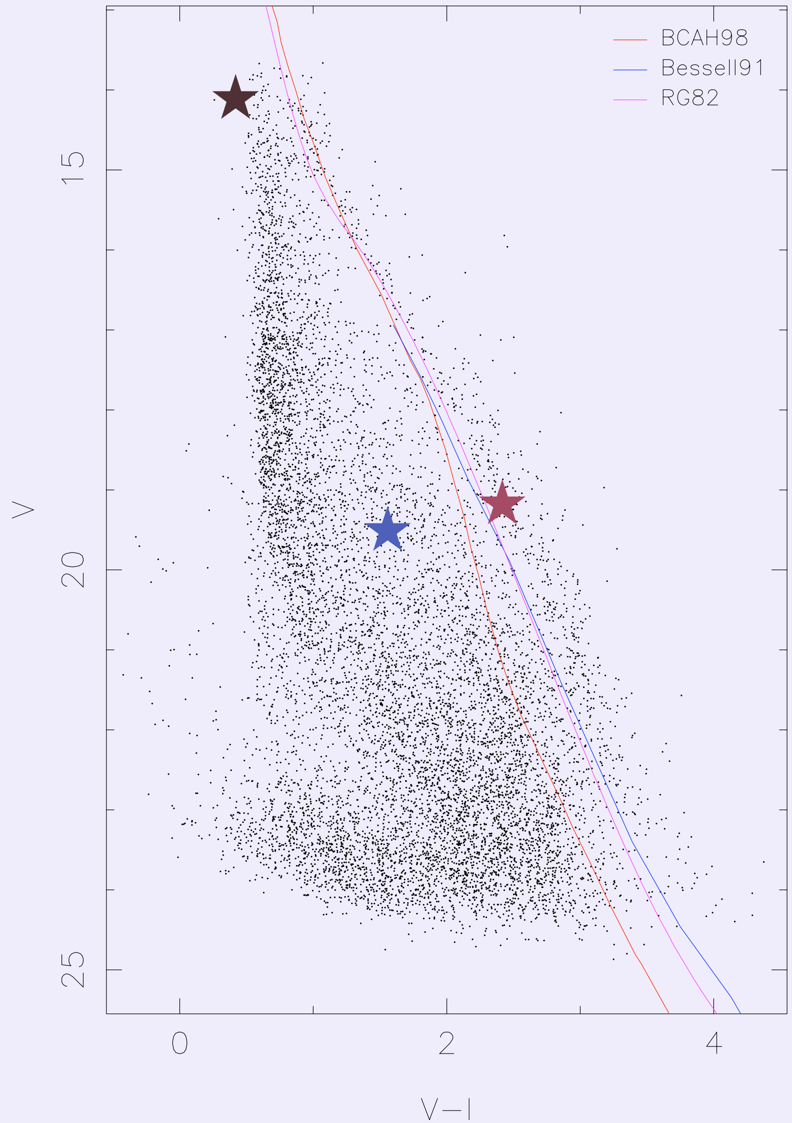




example light curves - M34 - 3



$P = 1.4342$ d, $R_C = 0.87 \pm 0.1 R_{Jup}$, $i = 90 \pm 2°$

