Summer project report of "Maitrise et Magistère de Physique d'Orsay"
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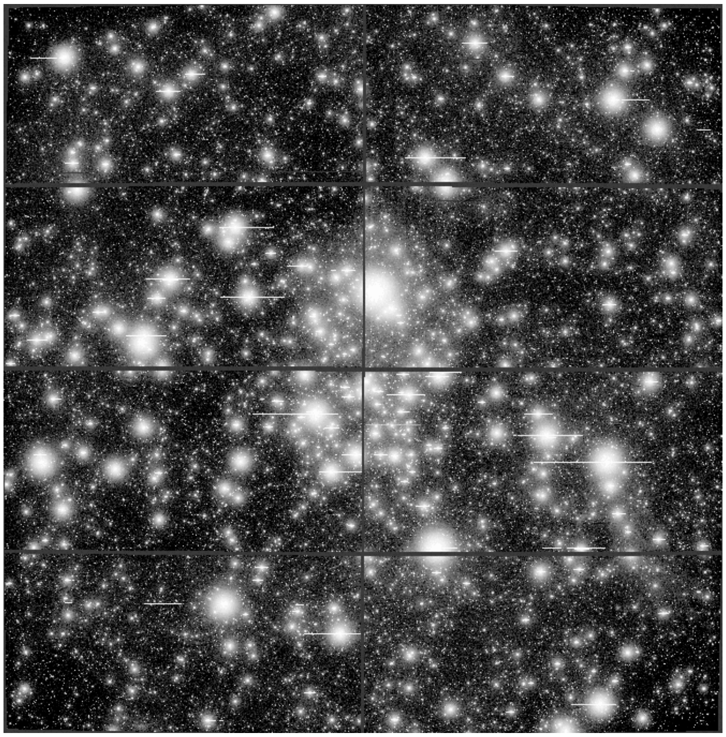

Searching for planetary transit in the M50 open cluster

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The picture on the previous page is an image of the open cluster M50, generated from our i-band observations of the M50 region. The data have been taken with the 0.36 sq. deg. FOV Mosaic Imager on the 4m Blanco telescope at the Cerro Tololo Interamerican Observatory (CTIO) in February 2005.
Approximately 80,000 objects are detected in this field, the vast majority of which are not associated with M50.
The grill on the image shows the 8 CCDs composing the Mosaic Imager.

Abstract

This report presents a search for planetary transit in the M50 open cluster. The work has been carried out at the Institute of Astronomy in Cambridge for two months. It is part of the Monitor Project (www.ast.cam.ac.uk/∼suz/monitor/monitor.php) whose primary goal is to search for close-in planets (and brown dwarfs) at young ages, through the detection of transit events. This paper contains an historical overview on planetary search and methods, data collection and an explanation on data reduction. Then, details are given on the method adopted to analyse the data and find planetary or brown dwarf transit candidates in the M50 open cluster. Among all the stars in the observed M50 field, 19 planetary/brown drwarfs candidates were found, of which 9 are members of the M50 open cluster. For each of the 9, mass limits of their companion were calculated. Four of the 9 candidates may be spotty stars. One candidate, 3782 in CCD 1, was found really promising, as it appears to have a central star of half the solar mass and a companion of mass less than 55 Jupiters.

Résumé

Ce rapport presente la recherche de transits planètaires dans l'amas ouvert M50. Le stage de deux mois, a été effectué à l'Intitut d'Astronomie de Cambridge. Il fait partie du projet Monitor (www.ast.cam.ac.uk/∼suz/monitor/monitor.php) qui a pour but principal la recherche de jeunes planetes (ou naines brunes) orbitant proche d'une etoile, en essayant de détecter leur transit en face de celle-ci. Ce document contient un survol historique sur la recherche de planètes, la prise des données utilisées dans ce project, ainsi que le traitement d'image effectué pour ces dernières. La methode, adoptée pour analyser les données et trouver des candidats de planète ou naine brune dans l'amas ouvert M50, est présentée par la suite. Parmis toutes les étoiles du champs pris sur M50, 19 candidats de planète ou naines brunes ont été trouvés, dont 9 sont membres de l'amas M50. Pour chacun des 9, des limites sur la masse ont été claculées. Quatre des 9 candidats sont peut-être des étoiles avec tâches solaires. Un candidat, 3782 de la CCD 1, a été decouvert ayant une étoile centrale de masse moitiée celle du soleil, et ayant un compagnion de masse inférieure à 55 Jupiters.

Acknowledgements

I acknowledge deeply in my heart, Simon Hodgkin and Suzanne Aigrain for being two great supervisors. Simon, thanks to have given me the opportunity of doing this summer project in Cambridge, invited me to the pub the first week I arrived, put me at ease and to have given me valuable feedback on my report. Thanks Suzanne, for being such a friendly and accessible person, to have taught me how to use IDL, re-explained to me in french all the things I didn't understand during group meetings and to have invited me to the cinema (that I unfortunatly missed).

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Contents

1 Introduction

My two-months summer project has been carried out at the Institute of Astronomy (IoA, *www.ast.cam.ac.uk*), a departement of the University of Cambridge (U.K.).
The IoA came into being in 1972 as a result of the amalgamation of the Cambridge University Observatory (established in 1823) the Solar Physics Observatory (1912) and the Institute of Theoretical Astronomy (1967). It is engaged in teaching and research in the fields of theoretical and observational Astronomy.

1.1 Background on planete searching

1.1.1 History of the Search

Pondering on the existence of worlds and solar systems other than our own is not new. It goes back as far as ancient times. The atomist Epicurus (341-270 B.C.) was already thinking "There are infinite worlds both like and unlike this world of ours. For the atoms being infinite in number, as was already proven, (...) there nowhere exists an obstacle to the infinite number of worlds." But his point of view had not been shared for the next two thousand years. For instance, the philosopher Aristotle (384-322 B.C.) was claming "There cannot be more worlds than one."
The eyes have been open on the existence of other planets since the invention of the telescope by Galileo in 1609.
The first documented search for extrasolar planets was by Christian Huygens 1698 (fac-simile: Cass F. and co. 1968), but it is only in the mid-twentieth century that the first extrasolar planets was reported. Discoveries regarding extrasolar planets were first published in 1989 by David W. Latham et al (HD 114762).
Extrasolar planets around solar-type stars began to be discovered in large numbers during the late 1990s as a result of instrumentation improvement, such as CCD, high precision stable radial velocity measurement, computer-based image processing. And the first definitive extrasolar planet around a main sequence star was announced on October 6, 1995 by Michel Mayor and Didier Queloz (51 Pegasi).
As of mid 2004, there were 108 known planetary systems around main sequence stars, containing at least 123 known planets. In July, 2004, it was announced that Hubble had been used to detect an additional 100 planets, but the presence of these planets has not yet been confirmed.

There are currently six methods of detecting extrasolar planets which are too faint to be directly detected by present conventional optical means. They are listed in the following table, with their explanation, requirements, efficiency and limitations. See the web sites *http : //encyclozine.com/Extrasolar_planet* and *http : //www.hao.ucar.edu/public/research/stare/search.html*, for more details.

Table 1: Planetary search methods

method	measurement	requirements of	efficent for	limitations
Astrometry	changes in star's proper motion due to rotation around system's center of mass	system oriented face-on with sin i dependance and planet massive enough	planete imaging, no successfull measurements, changes in proper motion too small	no possible confirmation by other methods
Pulsar timing	anomalies in the regularity of pulses from a plusar	precise measurement of pulsar's signal	planets with masses of the order of the Earth or greater	limited to pulsating central star
Radial velocity	variations in the parent star 's radial speed due to its wobbling around the system's center of mass	orbital plane nearly parallel to our line of sight	large planets in tight orbits, highly successfull, can be used to confirm transit method	magnitude limitation
Gravitational microlensing	magnification of distant background stars' light due to gravitational field of planet and parent star	large number of background stars	planets situated between Earth and our galactic center	lensing cannot be repeated, follow-up observations not possible
Transit method	stellar flux, blocked out by the planet crossing the stellar disk	orbits aligned with the central star from our vantage point	large, close-in planets, can be used on very distant stars	photometric accuracy (1% drop for M_J) and time sampling
Circumstellar disks	star disc dust's density and distortion caused by an orbiting planet	far infrared observations		

1.1.2 The transit method

When a planet (represented by the small, dark disk in the following figure) passes in front of its parent star, the stellar flux (lower part of the figure) drops by the ratio of the planet-to-star areas.
The transit method is used to survey large areas of the sky simultaneously and is more sensitive to large, close-in planets (proba for in-transit observation decreases rapidly as orbital period increases because alignement probability decreases and out of transit duration increases).

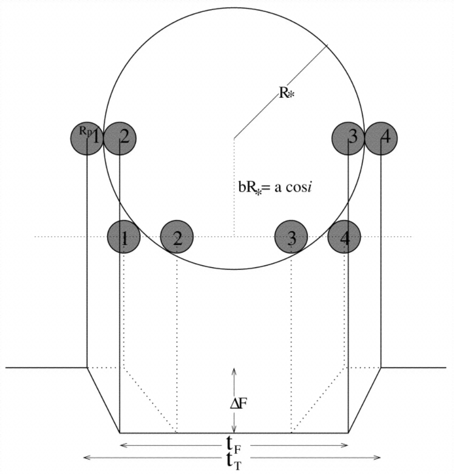

Figure 1: Two schematic light curves are shown on the bottom (solid and dotted lines), and the corresponding geometry of the star and planet is shown on the top.First, second,third, and fourth contacts are noted for a planet moving from left to right. Indicated on the solid light curve are the transit depth ΔF, the total transit duration t_T, and the transit duration between ingress and egress t_F (i.e., the "flat part" of the transit light curve when the planet is fully superimposed on the parent star).Also defined are R_*, R_p, and impact parameter b corresponding to orbital inclination i. Different impact parameters b (or different i) will result in different transit shapes, as shown by the transits corresponding to the solid and dotted lines.
(figure and comments have been taken from Seager and Mallén-Ornelas' article, 2003)

The equations for the transit duration and depth, as well as the probapility for a transit to occur while we are observing, are given in Perryman (2000).

1.2 The Monitor project

The Monitor project is an international collaboration between J. Irwin, S. Aigrain, S. Hodgkin, E. Moraux, M. Irwin, C. Clarke G. Gilmore (IoA, Cambridge), L. Hebb (JHU, Baltimore), J. Bouvier (LAOG, grenoble), F. Favata (ESA/ESTEC), E. Flaccomio (Palermo), M. MacCaughrean (Exeter) and M. Ashley (UNSW, Sydney).
Its primary goal is to search for close-in planets (and brown dwarfs) at young ages through the detection of transit events. The Monitor collaborators are particularly interested in finding the first transiting objects (planets or brown dwarf) of masses between 10^{-3} and 10^{-1} $M_\odot$. The mass vs. radius plot for observed low-mass stars and giant planets (Pont et al., 2005), given in appendix, shows the lack of data in this range of masses and at younger ages.
The Monitor Project is targeting nearby star forming regions and open clusters (range of age of 1 to 200 Myr), with the aims of detecting the first young transiting exoplanet(s) and of providing unprecedented observational constraints over the early evolution of these objects (planet formation and migration timescales).
About 10 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. 8 of them have been observed or are scheduled for observation by the end of 2005.
Some of the observed clusters are under analysis, such as M35 and ONC carried out by Jonathan Irwin and M50 by myself.

1.3 The open cluster M50

My summer project was to search for planetary transit in the open cluster M50.
M50 (ra = 07 02, dec = -08-23) is an 130 Myrs-old open cluster, distant of about 3000 light years. It is 18 light years wide with a central dense part of about 10 light years in diameter.

2 Data reduction and light curves production

2.1 Presentation of the data

The image acquision, for the data used during this project, was undertaken with the MosaicII (detector composed of 8 CCDs of 2k by 4k pixels, covering 36x36 arcmins) at the 4m Cerro ToloIoInter-American Observatory (CTIO) telescope in Chile.
The raw data are 244 images (75s exposure time each) of M50 in the filter *i* (centered on 773 nm), collected in February 2005 by Leslie Hebb, during 6 nights (2 spaced sets of 3 nights to be sensitive to longer transit period).
Data reduction and light curve production have been carried out by Jonathan Irwin.

2.2 Data reduction, photometry

The data reduction, consisting of bias substraction, trimming, flat fielding, non-linear and gain correction, has been carried out automatically using the Cambridge Astronomical Survey Unit (CASU) pipeline (Irwin Lewis 2001).
The electrical cross-talk between the detector readouts has also been corrected, as it could have led to false detection of objects.
Defringing, generation of an astrometric reference catalogue, astrometric and photometric calibration, have been carried out.

2.3 Data processing, ligth curves production

To produce light curves from our optical photometric monitoring data, apparture analysis has been applied. A master catalogue of objects and positions was generated from the master image, result of stacking up the best images.

List driven aperture photometry has then been performed on separate images using variable aperture sizes depending on the brightness of the stars being measured.
The flux is converted into magnitude and light curves are produced from the magniude and its time dependance.

For each stellar object of the master catalogue, the median and RMS flux is calculated and transform into magnitude (in the instrumental bandpasses).
Then, light curves, apparent magnitude of the stellar object as a function of time, are produced for each stellar object of the master frame.
The residuals from the light curve median are computed for each star in each frame. A map of residuals versus coordinates on the CCD is produced, a 2-D polynomial is fitted to this map and substracted from each star's light curve.
This way, the effect of differential atmospheric extinction across the field of view and other systematic errors are removed.

The photometric error (rms is called σ_i hereafter) includes the Poisson error, the sky noise (readout noise) and an additional quadrature "fudge factor" to account for residual systematics at the bright end (upturn at the bright end due to saturation of the pixels). The RMS diagram for M50 is showed in appendix.
This technique has allowed us to achive precisions down to 3-4 milimagnitudes atthe bright end over entire runs of observations.

3 Data analysis : Searching for transit-like events and mass-radius calculation

Here is where my work really begins. I have had to find transit-like variation among all the light curves created by Jonathan Irwin's light curves programme on M50.

3.1 Light curves selection

There is around 7000 stars per CCD, i.e around 50 000 light curves are generated. This make the examination by eye a way too time-consuming process.
Therefore, Aigrain & Irwin's automated transit detection algorithm (Aigrain & Irwin, 2004) has first been run on Jonathan's light curves, generated from the images.