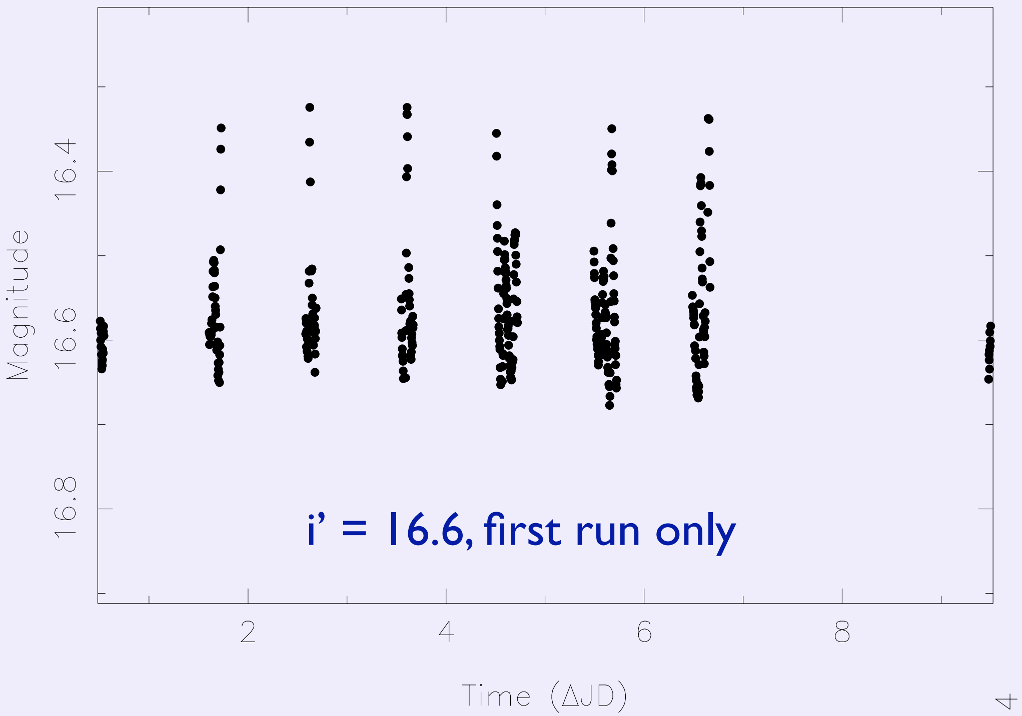


consistent with planet, but...

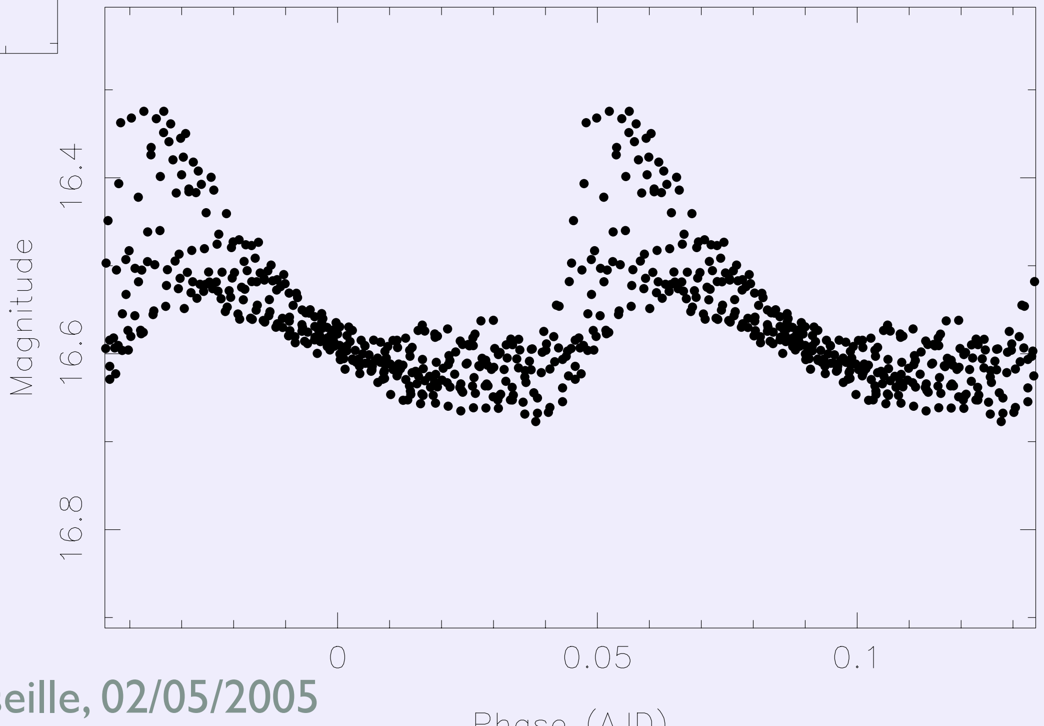
need more data to really constrain parameters

giant or MS?