3.1.1 Automtic transit detection algorithm

Aigrain & Irwin's algorithm performs the transit search on a single light curve, using ranges of trial transit durations, periods and epoch, with a possibility of pre-filtering before the search (non-linear or least-squares fitting of sine-waves, option not used during my project). This transit search algorithm approximate the transit shape as a box instead of the real shape showed in figure 1 (section 1.1.2).

The calling sequences were:

```
trsearch_sel 'lc.fits[ccd][class==-1 && bflag==0 && cflag<2 && medflux>15]'
               tdmin tdmax ntd tpmin tpmax ntp tout gout}
```

with "tdmin tdmax ntd tpmin tpmax ntp tout gout" as "0.05 0.25 21 -1 -1 -1 0 1(or ccd-star.ps/cps)".
-1 causes default value to be used.
or

```
trsearch 'lc_flagged.fits[ccd][class==-1 && bflag==0 && cflag<2 &&  medflux>15 &&
           member==1]' tdmin tdmax tds tpmin tpmax errlim tout gout
```

with "tdmin tdmax ntd tpmin tpmax ntp tout gout" as "0.04 0.21 0.1 0.3 12 5 0 1(or ccd-star.ps/cps)"

where, tdmin and tdmin are the min and max trial duration (in days) respectively, tpmin and tpmin the min and max trial period (in days) respectively. tout (set to 0 for none, 1 for concise, 2 for verbose, followed by a file name for informations to be saved in this file) and gout (set to 0 for none, 1 to appear on the screen, file.ps/cps to creat a postscript file) are the text and graphic output respectively. ntd and nts are the number of trial durations and periods respectively. tds is the trial duration step (in days), and errlim is chosen such that the error on the epoch of the last transit in the light curve is always less than $tdur/errlim$.

The range of transit duration (0.05-0.25 or 0.04-0.21 days) and period (0.3-12 days) are chosen to be physical. No planetary/brown dwarf transit can last less than 0.04 days and have a period less than 0.3 days (velocity would be to high to be physical).
The upper limit on the transit duration (0.21 days) and period (12 days) are chosen to be consistent with our observational method (our nights lasted in average 0.21 days and 12 days is the time between the first observation and the last one).

trsearch_sel.f and trsearch.f differ from each other in the way the transit duration range is sampled, and on the condition on the error on the last transit epoch.
trsearch.f find transit more precisely, especially the transit period, but is slower than the first version.
trsearch_sel.f has been run on all the stars of the master frame (50 000 stars), wherease trsearch.f has been run only on the stars belonging to M50 (5 000 stars).

The flags are used to add constraints on light curves selected for transit searching. They are columns in the lc.fits file.
The flag "class", taken equal to -1, is used to choose, in the master frame, only stellar objects.
The flag "bflag", taken equal to 0, selects only non-blended stars (isophotes of the star overlapps with

another object).
The flag "cflag", taken as been less than 2, is used to avoid taking in account low-confidence regions in the standard sized aperture.
The flag "medflux", taken to be greater than 15, selects only the light curves with a magnitude greater than 15 (i.e fainter objects) to avoid the bright objects saturating in good seeing to be selected as variable stars.
Finally, the flag "member", taken equal to 1, is used to choose only stars which are members of M50 (see section 3.1.2 for the method used to determine if a star is a member of M50).
This flag has been added to the original lc.fits file, using one of Jonathan Irwin's code. The command lines to do that on the APM3 machine, were

```
apm3:/data/apm19_b/alapini/m50/selection> chmod 755 ascii2memb
```

and then,

```
apm3:/data/apm19_b/alapini/m50/selection> .ascii2memb ccd-trsearch.txt
                                   /data/apm19\_b/alapini/m50/ lc.fits lc\_flagged.fits
```

where, ccd-trsearch.txt is a two-column file (CCD, star) listing all the stars of the master image belonging to M50. This file has been created using a version of the getstars.pro IDL code (see section 3.1.2) with no conditions on the signal to noise ratio and on the transit duration.

Another calling sequence, that has been of great use, is

```
trsearch 'lc_flagged.fits[ccd][pointer==star]' tdmin tdmax tds tpmin tpmax errlim tout
                                                 gout
```

where, pointer==star-number allows us to run the code on an individual object (star) with a new range of parameters.

At this stage all the lightcurves with a transit-like variation (according to the automated transit search algorithm) are listed in ccd#-trsearch.txt files (# = ccd number). Each of those files (one file per ccd, i.e 8 files) contains approximatly 7000 stars, with a row per star and 15 columns (of which: star number, median apparent magnitude, error on the magnitude, transit duration, epoch and period, signal to noise ratio, number of points inside a transit, number of transit found in the lightcurve, see appendix for a truncated example).

3.1.2 Light curves filtring using getstars.pro, IDL code

A part of my project was to write a programme called getstars.pro (full code given in appendix). For each CCD, this code gives a list of stars. Each of these star fulfills the following conditions: transit-like variation, member of M50, signal to noise ratio greater then 13 and transit duration less then 0.21 days. The reasons of this selection are described bellow.
A first run was done amongst all the stars, even the one out of the clsuter, for a SNR greater than 19. Then we refined th search to smaller SNR but only on the stars in the cluster.

First of all, we are particularly interessted in detecting a transit-like variation in stars belonging to M50, as we are then able to give them an age and to use Baraffe's BCAH98iso.1 model (1998) to constrain their masses and radii (see section 3.2.1 and table of the model in appemdix).
To know if a star belongs to M50 or not, we use a color magnitude diagram (CMD) with M50 main sequence and a given star of ccd#-trsearch.txt file (see the CMD for M50 in appendix). If this star is on or above M50 main sequence on the CMD, then it is likely to belong to the cluster (it is not a guarantee). This is the first condition written in the IDL code getstars.pro (code given in appendix).

Secondly, Among all the light curves selected until now, a lot a them have a too low signal to noise ratio (less then 13) to trust a real transit-like variation.
Therefore, another condition written in getstars.pro is to select only the ccd#-trsearch.txt light curves with a signal to noise ratio (SNR) (sn_min) above 13 (we tried down to 10 but the ligth curves selected with SNR between 10 and 13 had unrealistic transits).

Finally, the automated transit search detects transits when there is a dip in the light curve with regard to its median. Therefore, when it happens that the data for a night are systematically fainter, due to errors in the processing or normalisation of that star in that night, a transit is detected in this night and its duration will be the one of the night.
To avoid this type of false detection, the third condition written in getstars.pro is to select only the ccd#-trsearch.txt light curves with a transit duration (`tdur_max`) less than 0.21 days (duration of a night).

Getstars.pro is written in IDL and therfore must be run in the IDL environment. The calling sequence for this programme is

```
IDL> .com getstars.pro
```

to compile the code and,

```
IDL> getstars, ccd number, sn_min, tdur_max
```

to execute the code for a given ccd (`ccd number` = 1 to 8), with a lower limit on the signal to noise ratio(`sn_min`=13) and an upper limit on the transit duration (`tdur_max`=0.21).

3.1.3 Visual light curve examination

Now that we have a list of stars in M50 that have been detected by the automated transit search and that present a good signal to noise and a correct transit duration, we have to conduct a close examination of their light curves. Indeed, a lot of objects or systems other than planetary or brown dwarf systems can show variations, such as variable stars (spotty stars, RR-Lyrae type stars, ...) and binary systems (simple binaries, contact binaries, ...).

The requirements for a light curve to be considered as transit-like after close examination are:
- the shape of the variation. For planet candidates, the magnitude should be constant in time between two transits.
- the depth of the different transit should be the same when more than one transit are detected, otherwise it is a binary star system. If there is a secondary eclipse (shallower than the primary) and the eclipse depth is very small in comparaison with the primary's one, then it can be a brown dwarf candidate.
A secondary eclipse happens when the primary star eclipses the secondary, hidding the secondary's contribution to the light curve.
- the transit depth to rms ratio should be greater than one. A transit can be trusted only if the rms of the magnitude is lower than the transit depth (significant detection).
- number of transit detected in the lightcurve. Two transits or more gives us the transit period. For a single transit light curve, futher observations will be necessary to define the period.
- for better confidence in a transit detection, the more in transit data point there are, the better.

Some examples of light curves (simple sinisoidal variation, eclipse superimposed to a sinusoidal variation, contact binary and simple binary variation, transit-like variation) found during the close-in examination are given in appendix.

Once a transit, fulfilling all the requirements described above, is detected, we can try to calculate some parameters of the system, such as the primary and secondary's masses and radii.

3.2 Calculation of primary and secondary's parameters, using getparam.pro (IDL code)

Another part of my project was to write an IDL code called getparam.pro (see appendix for the full code) to calculate automatically the primary and the secondary's mass and radius, as well as the orbital radius. The calling sequence of the programme is:

```
IDL> .com getparam.pro
```

to compile the code and,

```
IDL> getM1_R1_R2_M2, age, distance modulus, $R$ apparent magnitude, $i$ apparent magnitude,
$J$ apparent magnitude, $H$ apparent magnitude, $K$ apparent magnitude, range of magnitude,
transit depth, transit dur, transit period
```

to execute it. The magnitudes in J,H and K are not compulsary and can be set to 0 if not needed.
The "range of magnitude" (typically set to 0.4, 0.5 or 0.6) is used by the program to know ,in Baraffe's table, which range around the given apparent magnitude(s) it should considere to interpolate the primary's mass(es).

The apparent magnitudes in R (central wavelenght of 644 nm), i (central wavelenght of 805 nm), J (central wavelenght of 1.2),H (central wavelenght of 1.6) and K (central wavelenght of 2.2) are obtained from the 2MASS (2 micron all-sky survey) catalogue using the IDL programme called mkatlas.pro, written by Suzanne Aigrain. The calling sequence of this programme is

```
IDL> .com mkatlas.pro
```

to compile the code and,

```
IDL> mkatlas, onestar=[ccd, star], ps='ccd-star-atlas.ps'
```

to execute it. ccd calls for the CCD number and star for the star number.
mkatlas.pro also gives other details on the star, such as its position (RA and DEC), its image in i, R and H_α wavelenghts, its color magnitude diagram and plenty of other informations.
As an example, the atlas of the star 3782 in CCD 1, produced by mkatlas.pro, is given in appendix.

3.2.1 Transit- and eclipse-like variation : primary and secondary's parameters

We assume the orbital plane to be in the line of sight (i.e full transit, impact parameter b equal to zero, orbital inclination equal to 90°). This assumption gives us a lower limit on the secondary's radius (because we underestimate the full transit duration).

Primary mass, and radius calculation

A way to get the primary's mass is to use Baraffe's BCAH98iso.1 model for log(t in yr) equal to 8.1, corresponding to the 130 Myr of M50 (table in appendix). This model is a theoritical stellar model for low mass stars (0.075 to 1 $M_\odot$) encompassing the equations of stellar structure
To use this model, we need to know the age of the star we are monitoring. Cluster members have the same age asuming they all formed at the same time. For the transit- or eclipse- like candidates belonging to M50, we are then able to constrain the age to 130Myr.
Knowing the absolute magnitude in i and R of a given star, Baraffe's table gives us the associated primary's mass (M_1), luminosity (L_1) andtemperature ($T_{eff,1}$) for each of those magnitudes.
The primary's radius (R_1) is calculated using the equation

$$L_1 = 4\pi R_1^2 \sigma T_{eff,1}^4, \tag{1}$$

where L_1 and $T_{eff,1)}$ are known from Baraffe's model, and where σ is the Stefan's constant (value given in appendix).
The programme getparam.pro uses the age given in the calling sequence to choose the right table in BCAH98iso.1 model. Then, using the apparent magnitude given in input, it interpolates to give the corresponding primary's mass, luminosity and temperature. Finally, using the interpolated luminosity and temperature, it deduces the primary's radius.

Secondary radius calculation

The secondary's radius R2 is derived from the transit depth (Seager et al., 2003), as

$$\Delta F = (\frac{R_2}{R_1})^2, \tag{2}$$

where ΔF is the transit depth in the observed flux.
The transit depth (Δm), calculated by the automated transit search algorithmis, is in magnitude. The relation between the magnitude and the flux is

$$\Delta m = -2.5 \log(\Delta F). \tag{3}$$

Therefore, the equation, used in the programme getparam.pro to calculate R2, is

$$R_2 = R_1 \sqrt{1 - 10^{-\Delta m/2.5}}. \tag{4}$$

Secondary mass calculation

There are different ways of getting the secondary's mass from the light curve's parameters and the so far calculated primary's mass and radius and secondary's radius.
If the period has been correctly determined by the automated transit search algorithm, and if the transit is planet-like (shallow depth gives $R_2 << R_1$), we can use Kepler's 3rd law to calculate the secondary's mass (see equation 6 bellow).
If those assumptions are not respected, we can use two other models of Baraffe to put upper and lower mass limits. The first one is the Baraffe's CB97 model for a zero metalicity (Baraffe et al., 1997) and the second one is the Baraffe's COND isochrones (Baraffe et al., 2003),see details bellow and tables in appendix.

Using the 3rd Kepler's law

Assuming a planet-like object with a mass $R_2 << R_1$ and an orbital radius $a >> R_1$, a can be calculated as follow

$$a = \frac{R_1}{\tan(\frac{\pi t_{dur}}{P})}, \tag{5}$$

where t_{dur} and P are the duration and the period of the transit respectively.

And the mass of the secondary (M_2) can be derived from the Kepler's 3rd law

$$(P)^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)}, \tag{6}$$

where G is the gavitational constant (value given in appendix) and where the transit period P, the orbital radius a and the mass of the primary M_1 has already been determined.

This is the way the programme getparam.pro calculates the orbital radius and the mass of the secondary.

Using Baraffe's mass-radius relation, CB97 model and COND isochrones

Another way to get the mass of the secondary is to use Baraffe's mass-radius relation, CB97 model and COND isochrones (tables given in appendix). With these models, we get M_2 directly from R_2, without having to calculate orbital radius.
Baraffe's CB97 mass-radius relation and Baraffe's COND isochrones are only given for ages of 0.01, 0.1, 1 and 10 Gyrs. M50 is 130 Myrs old. Therefore, only upper mass limit (1Gyrs) and lower mass limit (100Myrs) can be obtained by this method, not a unique value. Nevertheless, we will expect the exact mass to be closer to the lower mass limit, as 100Myrs is closer to 130Myrs than 1 Gyrs is.
The Baraffe's CB97 model gives us a mass-radius relation for object between 0.075 and 0.800 $M_\odot$. And, the Baraffe's COND isochrones gives us a mass-radius relation for object between 0.075 and 0.800 $M_\odot$.

Therefore, it is not possible to detect a secondary's mass lower than 0.075 $M_\odot$, corresponding to a secondary's radius smaller than 0.1 $R_\odot$.
No automatic secondary's mass calculation has been written for this method because of time limitation.

3.2.2 Well-shaped transit-like variation : planet and star parameters

In the cases when we have
- a transit-like variation confirmed by close examination (see typical transit shape in FIG.1, section 1.1.2)

- M_2 (also called M_p in this subsection) much smaller than M_1
- the companion dark compared to the central star (no secondary eclipse)

and assumming that

- the light curve is from a single star
- the orbit is circular
- the light curve has a flat bottom (companion fully superimposed on the central star's disk)

Seager and Mallén-Ornelas (2003) give us equations to calculate the impact parameter b (see definition on FIG.1, section 1.1.2), the orbital radius a, orbital inclination i, and the period of the transit P.
The equations make use of the parameters ΔF, t_F, t_T of the light curves (see FIG.1,section 1.1.2). M_* and R_*, also used in the equations, are calculated using the IDL code getparam.pro (see section 3.2.1).

The equation to get the impact parameter b from the light curve parameters is

$$b = (\frac{(1-\sqrt{\Delta F})^2 - [\sin(t_F\pi/P)/\sin(t_T\pi/P)]^2(1+\sqrt{\Delta F})^2}{1-[\sin(t_F\pi/P)/\sin(t_T\pi/P)]^2})^{1/2}. \tag{7}$$

The orbital radius a can be determined from the light curve parameters as follow

$$a = R_*(\frac{(1+\sqrt{\Delta F})^2 - b^2[1-\sin^2(t_T\pi/P)}{\sin^2(t_T\pi/P)})^{1/2}, \tag{8}$$

or for $M_p << M_*$, the orbital radius can also be calculated via

$$a = (\frac{P^2 G M_*}{4\pi^2})^{1/3}, \tag{9}$$

where G is the gravitational constant and P is the transit period.

The orbital inclination i can be derived from the light curve parameters using

$$i = \cos^{-1}(b\frac{R_*}{a}). \tag{10}$$

If the transit period P is unknown or uncertain because only one transit or eclipse has been detected by the automated transit search algorithm, it can always be estimated using the following formula

$$P = \frac{M_*}{R_*^3}\frac{G\pi}{32}\frac{(t_T^2 - t_F^2)^{3/2}}{\Delta F^{3/4}}. \tag{11}$$

4 Results and discussions

4.1 Results and comments

Among the 55 000 ligth curves selected by Aigrain Irwin's automated transit search algorithm in the M50 field, 400 were examinated by eye (SNR above 19 for all the stars in the M50 field and above 10 for the ones members of M50).
19 candidates have been found, 14 during the first getstars.pro run on all the stars of the field with SNR greater than 19.
9 of the 19 candidates are M50 cluster members.
The 5 objets found in the getstars.pro run only on the stars members of M50 with SNR greater than 10, seems to be spotty.

Here is a summary of the candidates found in M50 field during this summer project (see the associated ligth curves in appendix).

Table 2: Transit search candidates

ccd	star	position		i	σ_i	R	t_{dur}	period	t_{depth}	SNR	ntr	Comments
		RA	DEC	$<-$	mag	$->$	days	days	mag			
		00 07 ..	-00 ..									
1	3782	22.09	09 04.3	17.14	0.0061	17.68	0.042	0.645	0.03636	34.2	2	(In)
2	3089	21.97	08 52.7	16.56	0.0047	17.02	0.105	1.850	0.09286	132.9	2	(In), (1), (2)
2	3889	22.09	08 49.9	17.44	0.0079	18.18	0.120	1.427	0.02400	29.2	5	(In), (1)
3	6131	22.55	08 42.5	19.48	0.0322	20.81	0.200	0.728	0.03932	22.4	4	(In)
4	1532	21.75	08 36.8	18.64	0.0122	19.79	0.060	0.235	0.02727	13.5	6	(In), (1)
4	3031	22.01	08 28.4	19.62	0.0221	20.94	0.047	1.513	0.46154	50.5	2	(In)
5	241	22.81	09 06.2	16.12	0.0043	16.75	?	?	>0.04364	39.6	1	(In), (4)
7	1847	23.06	08 45.6	18.74	0.0161	19.92	0.100	0.421	0.02800	23.0	4	(In), (1)
8	2068	23.10	08 36.8	17.76	0.0058	19.11	0.040	1.839	0.31111	166.1	2	(In) or (5) ?
1	772	21.61	08 59.2	20.37	0.0554	21.12	0.045	0.262	0.22857	30.4	3	(Out)
2	6957	22.60	08 54.9	18.36	0.0546	18.93	0.090	1.459	0.35000	106.7	1	(Out), (2), (3)
4	5732	22.43	08 32.5	19.69	0.0262	20.48	0.070	1.155	0.47692	47.6	1	(Out)
5	5943	23.71	09 03.6	20.02	0.0287	20.84	0.070	0.842	0.23809	37.7	3	(Out)
5	6033	23.72	09 05.2	18.29	0.0234	19.02	0.050	0.432	0.08750	49.2	4	(Out), (1)
5	6597	23.83	09 04.8	18.62	0.0217	19.44	0.060	0.854	0.21667	83.2	3	(Out)
6	4070	23.40	08 49.5	20.06	0.0273	20.85	>0.120	?	0.38667	48.2	1	(Out), (4)
6	6609	23.87	08 55.9	19.13	0.0155	20.02	0.052	0.571	0.06411	35.2	3	(Out)
7	1671	23.04	08 44.3	19.93	0.0364	20.60	0.055	1.126	0.21111	37.0	2	(Out)
7	3715	23.32	08 43.8	18.05	0.0129	18.67	?	1.334	>0.26667	100.2	2	(Out), (4)

i and R stand for the apparent magnitude in i and R respectively. σ_i is the rms in i. t_{dur} and period (both in days) are the transit duration and period respectively. t_{depth} is the transit depth which had to be re-measured by hand in most of the cases. SNR stands for the signal to noise ratio and ntr for the number of transit detected inthe lightcurve.

(In) The candidate is a member of M50.
(Out) The candidate is outside M50. Its age cannot be determined.
(1) A sinusoidal variation of central star is distorting the eclipse/transit depth. The value of the secondary's radius (deduced from the primary's radius and the transit depth) is then biased. The sinisoidal component of the light curve should be removed before any futher calculation, particularly to get the transit depth right.
(2) A secondary eclipse is detected visually.
(3) Central star seems to have intrinsic variations.
(4) Incomplete transit. The transit duration is unknown and we can only put a lower limit on the transit depth, which will give us a lower limit on the secondary's radius. Need to perform more photometry on the object.
(5) Foreground star.
(6) For a single transit with a full and well-defined shape, and for a known age, the period can be calculated using equation 11 of subsection 3.2.2.

The blank line separates the candidates members of M50 (top pannel) and the ones that are not (bottom pannel).

Only for the members of the cluster we were able to calculate the parameters (mass and radius) of the central star and its compagnion.
The values found are listed in the following table.

Table 3: Parameters of the M50 member candidates

ccd	star	for i magnitudes					Comments
		$M_1/M_\odot$	$R_1/R_\odot$	$R_2/R_\odot$	$M_2/M_\odot$		
					min (100 Myr)	max (1 Gyr)	
1	3782	0.5531	0.5190	0.0911	?	0.060	(1)
2	3089	0.7534	0.6978	0.1999	0.110	0.200	(2), (3)
4	3031	0.3475	0.3417	0.2008	0.110	0.200	(1)
5	241	0.8264	0.7709	>0.1514	0.060	0.150	(1)
8	2068	0.6171	0.5702	0.2449	0.150	0.300	(1)
2	3889	0.6425	0.5922	0.0631	?	0.060	(4)
3	6131	0.3705	0.3586	0.0674	?	0.060	(4)
4	1532	0.4887	0.4567	0.0479	?	0.060	(4)
7	1847	0.4759	0.4449	0.0658	?	0.060	(4)

M_1, R_1, M_2 and R_2 are the mass and the radius of the primary and of the secondary repectively.
M_2 has not been calculated using the 3rd Kepler's law as it turned out that the calculated orbital radius and secondary's radius were not fulfilling the assumptions for this method.
M_2 has been calculated using Baraffe's CB97 model of mass-radius relation, for object with radius between 0.1606 and 0.7385 $R_\odot$ for 100Myr, and between 0.0977 and 0.7521 $R_\odot$ for 1Gyr.
For radii out of Baraffe's CB97 model range, we used Baraffe's COND isochrones which gives us the mass for radius down to 0.114 for 100Myr and to 0.092 for 1Gyr (seetables in appendix).

(1) Planet or brown dwarf candidate. We will get rid of the degenerancy by radial velocity measurement on the candidate.
(2) Presence of a secondary eclipse in the light curve.
(3) Brown dwarf candidate.
(4) Spotty-like.

The blank line separates the objects we trust to be real (top pannel) and the ones we don't (bottom pannel) because they have too long transit duration in comparaison with their period (more like spotty star). But as we are not sure, we still keep them as lower priority objects.

The candidate 3782 in CCD 1 is really interested as it has been calculated to have a central star mass of 0.5531 $M_\odot$ and a companion one of less than 0.055 $M_\odot$, i.e less than 55 Jupiter masses. Moreover it has a magnitude hight enough (17.14 in i) to be easely followed up. Spectroscopy will also be performed on it to determine accurately the radius and the mass of the central star's companion.

4.2 Discussions and futher analysis

In the case of planetary search using the transit method, the 3rd Kepler's law turned out not to be adapted to calculate the mass of the secondary object. This is, in fact, fully consistent with the fact that the transit search method is more sensitive to large, close-in planets, violating the assumptions made when using the 3rd Kepler's law.
The other way to constrain the mass of the secondary object is by using Baraffe's mass radius relations (CB97 model and COND isochrones). This method just gives us a range of possible masses. It gives an idea to the Monitor Project collaborators on what to expect when they will be performing spectroscopy on those candidates.

Radial velocity measurements are required to get rid of the mass degenerancy. It rules out the phenomena mimicing planetary transits, such as high mass ratio eclipsing binaries (dwarf around a giant), binaries whose eclipses are diluted by a third star within the aperture used for photometry, brown dwarf companions). Few kms^{-1} gives us a stellar companion (case of eclipsing binaries or eclipses diluted by a third star), few $100ms^{-1}$ gives us a substellar companion (brown dwarf), and few $10ms^{-1}$ determines a planetary nature of the companion. The velocity amplitude equations are given in Perryman (2000).

In this project, 5 central stars have been found having an intrinsic sinusoidal variation, of which 4 are in the cluster. The sinisoidal component of the light curve must be removed before estimating manually the depth of the transit. This hasn't been done during this project because of time limitation, but should be processed for more accurate secondary's radius calculation.

Ten candidates, found in this project, have unknown age. In their case, it is impossible to use Baraffe's model to constrain the mass of the central star.
Gallardo et al. (2005) use a method to "characterise extrasolar planetary transit candidates" which do not need an age determination. In futher work, this method should then be investigated and applied to those candidates.
If more close-in examination of the light curves, selected by Aigrain Irwin's automated transit search algorithm, is carried out, more faint candidates, not members of M50, could be found. And their parameters could be constrained using Gallardo's method.

The candidates found in M50 need to be followed up to confirm or determine (in the case of single transit detected so far) the period. The more transit are detected, the more accurate is the period determined.
More photometry are also needed for all the candidates, and particularly on the ones with an incomplete transit in order to measure their transit depth and duration. More photometry will allow us better shape determination for which we will be able to measure the total transit duration (t_T) and the full transit duration (t_F) (see figure in section 1.1.2). And therefore, using Seager's equation (section 3.2.2), we will be able to calculate the orbital radius and inclination, as well as the period in the case where only one transit has been observed.

We also have to be aware that the transit depth could be diluted by a blended object and will therefore appears shallower, and the eclipse could be grazing, i.e. the secondary is larger radius than we infer.

Writing a program to automate parameter calculation, especially to determine the range of secondary's mass from Baraffe's CB97 model, or from the COND isochrones tables depending on the range of secondary's radius, could be very useful in the future.
This project was built to detect transit-like candidates in the M50 cluster and just gave a foretaste on mass measurement of the companion. The following step of the Monitor Project is to perform spectroscopy on those candidates to measure accurately their mass and radius. The transit method is the only method allowing direct measurements (does not rely on models) of those parameters, which makes it an even more interesting method.

5 Conclusion

5.1 Conclusions the planetary transit search method

The combined efforts of Aigrain & Irwin's automated transit search algorithm with my getstars.pro code, came to fruition during this project. Among all the stars in the M50 field, 19 planetary candidates were found, of which 9 are members of the M50 open cluster. For each of the 9, mass limits of their companion were calculated. It is possible for 4 of the 9 candidates to be spotty stars.

One candidate, 3782 in CCD 1, is really promising as it appears to have a companion with a mass less than 55 Jupiters. Follow up and spectroscopy will be performed on this object, and on the 8 other candidates with lower priority.

Ground-based observations have limitations in planetary transit detection, as the data collected by this method are irregularly sampled (finite night duration and limited telescope time). For instance, detecting one Earth transit on the Sun from outside our solar system, will need at least a year of continuous monitoring.
Space-based observations have the advantage of not being constrained by the duration of the night.
The Kepler Space Mission is a space-based telescope set to launch in 2007. It is designed specifically to search large numbers of stars for Earth-sized terrestrial planets using the transit method.

Once an earth-like planet will be found, the next step will be to characterize its surface and atmosphere, and to look for the chemical signatures of life.

5.2 Conclusions on the summer project in general

This summer project has enriched me a lot, not only in improving my scientific knowledge on planetary search, but also in learning IDL (Interactive Data Language), a key software used by astrophysicists.
This project has also been my first work experience with british astronomers and astrophysicists. Having to convey scientific ideas and reflections on the project, as well as producing this report, have greatly improved my communication skills in English.