example light curves - ONC - 1

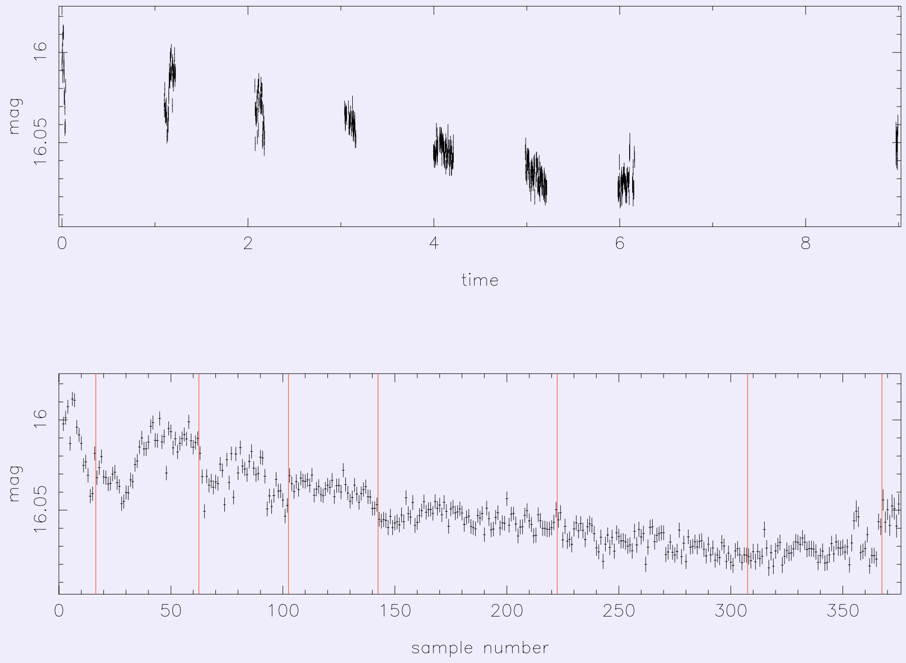


P = 0.09 d,
amplitude 0.1 to 0.3 mag

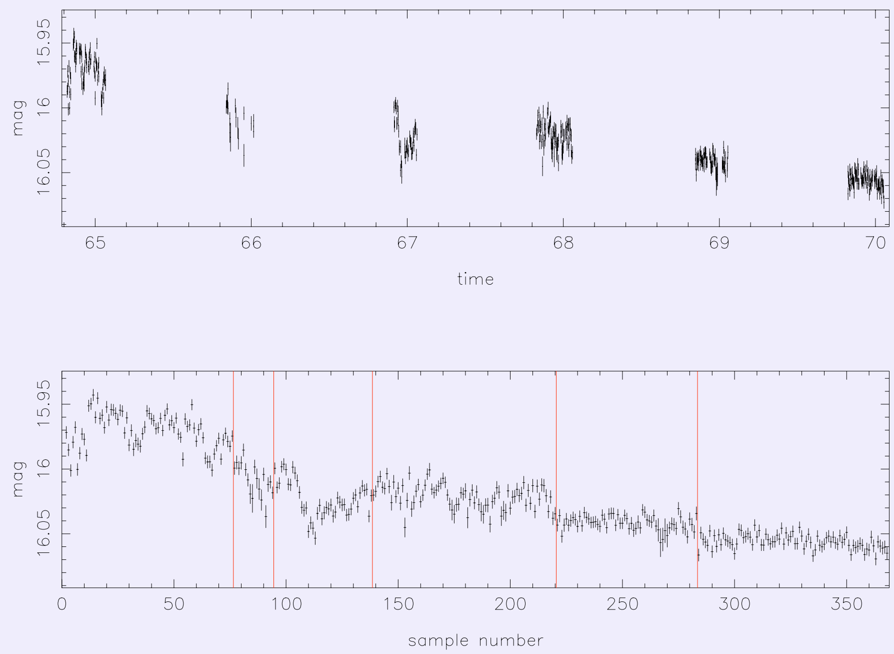


example light curves - ONC - 2

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 amd compare ours to published distributions
- then we will start searching for transits
    - after removal of sine-like periodic components
    - after filtering in Fourier domain

monitor

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