Writing this report has been the hardest part of my summer project. It has cost me several sleepless nights. However, the loss of sleep was without regret, thanks to the wealth of information gathered in the passionate field of planet hunting.

Hide, hide, little green men, a new planet hunter is after you ! ;)

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"Evolutionary models for cool brown dwarfs and extrasolar giant planets. The case of HD 209458",
I. Baraffe1, G. Chabrier, T. S. Barman, F. Allard and P. H. Hauschildt, 2003

Relevant web pages

http://www.ast.cam.ac.uk/~suz/monitor/monitor.php
http://www.seds.org/messier/m/m050.html

Baraffe's models
http://perso.ens-lyon.fr/isabelle.baraffe/CB97_models
http://perso.ens-lyon.fr/isabelle.baraffe/BCAH98_iso.1

Other projects on planetary search
http://www.hao.ucar.edu/public/research/stare/stare.html
http://www.iac.es/proyect/tep/tephome.html
http://encyclozine.com/Extrasolar_planet

A Appendix: Divers

A.1 RMS diagram for M50

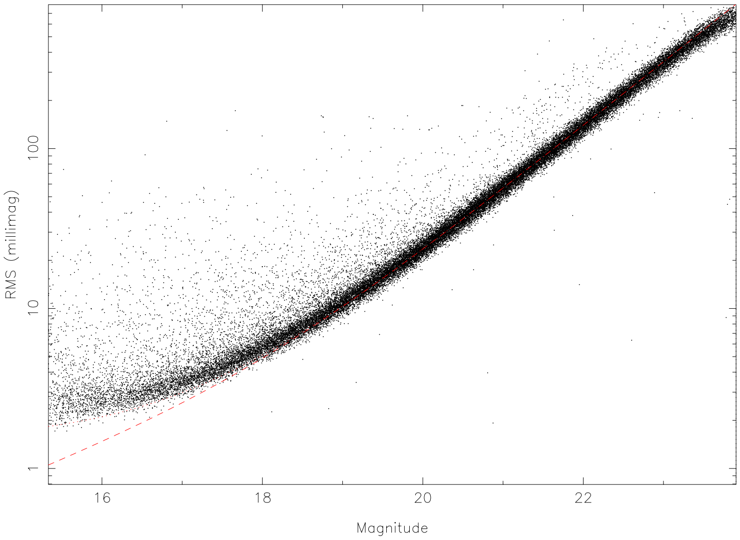


Figure 2: RMS diagram for M50. The bottom red dotted line is the theoritical photometric noise for M50. The light top red dotted line is the same but with the additional quadrature "fudge factor" used to account for residual systematics at the bright end

A.2 Astronomical parameters

Solar luminosity $L_\odot$	3.84E26 W	
Solar mass $M_\odot$	1.989E30 kg	
Solar radius $R_\odot$	6.960E8 m	
Earth mass $M_\oplus$	5.9742E24 kg	3E-6 $M_\odot$
Earth radius $R_\oplus$	6.356E6 m	10^{-2}R$_\odot$
Jupiter mass M_J	1.9E27 kg	10^{-3}M$_\odot$
Jupiter radius R_J	7.1492E7 m	10^{-1}R$_\odot$, 10 $R_\oplus$
Astronomical unit AU (earth-sun distance)	150E9 m	
Gravitational constant G	6.6742E-11 m^{3}kg^{-1}s^{-2}	
Stefan's constant	5.67E-8 W m^{-2}K^{-4}	

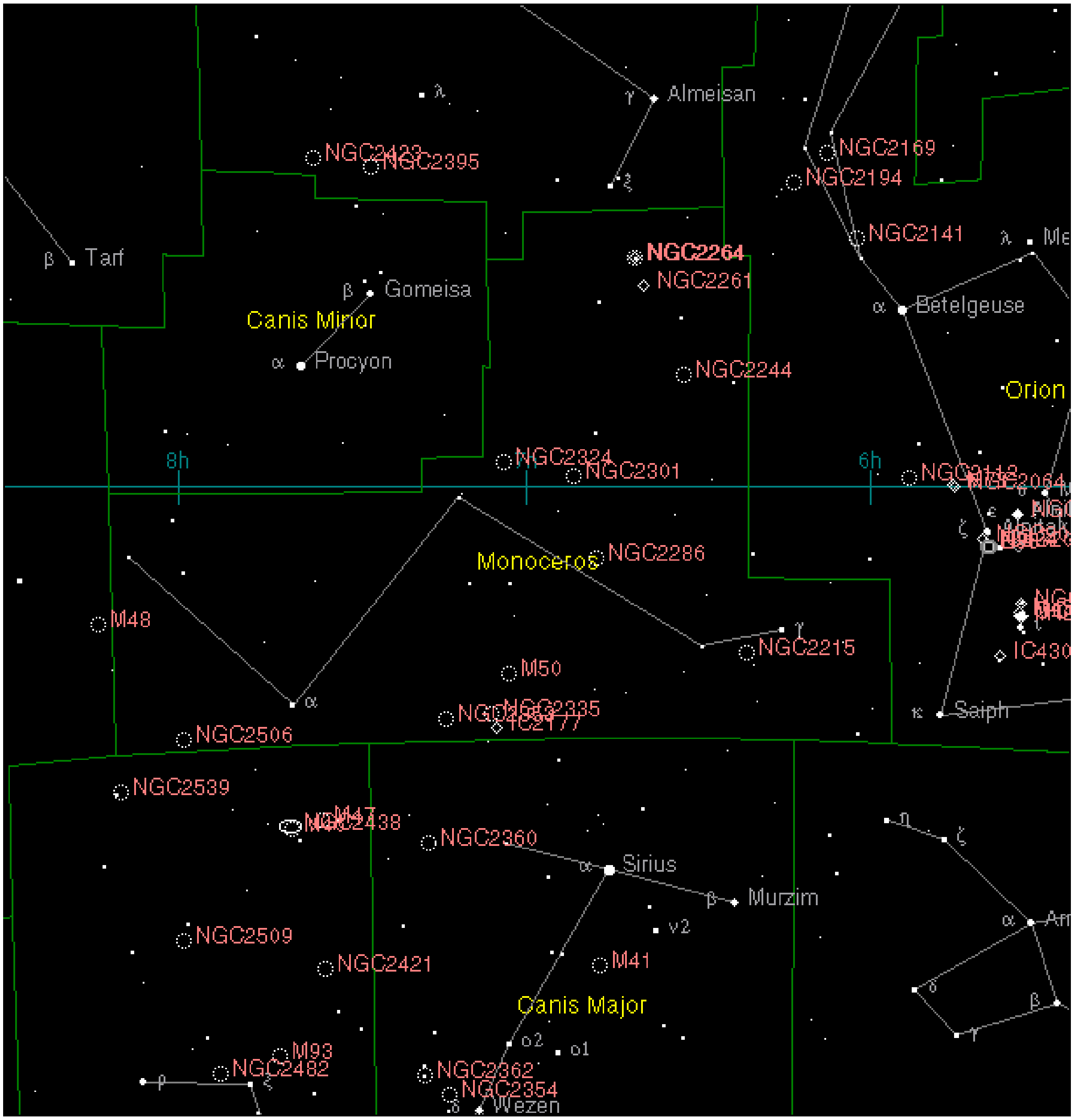
A.3 Some definitions

Planetary transit : periodic dips caused by planets as they cross the disk of their parent star.
Photometry : measurement of apparent magnitudes of astronomical objects, like stars.
Astrometry : part of astronomy that measures the proper motion of stars as a function of time.

A.4 Monitor logo

For the inquirers, the Monitor Project logo is a Varanus Salvator, an asiatic water monitor. Monitor is a race of lezard. This is where the lizard as logo for the Monitor project, comes from.
For more information see *http : //mampam.*50*megs.com/monitors/salvator*2*.html*

B Appendix: Where is M50 in the sky ?



M50 is situated in Monoceros (Latin for Unicorn), a faint constellation on the winter night sky, surrounded by Orion to the west, Gemini to the north, Canis Major to the south and Hydra to the east. Other bordering constellations includes Canis Minor, Lepus and Puppis.

C Appendix: troncated ccd1-trsearch.txt file

star	npts	median	sigma	tdur	es	sns	trds	nins	pm	em	snm	trdm	ninm	ntr
12	207	22.739	0.33985	0.062	2.070	2.642	0.22256	9.7	9.999	2.070	3.482	0.21692	23.2	2
14	197	19.782	0.02370	0.053	12.074	4.404	0.02369	12.4	1.550	1.215	5.019	0.02337	14.6	2
15	239	22.166	0.19770	0.077	12.056	2.637	0.10510	17.5	1.548	1.219	3.121	0.10170	18.8	2
16	211	20.450	0.03792	0.062	1.219	3.345	0.10159	1.2	2.169	1.219	4.150	0.03585	15.3	2
20	234	23.025	0.40028	0.202	2.189	1.559	0.18657	9.1	0.477	-0.196	2.182	0.21260	14.4	3
22	223	23.586	0.54046	0.053	12.092	1.476	0.42608	6.3	1.972	0.247	2.106	0.36457	16.4	3
23	244	18.048	0.00729	0.059	12.072	4.805	0.00646	13.4	0.642	0.523	7.013	0.00487	38.2	3
24	244	22.187	0.20446	0.053	12.072	4.762	0.31202	12.5	5.568	0.934	4.876	0.31202	12.5	1
25	242	22.936	0.36381	0.054	12.065	2.073	0.23454	11.7	10.022	2.044	2.478	0.17452	22.0	2
27	244	18.286	0.00835	0.085	10.147	5.425	0.00853	12.3	1.136	-0.079	7.214	0.00609	39.0	4
30	244	21.898	0.14918	0.053	11.955	2.443	0.19432	2.8	1.871	0.726	3.090	0.10820	10.1	2
31	244	22.613	0.27213	0.133	9.907	1.903	0.14630	8.2	0.480	0.299	2.486	0.14335	14.6	3
32	244	22.184	0.17630	0.069	12.072	5.115	0.26690	15.8	9.997	2.075	5.335	0.17914	26.4	2
33	244	19.451	0.01586	0.091	12.088	3.665	0.01144	20.0	0.932	0.001	5.649	0.01073	45.8	4
34	244	19.347	0.01491	0.053	0.950	4.184	0.03264	3.4	3.715	0.955	4.574	0.01450	16.8	2
36	244	21.167	0.06982	0.075	12.056	3.246	0.05050	17.0	2.169	1.206	3.872	0.04986	21.1	2
37	241	23.295	0.43782	0.070	1.214	0.871	0.43885	2.2	1.032	0.934	1.077	0.15986	9.4	2
40	244	21.150	0.07460	0.053	2.069	3.928	0.07222	9.0	0.437	0.326	4.994	0.05403	25.7	3
41	244	16.068	0.00359	0.251	11.955	7.002	0.00244	41.1	0.865	-0.154	8.765	0.00213	79.2	3
42	244	20.707	0.04785	0.069	2.117	4.512	0.05002	10.6	1.158	0.966	5.274	0.04461	20.2	2
43	244	17.916	0.00524	0.107	2.096	2.743	0.00325	17.8	0.826	0.443	4.158	0.00317	47.1	3
44	244	20.473	0.03363	0.053	1.200	3.886	0.05410	5.0	10.001	1.200	4.487	0.05570	6.4	2
45	244	21.659	0.09617	0.128	11.896	2.398	0.09722	5.8	2.250	0.886	3.251	0.07105	20.9	3
46	244	21.242	0.07479	0.053	0.939	2.459	0.18479	1.1	0.585	0.390	3.529	0.02810	30.3	3
47	244	22.337	0.23513	0.080	2.064	3.125	0.15181	12.7	1.262	0.801	3.801	0.14966	20.6	2
48	244	21.367	0.09038	0.139	2.075	4.351	0.06121	22.5	4.396	2.075	4.633	0.05950	27.2	2
49	244	18.708	0.00976	0.096	0.897	3.168	0.02337	1.1	1.333	0.897	4.480	0.02338	2.2	2
50	244	21.549	0.11265	0.107	2.064	4.805	0.09096	17.6	1.768	0.305	5.336	0.08688	23.1	2
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

The fifty first rows of ccd1-trsearch.txt file, obtained with the calling sequence

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trsearch_sel  lc.fits[ccd][class==-1 && bflag==0 && cflag<2 && medflux>15] 0.05 0.25 21 -1 -1 -1 1ccd1-
trseaarch.txt 1
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D Appendix: Some examples of light curves found during the close-in examination

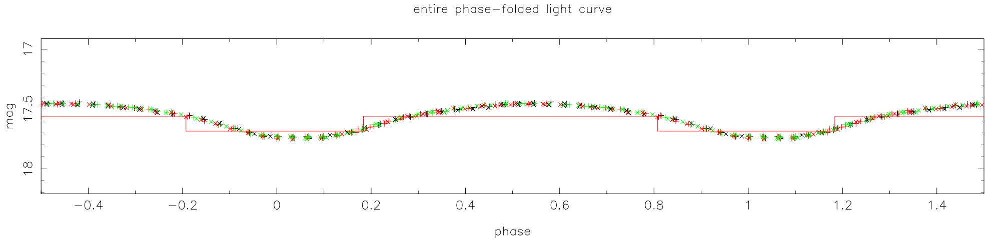


Figure 3: i phase folded light curve of star 3842 in CCD 1, an example of **simple sinisoidal variation**. σ_i=0.1296, period=0.146, snr=194.986

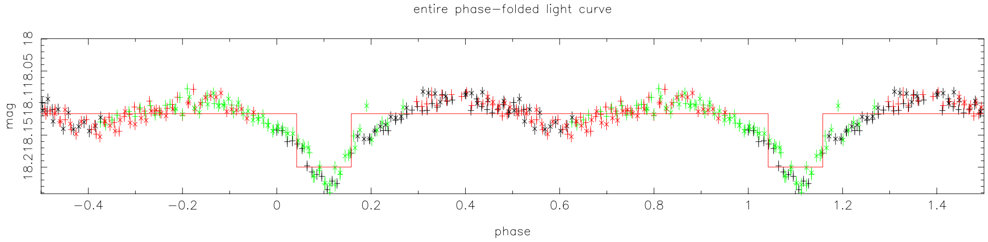


Figure 4: i phase folded light curve of star 6033 in CCD, an example of **eclipse superimposed to a sinusoidaly variable star**. σ_i=0.0234, t_{dur}=0.05, period=0.432, t_{depth}=0.07391,snr=49.154

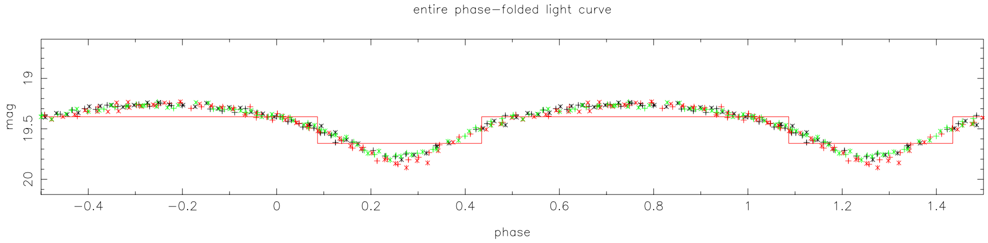


Figure 5: i phase folded light curve of star 563 in CCD 8, an example of **contact binary stars**, WUMa type. The non-constant magnitude outside the eclipse (cambered shape), can be due to deformed compagnions and/or heating effect of the primary on the secondary. σ_i=0.1540, period=0.201, snr=99.716

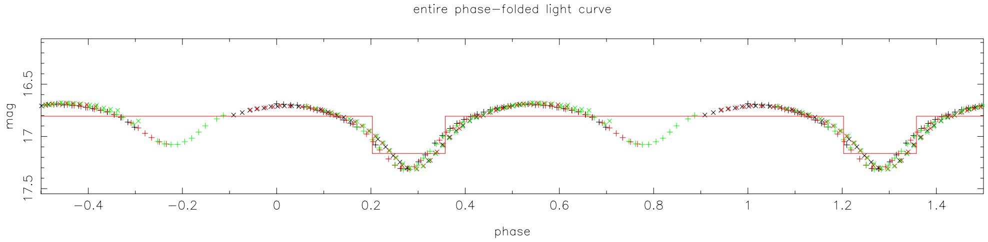


Figure 6: i phase folded light curve of star 5185 in CCD 4, an example of typical **simple binary stars** system, where the compagnion appears as been rougthly half (eye estimation) the size of its host. σ_i=0.1485, period=0.324, snr=729.646

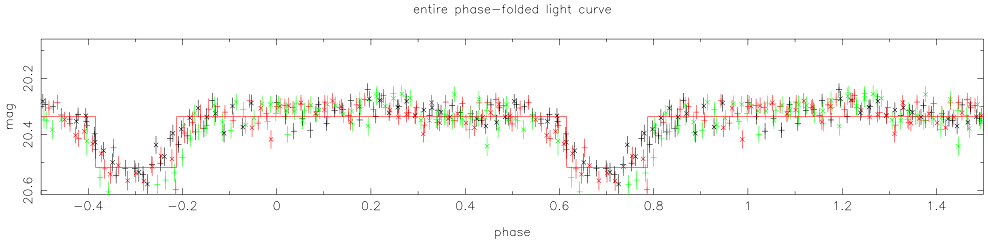
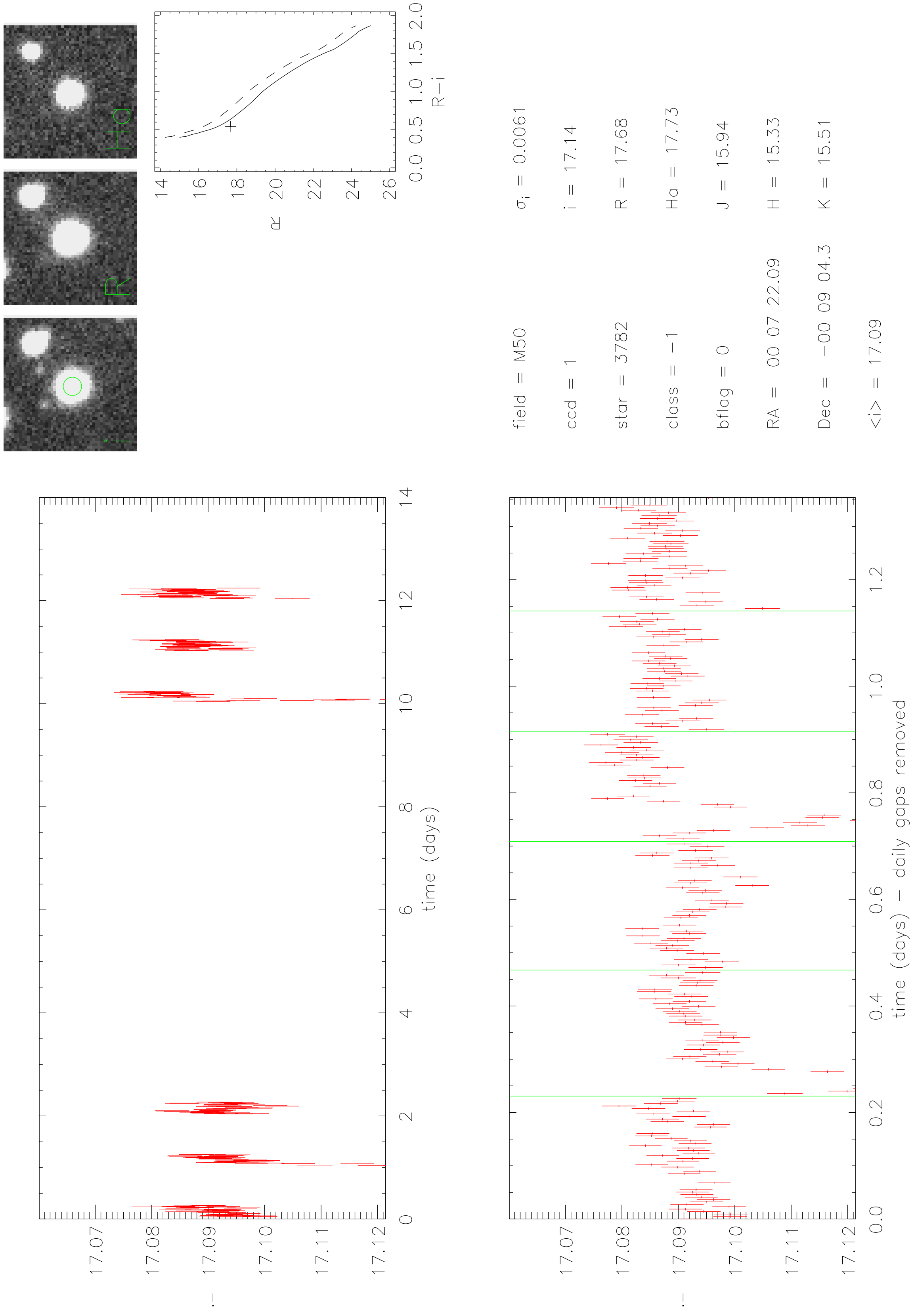


Figure 7: i phase folded light curve of star 772 in CCD 1, an example of **transit candidate**. σ_i=0.0554, t_{dur}, period=0.262, t_{depth}=0.15326, snr=30.425

E Appendix: Atlas of the star 3782 in CCD 1, produced by mkatlas.pro



F Appendix: IDL codes

F.1 getstars.pro

```
;*******************************************************************
;* need files:
; /home/alapini/results/ccd-trsearch/ccd'+lts+'-trsearch.txt ;
; /home/alapini/results/ccd-trsearch-select/ccd'+lts+'-trsearch-selec.txt
; /home/alapini/results/clus_seq.dat
;
;(see def of lts in getstars)
;*****************************************************************
; code written by Aude Alapini}
;*****************************************************************

;Calling sequence :
;IDL> .com getstars.pro
;IDL> getstars, ccd, sn_min, tdur_max


pro getstars, ccd, sn_min, tdur_max
   case ccd of
      1:   lts = '1'
      2:   lts = '2'
      3:   lts = '3'
      4:   lts = '4'
      5:   lts = '5'
      6:   lts = '6'
      7:   lts = '7'
      8:   lts = '8'
      else: begin
         print, "Error: 8 CCDs, choose CCD 1 to 8"
         return
      end
   endcase

   r=read_ascii('/home/alapini/results/ccd-trsearch/ccd'+lts+'-trsearch.txt', $
da=1})
   ;help, /str, r
   rselec=read_ascii('/home/alapini/results/ccd-trsearch-select/ccd'+lts+'- $
trsearch-selec.txt', da=1)}
   ;help, /str, rselec
   s = read\_ascii('/home/alapini/results/clus_seq.dat', da=1)
   ;help, /str, s
   str = mrdfits('/home/suz/data/monitor/lightcurves/m50/i/lc.fits', ccd)}

   n_star=N_ELEMENTS(r.field01[0,*])
   print, "number of stars in input file",  n_star

   list_in_cluster =0
   list_mag_missing=0
   list_mag_gt     =0

   for i=0, n\_star-1 do begin
      if finite(str[r.field01[0,i]-1].rflux) and  finite(str[r.field01[0,i]-1].iflux) $
then begin
```

```
         if (str[r.field01[0,i]-1].rflux lt 25.0) and (str[r.field01[0,i]-1].rflux gt 15.0) $
then begin

    l=where((s.field1[0,*] lt str[r.field01[0,i]-1].rflux+0.1) and $
(s.field1[0,*] gt str[r.field01[0,i]-1].rflux-0.1))
    n_l=N_ELEMENTS(l)
    R_selec= FLTARR(n_l)
    Ri_selec= FLTARR(n_l)

    for j=0, n_l-1 do begin
    R_selec[j] = s.field1[0,l[j]]
    Ri_selec[j]= s.field1[1,l[j]]
    endfor

    U=[str[r.field01[0,i]-1].rflux]
    int = interpol(Ri_selec, R_selec, U)

    if (str[r.field01[0,i]-1].rflux - str[r.field01[0,i]-1].iflux + $
str[r.field01[0,i]-1].rms) ge int then begin
       ;print, "-----------------------------------"
       ;print, "iteration", i
       ;print, "star", str[r.field01[0,i]-1].pointer
       ;print, "STAR IN CLUSTER"
       ;print, "rflux  ", str[r.field01[0,i]-1].rflux
       ;print, "iflux  ", str[r.field01[0,i]-1].iflux
       ;print, "rms    ", str[r.field01[0,i]-1].rms
       ;print, "l      ", l
       ;print, "R_selec ",  R_selec
       ;print, "Ri_selec", Ri_selec
       ;print, "* Interpolation"
       ;print, "Ri_interpol =", int
       ;print, "i_interpol =", int
       list_in_cluster=[list_in_cluster, str[r.field01[0,i]-1].pointer]
    endif

 endif else begin
 ;print, "iteration", i
 ;print, "star", str[r.field01[0,i]-1].pointer
 ;print, "rflux  ", str[r.field01[0,i]-1].rflux
 ;print, "ERROR: rflux > 25"
 ;print, "-----------------------------------"
 list_mag_gt=[list_mag_gt, str[r.field01[0,i]-1].pointer]
 endelse

 endif else begin
    ;print, "iteration", i
    ;print, "star", str[r.field01[0,i]-1].pointer
    ;print, "rflux  ", str[r.field01[0,i]-1].rflux
    ;print, "iflux  ", str[r.field01[0,i]-1].iflux
    ;print, "ERROR: rflux or iflux missing"
    ;print, "-----------------------------------"
    list_mag_missing=[list_mag_missing, str[r.field01[0,i]-1].pointer]
 endelse

   endfor
```

```
n_list_in_cluster=N_ELEMENTS(list_in_cluster)
list_in_cluster =list_in_cluster[1:n_list_in_cluster-1]
;print, "Stars in cluster"
;print, list_in_cluster
n_list_in_cluster=N_ELEMENTS(list_in_cluster)
print,"nbr of stars in cluster     ", n_list_in_cluster

ccd_array=ccd
for i=0, n_list_in_cluster-2 do ccd_array=[ccd_array, ccd]
;n_ccd= N_ELEMENTS(ccd_array)
;print,"nbr      :", n_ccd

;openw,1,'~alapini/results/ccd-trsearch-select/ccd-'+lts+'-trsearch.txt'
;for j=0,  n_list_in_cluster-1 do $
   ;printf, 1, ccd_array[j], list_in_cluster[j], format='(i5,2x,i5)'
;close, 1

;n_list_mag_gt=N_ELEMENTS(list_mag_gt)
;list_mag_gt  =list_in_cluster[1:n_list_mag_gt-1]
;n_list_mag_gt=N_ELEMENTS(list_mag_gt)
;print,"nbr of rflux $>$ 25             :", n_list_mag_gt

;n_list_mag_missing=N_ELEMENTS(list_mag_missing)
;list_mag_missing  =list_in_cluster[1:n_list_mag_missing-1]
;n_list_mag_missing=N_ELEMENTS(list_mag_missing)
;print,"nbr of rflux or iflux missing :", n_list_mag_missing

sn  = 0
tdur= 0
for i=0, n_list_in_cluster-1 do begin
   sn   =[sn,  rselec.field01[7,i]]
   tdur =[tdur,rselec.field01[4,i]]
endfor

n_sn=N_ELEMENTS(sn)
sn  =sn[1:n\_sn-1]
n_sn=N_ELEMENTS(sn)
;print, "sn"
;print, sn
;print, "n_sn", n_sn

n_tdur=N_ELEMENTS(tdur)
tdur  =tdur[1:n_tdur-1]
n_tdur=N_ELEMENTS(tdur)
;print, "tdur"
;print, tdur
;print, "n_tdur", n_tdur

l_sn_tdur = where((sn gt sn_min) and (tdur lt tdur_max))
;print, l_sn_tdur

star=rselec.field01[1,*]
n_sn_tdur= N_ELEMENTS(l_sn_tdur)
s= FLTARR(n_sn_tdur)\\
for i=0, n_sn_tdur-1 do s[i]=star[l_sn_tdur[i]]
print, "Stars in cluster with sn > sn_min and tdur < tdur_max "
print,s
```

```
   return
end ;*****************************************************************
```

F.2 getparam.pro

```
;******************************************************************;
;* run IDL in directory  /home/alapini/results/} because need $
Baraffe directory which contains the Baraffe's table for different ages $
(called t'lts'.dat, see def of lts in getM1_R1_R2\_M2)
;need template t.tpl in (/home/alapini/idl/t.tpl)
;
;* Assumption: secondary far from the primary and M2 $<<$ M1
;******************************************************************;
; code written by Aude Alapini
;******************************************************************;

;Calling sequence :
;IDL> .com getparam.pro
;IDL> getM1_R1_R2_M2, age, dmod, ap_mag in R, ap_mag in i, $
ap_mag in J, ap_mag in H, ap_mag in K, mag_range, transit_depth,$
transit_dur, transit_period

function constants
   c = create\_struct('Rsun', 6.96E8,         $
                      'Lsun', 3.84E26,        $
                      'Msun', 1.989E30,       $
                      'stefan_sigma', 5.67E-8,$
                      'AU', 150E9,            $
                      'G', 6.6742E-11         )
   return, c
end ;************************************************************************

function func_abs_mag, dmod, ap_mag
   return, ap_mag - dmod
end ;************************************************************************

function func_radius, L, Teff
   ;using luminosity = surface area * flux
   ;flux = stefan_sigma * Teff^4
   ;surface area = 4*\pi*R
   c = constants()
   R = sqrt(L/(4*!PI*c.stefan_sigma*Teff^4))/c.Rsun
   return, R
end ;************************************************************************

function func_M1, abs_mag, mag_range, baraffe_mag, baraffe_mass
   ;Search in baraffe, masses corresponding to abs_mag +/- mag_range
   l=where((baraffe_mag gt abs_mag-mag_range) and (baraffe_mag lt abs_mag+mag_range))
   n= N_ELEMENTS(l)
   mag= FLTARR(n)
   mass= FLTARR(n)

   for p=0, n-1 do begin
      mag[p] =baraffe_mag[l[p]]
```

```
      mass[p]=baraffe_mass[l[p]]
   endfor

   print, "mag   =", mag
   print, "masses=", mass
   print, "* Interpolation to get primary's mass"
   U=[abs_mag]
   M1 = interpol(mass,mag,U)
   print, "M1    (in solar masses) =", M1
   print, "---------------------------------------"
   return, M1
end ;*********************************************************************

function func_R1, abs_mag, mag_range, baraffe_mag, baraffe_teff, baraffe_logL
    c = constants()
    ;Search in baraffe, masses corresponding to abs_mag $\pm$ mag_range"
    l=where((baraffe_mag gt abs_mag-mag_range) and (baraffe_mag lt abs_mag+mag_range))
    n= N_ELEMENTS(l)
    mag= FLTARR(n)
    Teff= FLTARR(n)
    logL= FLTARR(n)

    for p=0, n-1 do begin
       mag[p] =baraffe_mag[l[p]]
       Teff[p]=baraffe_teff[l[p]]
       logL[p]=baraffe_logL[l[p]]
    endfor

    ;print, "mag   =", mag
    ;print, "Teff  =", Teff
    ;print, "logL  =", logL
    print, "* Interpolation to get Teff1, L1"
    U=[abs_mag]
    Teff1 = interpol(Teff ,mag,U)
    logL1 = interpol(logL ,mag,U)
    L1    = 10\^{}logL1*c.Lsun
    ;print, "Teff1 (in K)            =", Teff1
    ;print, "logL1                   =", logL1
    ;print, "L1                      =", L1
    print, "* Calculation of primary's radius"\\
    R1 = func_radius(L1, Teff1)
    print, "R1    (in solar radius) =", R1
    print, "---------------------------------------"
    return, R1
end ;*********************************************************************

function func_R2, R1, trans_depth
   print, "* Calculation of secondary's radius"
   R2 = R1*sqrt(1-10\^{}(-trans_depth/2.5))
   print, "R2    (in solar radius) =", R2
   print, "---------------------------------------"
   return, R2
end ;*********************************************************************

function func_a, R1, trans_dur, trans_period, R2
   c = constants()
   print, "* Calculation of orbital radius"
```

```
   a = R1/tan(!PI*trans_dur/trans_period)
   print, "a     (in solar radius) =", a

   if a ge (R1+R2) then begin
      a_au = a * c.Rsun/c.AU
      print, "a     (in AU)           =", a_au
   endif else begin
      print, "ERROR, secondary touches primary"
      a_au = 0.0
   endelse

   print, "---------------------------------------"
   return, a_au
end ;*********************************************************************

function func_M2, orbital_radius, trans_period, mass1
   c = constants()
   print, "* Calculation of secondary's mass"
   M2 = abs((4*!PI\^{}2*(orbital_radius*c.AU)\^{}3/(c.G*(trans_period*24*3600)\^{}2) - $
mass1*c.Msun))/c.Msun}
   print, "M2    (in solar masses) =", M2
   print, "---------------------------------------"
   return, M2
end ;*********************************************************************

pro getM1_R1_R2_M2, age, dmod, ap_magr, ap_magi, ap_magJ,
ap_magK, ap_magH, mag_range, $
transit_depth, transit_dur, transit_period
   print, "* Calculation of absolute magnitudes in R_ and I_johnson (FUNC_ABS_MAG)"
   abs_magr = func_abs_mag(dmod, ap_magr)
   abs_magi = func_abs_mag(dmod, ap_magi)
   abs_magJ = func_abs_mag(dmod, ap_magJ)
   abs_magK = func_abs_mag(dmod, ap_magK)
   abs_magH = func_abs_mag(dmod, ap_magH)

   RI= (abs_magr - abs_magi)/0.797
   abs_magr_johnson = abs_magr - 0.011*RI
   abs_magi_johnson = abs_magi - 0.214*RI
   JK= (abs_magJ - abs_magK + 0.020)/1.068
   abs_magK_cit = abs_magK - 0.001*JK + 0.019
   abs_magJ_cit = JK + abs_magK_cit
   HK= (abs_magH - abs_magK - 0.034)/1.000
   abs_magH_cit = HK + abs_magK_cit
   print, "DONE"

   print, "* Search table corresponding to given age, creating structure baraffe"
   case age of
      1:   lts = '600'
      3:   lts = '650'
      7:   lts = '670'
      13:  lts = '710'
      30:  lts = '750'
      50:  lts = '770'
      100: lts = '800'
      130: lts = '810'
      150: lts = '820'
      180: lts = '830'
```

```
   else: begin
       print, "Error: need to set up Baraffe's table for this age"
       return
   end
   endcase

   restore, '/home/alapini/idl/t.tpl'
   baraffe=read_ascii('/home/alapini/results/Baraffe/t'+lts+'.dat', template=tpl)
   ;help, /str, baraffe
   print, "DONE"

   ;print, "* Use of functions CONSTANTS, FUNC_RADIUS, FUNC_M1, FUNC_R1, $
FUNC_R2, FUNC_A, FUNC_M2"
   print, ""

   print, "        R MAGNITUDE"
   print, "Johnson absolute mag =", abs_magr_johnson
   M1_r = func_M1(abs_magr_johnson, mag_range, baraffe.MR, baraffe.M)
   R1_r = func_R1(abs_magr_johnson, mag_range, baraffe.MR, baraffe.TEFF, baraffe.LOGL)
   R2_r = func_R2(R1_r, transit_depth)
   a_r  = func_a(R1_r, transit_dur, transit_period, R2_r)
   M2_r = func_M2(a_r, transit_period, M1_r)
   print, ""

   print, "        I MAGNITUDE"
   print, "Johnson absolute mag=", abs_magi_johnson
   M1_i = func_M1(abs_magi_johnson, mag_range, baraffe.MI, baraffe.M)
   R1_i = func_R1(abs_magi_johnson, mag_range, baraffe.MI, baraffe.TEFF, baraffe.LOGL)
   R2_i = func_R2(R1_i, transit_depth)
   a_i  = func_a(R1_i, transit_dur, transit_period, R2_i)
   M2_i = func_M2(a_i, transit_period, M1_i)
   print, ""

   ;print, "         J MAGNITUDE"
   ;print, "CIT absolute mag=", abs_magJ_cit
   ;M1_J = func_M1(abs_magJ_cit, mag_range, baraffe.MJ, baraffe.M)
   ;print, ""

   ;print, "         H MAGNITUDE"
   ;print, "CIT absolute mag=", abs_magH_cit
   ;M1_H = func_M1(abs_magH_cit, mag_range, baraffe.MH, baraffe.M)
   ;print, ""

   ;print, "         K MAGNITUDE"
   ;print, "CIT absolute mag=", abs_magK_cit
   ;M1_K = func_M1(abs_magK_cit, mag_range, baraffe.MK, baraffe.M)
   ;print, ""

   return
end ;*********************************************************************
```

G Appendix: Baraffe's model BCAH98iso.1, for log(t in year) equal to 8.1 corresponding to the 180 Myrs of M50

m	Teff	g	log L	Mv	Mr	Mi	Mj	Mh	Mk	Ml'	Mm
0.030	1817.	4.756	-3.86	22.77	19.78	16.83	12.15	11.36	11.07	9.84	10.44
0.040	2170.	4.848	-3.52	20.02	17.89	15.19	11.25	10.57	10.23	9.36	9.86
0.050	2434.	4.900	-3.27	18.01	16.34	13.94	10.69	10.05	9.70	9.02	9.41
0.055	2532.	4.919	-3.18	17.30	15.75	13.47	10.49	9.86	9.52	8.89	9.23
0.060	2616.	4.932	-3.10	16.70	15.23	13.07	10.31	9.69	9.35	8.77	9.08
0.070	2748.	4.952	-2.97	15.80	14.44	12.46	10.03	9.42	9.09	8.56	8.82
0.072	2770.	4.954	-2.94	15.65	14.31	12.35	9.98	9.36	9.04	8.52	8.77
0.075	2802.	4.957	-2.91	15.44	14.12	12.20	9.90	9.29	8.97	8.47	8.71
0.080	2844.	4.964	-2.86	15.17	13.88	12.01	9.80	9.20	8.88	8.39	8.62
0.090	2919.	4.972	-2.77	14.67	13.44	11.66	9.61	9.01	8.69	8.24	8.44
0.100	2982.	4.972	-2.69	14.26	13.07	11.37	9.42	8.83	8.52	8.09	8.27
0.110	3030.	4.976	-2.62	13.95	12.79	11.14	9.28	8.68	8.38	7.97	8.14
0.130	3115.	4.971	-2.50	13.40	12.29	10.74	8.99	8.40	8.11	7.72	7.88
0.150	3191.	4.972	-2.40	12.94	11.87	10.40	8.76	8.18	7.89	7.53	7.67
0.175	3251.	4.966	-2.29	12.55	11.51	10.09	8.52	7.94	7.66	7.32	7.45
0.200	3298.	4.955	-2.20	12.21	11.20	9.82	8.30	7.72	7.44	7.12	7.25
0.250	3374.	4.938	-2.04	11.70	10.72	9.39	7.94	7.36	7.10	6.80	6.92
0.300	3429.	4.923	-1.92	11.30	10.34	9.06	7.64	7.07	6.81	6.53	6.66
0.350	3477.	4.902	-1.81	10.95	10.01	8.75	7.38	6.81	6.56	6.29	6.42
0.400	3533.	4.872	-1.69	10.58	9.66	8.44	7.11	6.53	6.29	6.04	6.17
0.450	3602.	4.836	-1.57	10.19	9.29	8.11	6.82	6.25	6.02	5.79	5.92
0.500	3687.	4.789	-1.44	9.75	8.87	7.75	6.51	5.93	5.72	5.52	5.66
0.570	3883.	4.730	-1.23	9.01	8.18	7.19	6.05	5.43	5.27	5.15	5.31
0.600	3962.	4.715	-1.16	8.74	7.93	7.00	5.90	5.27	5.12	5.03	5.19
0.620	4007.	4.705	-1.12	8.58	7.77	6.88	5.80	5.17	5.03	4.95	5.12
0.700	4225.	4.650	-0.92	7.84	7.08	6.34	5.37	4.75	4.65	4.61	4.79
0.750	4423.	4.622	-0.78	7.29	6.56	5.96	5.10	4.51	4.43	4.41	4.58
0.800	4604.	4.589	-0.65	6.81	6.13	5.62	4.84	4.30	4.23	4.21	4.37
0.850	4772.	4.554	-0.53	6.39	5.77	5.30	4.58	4.09	4.03	4.02	4.17
0.900	4952.	4.521	-0.40	5.99	5.43	4.99	4.33	3.89	3.83	3.83	3.96
0.950	5114.	4.490	-0.29	5.64	5.12	4.71	4.10	3.70	3.65	3.65	3.77
1.000	5271.	4.457	-0.18	5.32	4.84	4.45	3.89	3.52	3.48	3.48	3.58
1.050	5426.	4.420	-0.08	5.00	4.55	4.19	3.67	3.33	3.29	3.30	3.39
1.100	5580.	4.385	0.03	4.71	4.29	3.94	3.46	3.15	3.12	3.13	3.21
1.150	5731.	4.352	0.13	4.44	4.04	3.72	3.27	2.99	2.95	2.97	3.04
1.200	5888.	4.325	0.22	4.19	3.82	3.51	3.10	2.84	2.81	2.82	2.89
1.300	6232.	4.285	0.39	3.72	3.40	3.13	2.78	2.57	2.55	2.57	2.61
1.400	6642.	4.275	0.55	3.32	3.05	2.82	2.54	2.38	2.36	2.38	2.41

H Appendix: Colour Magnitude Diagram of the M50 field with M50 main sequence

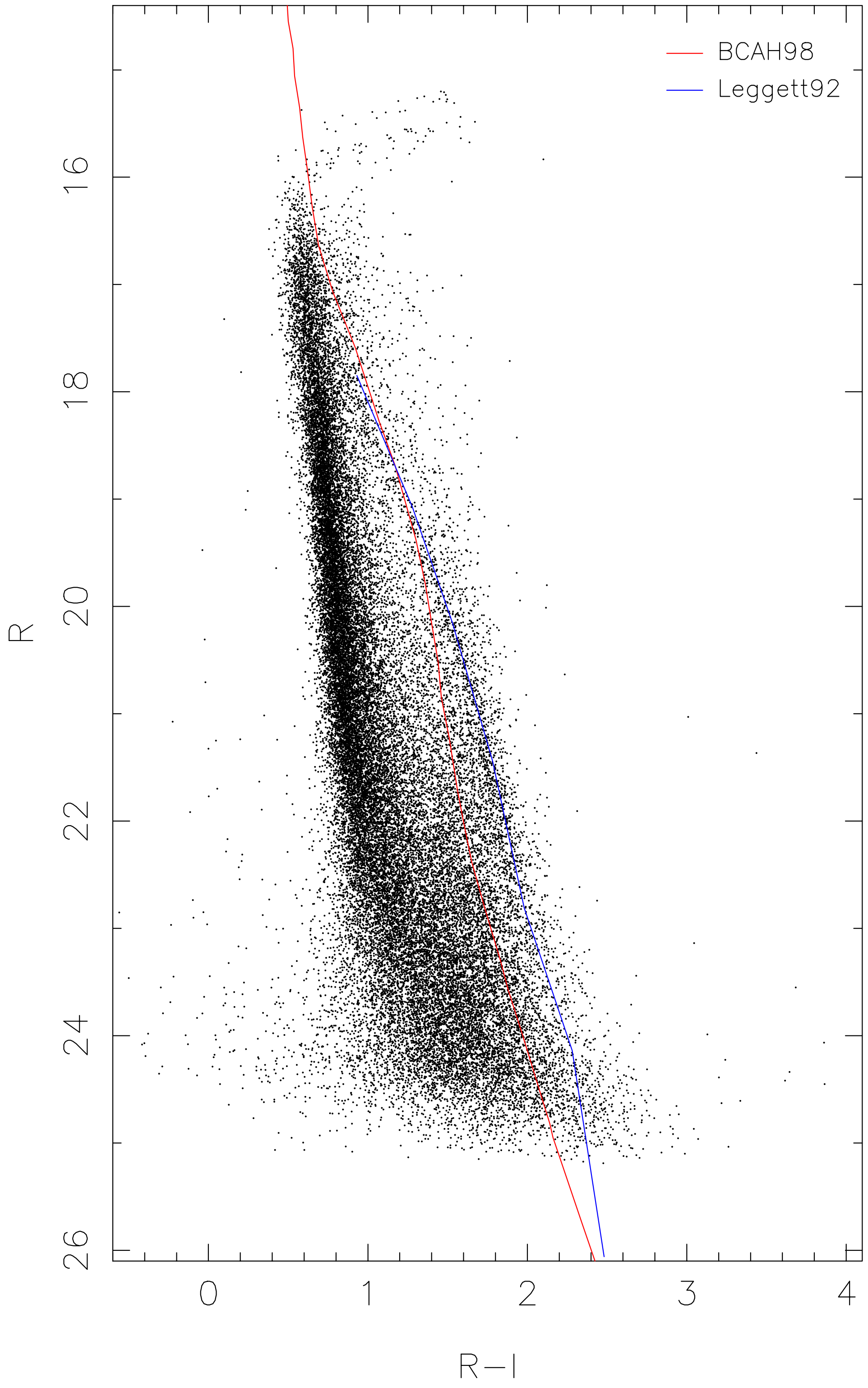
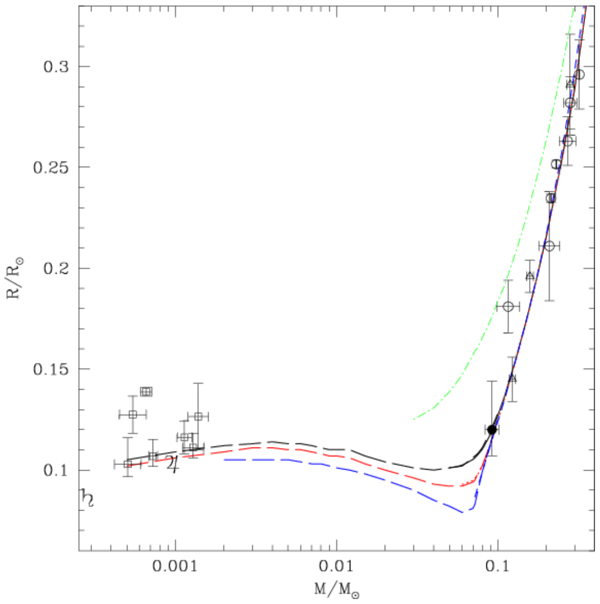


Figure 8: Color Magnitude Diagram of the M50 field, with in red the M50 main sequence calculated from Baraffe's BCHA98 model

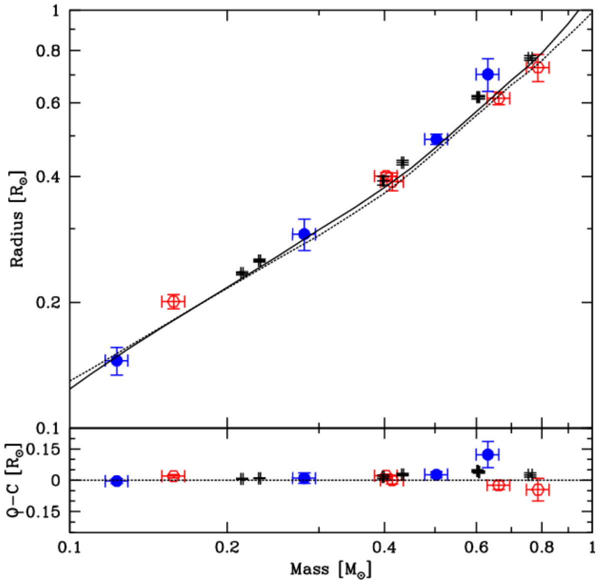
I Appendix: Mass-radius relation, theoritical isochrones

Pont et al., “A planet-sized transiting star around OGLE-TR-122”, **2005**



Mass vs. radius for observed low-mass stars and giant planets and theoretical isochrones. Eclipsing binaries are shown as circles (OGLE-TR-122b in black), interferometric data as open triangles. Baraffe et al. (1998) isochrones for masses from 0.06 $M_\odot$ to 1.4 $M_\odot$ are plotted for 5 Gyr (solid) and 0.1 Gyr (dash-dotted). Dashed lines represent the Baraffe et al. (2003) CON models for masses for 0.5, 1 and 5 Gyr, from top to bottom.

Ségransan et al., “First radius measurements of very low mass stars with the VLTI”, **2003**



Comparison between observational radii masses measurements and the theoretical mass-radius relation. The solid and dashed curves are the 5 Gyr and 0.4-1 Gyr theoretical isochrones of Baraffe et al. (1998), which do not differ much over the present mass range. The filled circles are radius measurements from this paper, the open circles are PTI measurements by Lane et al. (2001), and the dots are masses and radii of three eclipsing binaries (Metcalfe et al. 1996; Torres Ribas 2002; Ribas 2002). The error bars and the residuals from the model are shown at the bottom of the figure.

J Appendix: Baraffe's CB97models, [M/H]=0.0, Y=0.275

M	age(Gyr)	Teff	L	R($10^8 m$)	logTc	log $\rho_c (gr/cm^3)$	Li/Lio	Be/Beo	B/Bo
0.075	0.01	3006.	-2.048	2.449	6.199	1.108	1.00000	1.00000	1.00000
	0.10	2835.	-2.831	1.118	6.459	2.125	0.35600	0.99800	1.00000
	1.00	2211.	-3.695	0.680	6.510	2.789	0.00000	0.03180	1.00000
	10.00	2002.	-3.929	0.634	6.492	2.882	0.00000	0.00000	0.99667
0.080	0.01	3025.	-2.010	2.528	6.215	1.097	1.00000	1.00000	1.00000
	0.10	2876.	-2.780	1.152	6.482	2.117	0.17100	0.99400	1.00000
	1.00	2374.	-3.536	0.708	6.554	2.765	0.00000	0.00120	0.99333
	10.00	2314.	-3.605	0.689	6.552	2.803	0.00000	0.00000	0.91667
0.090	0.01	3059.	-1.939	2.682	6.242	1.076	1.00000	1.00000	1.00000
	0.10	2946.	-2.694	1.213	6.522	2.106	0.02050	0.96100	1.00000
	1.00	2645.	-3.261	0.784	6.617	2.686	0.00000	0.00000	0.90333
	10.00	2642.	-3.265	0.781	6.619	2.691	0.00000	0.00000	0.16200
0.100	0.01	3090.	-1.874	2.833	6.266	1.054	1.00000	1.00000	1.00000
	0.10	3006.	-2.614	1.278	6.555	2.087	0.00180	0.85200	1.00000
	1.00	2811.	-3.070	0.863	6.658	2.607	0.00000	0.00000	0.59333
	10.00	2814.	-3.069	0.863	6.659	2.607	0.00000	0.00000	0.00038
0.110	0.01	3112.	-1.821	2.968	6.288	1.038	1.00000	1.00000	1.00000
	0.10	3051.	-2.550	1.334	6.585	2.075	0.00009	0.61000	1.00000
	1.00	2919.	-2.932	0.939	6.687	2.539	0.00000	0.00000	0.26533
	10.00	2922.	-2.929	0.940	6.688	2.538	0.00000	0.00000	0.00000
0.150	0.01	3186.	-1.636	3.503	6.354	0.964	1.00000	1.00000	1.00000
	0.10	3199.	-2.328	1.567	6.669	2.009	0.00000	0.02640	0.99667
	1.00	3149.	-2.581	1.209	6.759	2.349	0.00000	0.00000	0.00293
	10.00	3153.	-2.577	1.212	6.760	2.346	0.00000	0.00000	0.00000
0.200	0.01	3251.	-1.464	4.101	6.412	0.889	1.00000	1.00000	1.00000
	0.10	3299.	-2.137	1.835	6.738	1.934	0.00000	0.00009	0.91000
	1.00	3290.	-2.316	1.502	6.813	2.196	0.00000	0.00000	0.00000
	10.00	3295.	-2.302	1.523	6.810	2.177	0.00000	0.00000	0.00000
0.300	0.01	3345.	-1.232	5.060	6.498	0.798	0.98700	1.00000	1.00000
	0.10	3424.	-1.873	2.310	6.818	1.831	0.00000	0.00000	0.79333
	1.00	3437.	-1.984	2.016	6.879	1.996	0.00000	0.00000	0.00000
	10.00	3436.	-1.945	2.112	6.863	1.935	0.00000	0.00000	0.00000
0.350	0.01	3396.	-1.138	5.469	6.531	0.766	0.95300	1.00000	1.00000
	0.10	3471.	-1.767	2.540	6.836	1.821	0.00000	0.00000	0.97667
	1.00	3478.	-1.857	2.282	6.897	1.907	0.00000	0.00000	0.00847
	10.00	3475.	-1.822	2.380	6.882	1.850	0.00000	0.00000	0.00000
0.400	0.01	3451.	-1.050	5.863	6.559	0.735	0.87600	1.00000	1.00000
	0.10	3525.	-1.660	2.786	6.853	1.827	0.00000	0.00016	0.99667
	1.00	3522.	-1.727	2.581	6.905	1.852	0.00000	0.00000	0.82667
	10.00	3524.	-1.707	2.640	6.897	1.859	0.00000	0.00000	0.13533
0.500	0.01	3555.	-0.903	6.547	6.608	0.691	0.52200	0.99700	1.00000
	0.10	3658.	-1.429	3.374	6.898	1.875	0.00000	0.30000	1.00000
	1.00	3649.	-1.478	3.205	6.935	1.848	0.00000	0.09220	1.00000
	10.00	3654.	-1.454	3.285	6.930	1.880	0.00000	0.00000	1.00000
0.600	0.01	3645.	-0.785	7.134	6.645	0.668	0.28900	0.99300	1.00000
	0.10	3987.	-1.119	4.058	6.979	1.935	0.00000	0.86400	1.00000
	1.00	3883.	-1.195	3.919	6.969	1.860	0.00000	0.84200	1.00000
	10.00	3914.	-1.156	4.035	6.976	1.921	0.00000	0.70200	1.00000
0.700	0.01	3719.	-0.681	7.721	6.669	0.655	0.38200	0.99600	1.00000
	0.10	4246.	-0.910	4.551	7.027	1.880	0.00205	0.97400	1.00000
	1.00	4209.	-0.909	4.637	7.009	1.876	0.00105	0.97300	1.00000
	10.00	4284.	-0.841	4.841	7.031	1.992	0.00000	0.96800	1.00000
0.800	0.01	4091.	-0.539	7.515	6.729	0.796	0.10400	0.98900	1.00000
	0.10	4647.	-0.647	5.140	7.059	1.876	0.00173	0.97000	1.00000
	1.00	4647.	-0.632	5.235	7.051	1.897	0.00157	0.97000	1.00000
	10.00	4762.	-0.515	5.705	7.097	2.111	0.00085	0.96900	1.00000

K Appendix: Baraffe's COND isochrones for 0.1 and 1 Gyr

Baraffe et al., "Evolutionary models for cool brown dwarfs and extrasolar giant planets. The case of HD 209458", **2003**

The treatment of dust in the atmosphere is described in detail in Allard et al. (2001), with two limiting cases of dust treatment. "DUSTY",takes into account the formation of dust in the equation of state, andits scattering and absorption in the radiative transfer equation.The second case, referred to as "COND", neglects dust opacity in theradiative transfer equation.The COND approach is more appropriate to objects with effective temperatures T_{eff}1300 K, such as methane dwarfs or EGPs at large orbital separation.

Isochrone for 100 Myr

$m/M_\odot$	T_{eff}	$\log L/L_\odot$	$R/R_\odot$	log g	MV	MR	MI	MJ	MH	MK	ML'	MM
0.0005	240.	-7.418	0.114	3.020	41.98	37.51	34.00	28.42	26.59	37.66	19.57	17.64
0.0010	309.	-6.957	0.117	3.300	32.58	28.68	25.89	22.43	22.38	29.11	17.41	15.69
0.0020	425.	-6.383	0.120	3.580	29.69	25.62	22.79	20.05	19.76	23.13	15.94	14.55
0.0030	493.	-6.112	0.121	3.746	28.71	24.48	21.66	18.88	18.57	20.88	15.21	13.93
0.0040	563.	-5.880	0.122	3.869	28.09	23.77	20.95	17.95	17.71	19.35	14.59	13.50
0.0050	630.	-5.686	0.122	3.965	27.65	23.25	20.44	17.23	17.02	18.15	14.06	13.14
0.0060	688.	-5.534	0.121	4.048	27.36	22.92	20.09	16.71	16.51	17.26	13.67	12.83
0.0070	760.	-5.365	0.121	4.117	27.03	22.55	19.74	16.16	16.01	16.38	13.26	12.55
0.0080	816.	-5.246	0.120	4.180	26.77	22.28	19.49	15.76	15.65	15.79	12.97	12.35
0.0090	886.	-5.103	0.120	4.232	26.45	21.96	19.19	15.32	15.23	15.16	12.63	12.13
0.0100	953.	-4.978	0.120	4.279	26.10	21.66	18.92	14.94	14.86	14.69	12.34	11.96
0.0120	1335.	-4.332	0.129	4.297	23.53	19.44	16.79	13.20	12.97	12.76	10.90	11.17
0.0150	1399.	-4.281	0.124	4.424	23.30	19.24	16.46	13.05	12.82	12.65	10.83	11.15
0.0200	1561.	-4.110	0.122	4.569	22.30	18.55	16.08	12.60	12.34	12.17	10.53	10.99
0.0300	1979.	-3.668	0.126	4.715	19.96	16.80	14.48	11.52	11.20	10.90	9.82	10.38
0.0400	2270.	-3.386	0.132	4.797	18.46	15.63	13.31	10.89	10.52	10.19	9.39	9.84
0.0500	2493.	-3.167	0.141	4.837	17.09	14.77	12.53	10.43	10.02	9.71	9.04	9.37
0.0600	2648.	-3.008	0.150	4.863	16.08	14.12	12.01	10.10	9.68	9.37	8.78	9.03
0.0700	2762.	-2.879	0.160	4.874	15.33	13.59	11.60	9.82	9.39	9.10	8.55	8.75
0.0720	2782.	-2.856	0.162	4.875	15.20	13.50	11.53	9.77	9.34	9.05	8.51	8.70
0.0750	2809.	-2.821	0.166	4.875	15.01	13.36	11.42	9.69	9.26	8.97	8.44	8.63
0.0800	2846.	-2.776	0.170	4.880	14.77	13.18	11.29	9.60	9.16	8.87	8.36	8.53
0.0900	2910.	-2.689	0.180	4.884	14.34	12.85	11.03	9.40	8.96	8.68	8.19	8.35
0.1000	2960.	-2.617	0.189	4.887	14.02	12.58	10.82	9.24	8.80	8.52	8.05	8.19

Isochrone for 1 Gyr

$m/M_\odot$	T_{eff}	$\log L/L_\odot$	$R/R_\odot$	log g	MV	MR	MI	MJ	MH	MK	ML'	MM
0.0005	111.	-8.851	0.102	3.115	60.75	55.23	50.50	40.19	35.07	55.87	24.15	21.49
0.0010	160.	-8.185	0.106	3.386	54.15	49.10	44.69	35.58	32.06	49.17	22.40	19.95
0.0020	226.	-7.560	0.109	3.662	44.39	39.91	36.34	29.28	27.80	40.31	20.18	17.94
0.0030	270.	-7.244	0.111	3.827	37.64	33.60	30.73	25.29	24.99	34.51	18.84	16.66
0.0040	304.	-7.031	0.111	3.950	32.62	28.93	26.60	22.49	22.91	30.25	17.91	15.73
0.0050	342.	-6.831	0.110	4.051	31.58	27.79	25.36	21.71	21.98	28.28	17.38	15.36
0.0060	377.	-6.664	0.110	4.134	30.53	26.63	24.12	20.96	21.07	26.39	16.87	15.01
0.0070	403.	-6.556	0.109	4.208	29.77	25.79	23.26	20.41	20.43	25.04	16.54	14.76
0.0080	438.	-6.417	0.108	4.272	29.37	25.31	22.73	19.93	19.89	23.77	16.18	14.50
0.0090	464.	-6.325	0.107	4.331	29.06	24.94	22.33	19.59	19.49	22.85	15.93	14.31
0.0100	491.	-6.235	0.107	4.383	28.74	24.55	21.89	19.23	19.07	21.90	15.65	14.11
0.0120	578.	-5.955	0.106	4.467	28.09	23.75	21.01	18.15	18.03	19.86	14.88	13.60
0.0150	628.	-5.835	0.103	4.587	27.86	23.47	20.72	17.70	17.62	19.05	14.56	13.38
0.0200	766.	-5.514	0.100	4.736	27.31	22.85	20.05	16.56	16.55	17.19	13.72	12.80
0.0300	1009.	-5.071	0.096	4.948	26.40	21.96	19.15	15.10	15.16	15.14	12.67	12.15
0.0400	1271.	-4.696	0.093	5.099	25.19	20.99	18.13	14.04	14.04	13.90	11.88	11.80
0.0500	1543.	-4.374	0.092	5.211	23.73	19.81	17.15	13.21	13.12	13.04	11.25	11.53
0.0600	1801.	-4.106	0.092	5.291	22.13	18.59	16.10	12.56	12.36	12.27	10.77	11.26
0.0700	2082.	-3.829	0.094	5.333	20.44	17.31	14.87	11.93	11.62	11.43	10.32	10.85
0.0720	2140.	-3.772	0.095	5.336	20.12	17.05	14.61	11.80	11.48	11.27	10.23	10.75
0.0750	2234.	-3.679	0.098	5.334	19.59	16.63	14.21	11.60	11.25	11.02	10.08	10.58
0.0800	2383.	-3.527	0.102	5.323	18.67	15.96	13.61	11.26	10.89	10.63	9.84	10.27
0.0900	2627.	-3.268	0.113	5.285	16.98	14.86	12.67	10.72	10.30	10.03	9.40	9.72
0.1000	2784.	-3.083	0.125	5.246	15.86	14.09	12.09	10.33	9.89	9.62	9.07	9.31

Notes on both tables: T_{eff} is in K, the gravity g in cgs. The VRI magnitudes are in the Johnson-Cousins system (Bessell 1990), JHK in the CIT system (Leggett 1992), L' in the Johnson-Glass system and M in the Johnson system.

L Appendix: Light curves of the 9 M50 member candidates

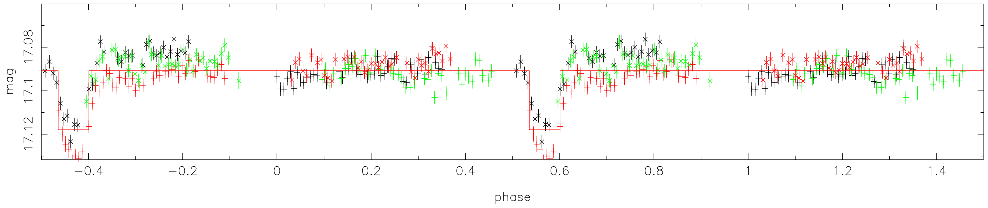


Figure 9: i phase folded light curve of star **3782 in CCD 1**.
σ_i=0.0061, t_{dur}=0.042, period=0.645, t_{depth}=0.03636, SNR=34.2

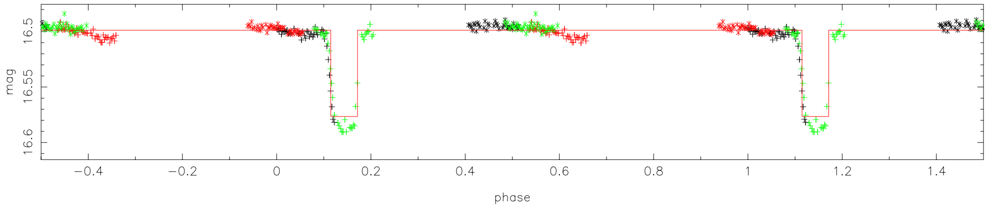


Figure 10: i phase folded light curve of star **3089 in CCD 2**.
σ_i=0.0047, t_{dur}=0.105, period=1.850, t_{depth}=0.09286, SNR=132.9

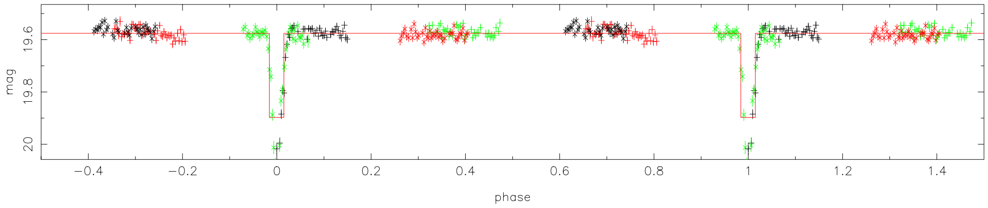


Figure 11: i phase folded light curve of star **3031 in CCD 4**.
σ_i=0.0221, t_{dur}=0.047, period=1.513, t_{depth}=0.46154, SNR=50.5

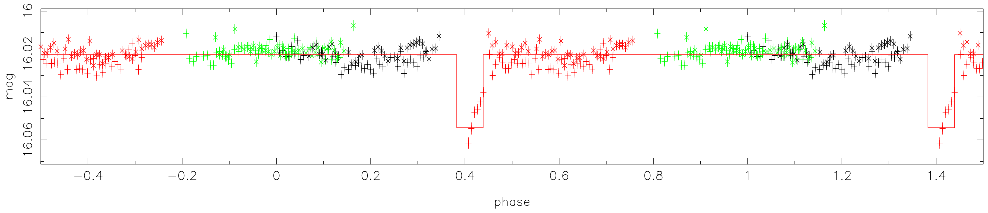


Figure 12: i phase folded light curve of star **241 in CCD 5**.
σ_i=0.0043, t_{dur}=?, period=?, t_{depth}¿0.04364, SNR=39.6

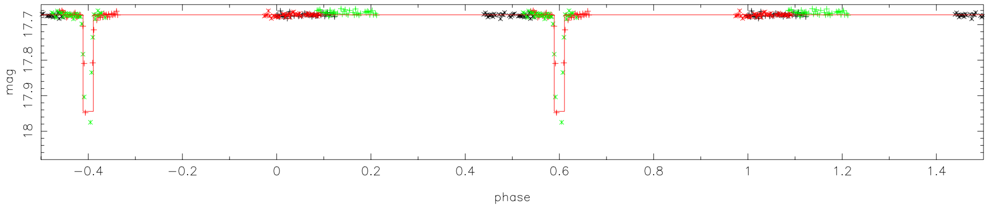


Figure 13: i phase folded light curve of star **2068 in CCD 8**.
σ_i=0.0058, t_{dur}=0.040, period=1.839, t_{depth}=0.31111, SNR=166.1

Objects we don't believe to have a real transit because they have too long transit duration in comparaison with their period (more like spotty star). But as we are not sure, we still keep them as lower priority objects.

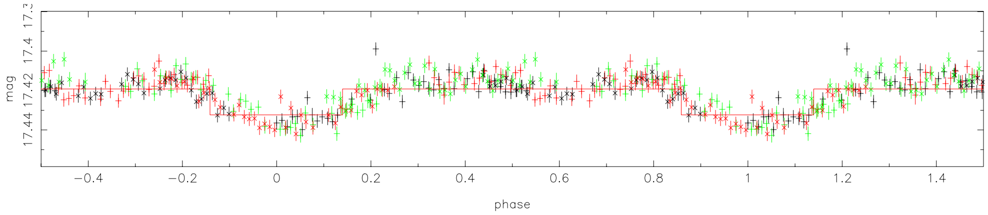


Figure 14: i phase folded light curve of star **3889 in CCD 2**.
σ_i=0.0079, t_{dur}=0.120, period=1.427, t_{depth}=0.02400, SNR=29.2

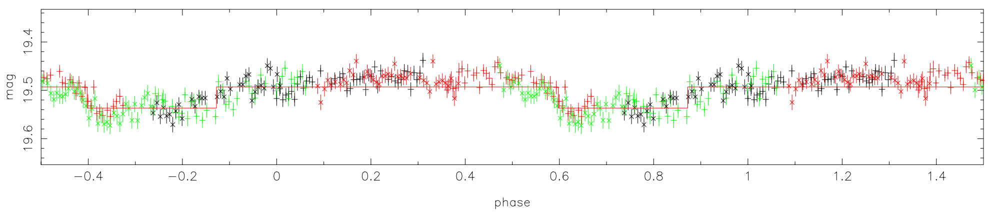


Figure 15: i phase folded light curve of star **6131 in CCD 3**.
σ_i=0.0322, t_{dur}=0.200, period=0.728, t_{depth}=0.03932, SNR=22.4

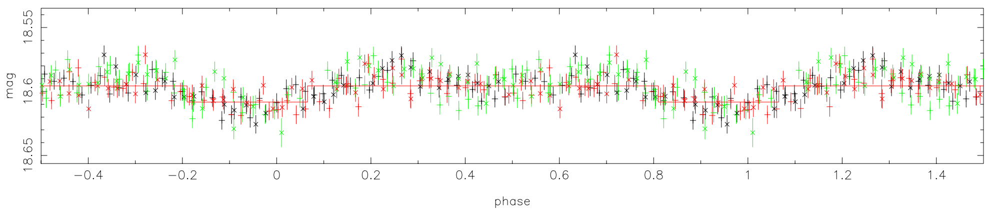


Figure 16: i phase folded light curve of star **1532 in CCD 4**.
σ_i=0.0122, t_{dur}=0.060, period=1.235, t_{depth}=0.02727, SNR=13.5

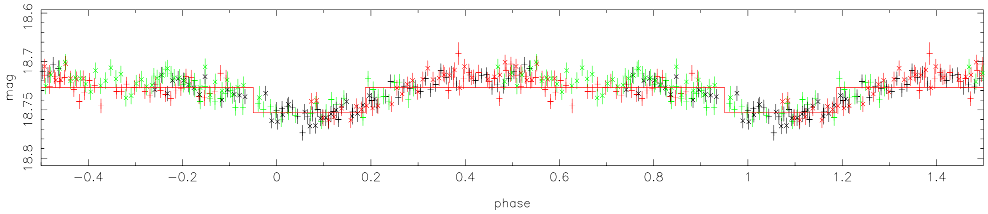


Figure 17: i phase folded light curve of star **1847 in CCD 7**.
σ_i=0.0161, t_{dur}=0.100, period=0.421, t_{depth}=0.02800, SNR=23.0