The Search for Transiting Extrasolar Planets in the Open Cluster M52

Tiffany M. Borders
San Diego State University
Master of Science in Astronomy
Thesis Defense
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Advisor: Eric Sandquist

Image Credit: Lynette Cook
Overview

I. Introduction
   - Transit Technique/Extrasolar Planets
   - Open Cluster M52

II. Observations

III. Data Reduction/Analysis
   - ISIS
   - BLS

IV. Results
   - Variable stars
   - Planets?

V. Summary/Conclusions
Known Extrasolar Planets

- 294 extrasolar planets detected
  (see http://exoplanet.eu/ for an updated list)
- 51 transiting planets
Transits

• Assuming
  - The whole planet passes in front of the star
  - And ignoring limb darkening as negligible
• Then the depth of the eclipse is simply the ratio of the planetary and stellar disk areas:
  - i.e. \( \Delta f / f_* = \pi R_p^2 / \pi R_*^2 = (R_p / R_*)^2 \)
• If \( R_* \) can be estimated then \( R_p \) can be deduced
• For an edge-on orbit, transit duration is given by:
  \( \Delta t = (PR_*) / (\pi a) \)
  Where \( P = \) period in days, \( a = \) semi-major axis of orbit
Transits

• Probability of transit (for random orbit)

\[ P_{\text{transit}} = \frac{R_*}{a} \]

- For Earth (P=1yr, a=1AU), \( P_{\text{transit}} = 0.5\% \)
- But for close, “hot” Jupiters (P = 4 days, a=0.05 AU), \( P_{\text{transit}} = 10\% \)
- Of course, relative probability of detecting Earths is lower since would have to observe for up to 1 year
Transits

• **Advantages**
  – Easy. Can be done with small, cheap telescopes
  – Great scientific potential

• **Disadvantages**
  – Probability of seeing a transit is low
    - Accuracy to at least 1% in flux (0.01 mag) for the detection of a giant planet
  – Need to observe many stars simultaneously
  – Easy to confuse with starspots, binary/triple systems
  – Need radial velocity measurements for confirmation, masses
Of the 1330 stars surveyed:

- >7% of stars have giant planets within 5 AU (most beyond 1 AU)
- 1.2% of FGK stars have hot Jupiters (a < 0.1 AU) (Marcy et al. 2005)
Probability of Finding a Transit of a Hot Jupiter?

- Consider
  - Frequency of hot Jupiters around surveyed stars
  - Likelihood of geometric alignment
  - Binary fraction

- Von Braun et al. 2005 estimates
  - 0.7% planet frequency around isolated stars with $a \sim 0.05$ (Marcy et al. 2005)
  - 10% - 20% of those hot Jupiters have favorable orientation
  - Binary fraction of 50% is assumed

1 star in 3000 ($a \sim 0.05$ AU) has a transiting hot Jupiter around a main-sequence star
Planet-Metallicity Correlation

- \(~25\%\) of stars with twice the metal content of the Sun are orbited by a giant planet, 5\% for solar metallicity (Fischer & Valenti 2005)
- Metallicity plays a critical role in formation and/or evolution of planets

$$P_{(planet)} = 0.03 \times \left( \frac{N_{Fe}/N_H}{N_{Fe}/N_H\odot} \right)^2$$

Fischer & Valenti 2005
Why Search for Transits in Open Clusters?

- Relatively large number of stars of same age, metallicity, and distance
- Less crowded than globular clusters and offer an range of metallicities
- No yet confirmed planet detection
- Variable stars
M52

- $\alpha = 23^h24^m42^s$, $\delta = 61^\circ35.42''$
- Distance: $1.4 \pm 0.2$ kpc (Bonatto & Bica 2006)
- Close to solar metallicity?
- Age: $60 \pm 10$ Myr (Bonatto & Bica 2006)
- $7.9 \pm 0.2$ kpc from the Galactic center (Bonatto & Bica 2006)
- $l = +112.81^\circ$, $b = 44^\circ$
## R Band Observations

<table>
<thead>
<tr>
<th>Date</th>
<th>Heliocentric Julian Day</th>
<th>Duration (hr)</th>
<th>Seeing (&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 Aug 24</td>
<td>2452146.0</td>
<td>4.94</td>
<td>3.08 ± 0.58</td>
</tr>
<tr>
<td>2001 Aug 25</td>
<td>2452147.0</td>
<td>5.07</td>
<td>2.73 ± 0.26</td>
</tr>
<tr>
<td>2001 Aug 26</td>
<td>2452148.0</td>
<td>4.88</td>
<td>2.92 ± 0.27</td>
</tr>
<tr>
<td>2001 Sept 17</td>
<td>2452170.0</td>
<td>6.53</td>
<td>2.73 ± 0.26</td>
</tr>
<tr>
<td>2001 Sept 18</td>
<td>2452171.0</td>
<td>6.02</td>
<td>2.71 ± 0.15</td>
</tr>
<tr>
<td>2001 Sept 19</td>
<td>2452172.0</td>
<td>6.52</td>
<td>2.70 ± 0.16</td>
</tr>
<tr>
<td>2001 Sept 20</td>
<td>2452173.0</td>
<td>6.52</td>
<td>2.76 ± 0.18</td>
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<tr>
<td>2001 Oct 13</td>
<td>2452196.0</td>
<td>5.52</td>
<td>2.72 ± 0.22</td>
</tr>
<tr>
<td>2001 Oct 14</td>
<td>2452197.0</td>
<td>5.73</td>
<td>2.82 ± 0.19</td>
</tr>
<tr>
<td>2001 Oct 15</td>
<td>2452198.0</td>
<td>5.16</td>
<td>2.89 ± 0.28</td>
</tr>
<tr>
<td>2001 Oct 16</td>
<td>2452199.0</td>
<td>5.91</td>
<td>2.84 ± 0.20</td>
</tr>
<tr>
<td>2001 Nov 14</td>
<td>2452227.0</td>
<td>3.15</td>
<td>3.18 ± 0.43</td>
</tr>
<tr>
<td>2001 Nov 15</td>
<td>2452228.0</td>
<td>0.29</td>
<td>2.67 ± 0.19</td>
</tr>
<tr>
<td>2001 Nov 16</td>
<td>2452229.0</td>
<td>3.12</td>
<td>2.91 ± 0.33</td>
</tr>
<tr>
<td>2007 Dec 06</td>
<td>2454444.0</td>
<td>1.13</td>
<td>2.51 ± 0.29</td>
</tr>
</tbody>
</table>
## V Band Observations

<table>
<thead>
<tr>
<th>Date</th>
<th>Heliocentric Julian Day</th>
<th>Duration (hr)</th>
<th>Seeing (&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 Aug 25</td>
<td>2452147.0</td>
<td>0.24</td>
<td>2.73 ± 0.26</td>
</tr>
<tr>
<td>2001 Aug 26</td>
<td>2452148.0</td>
<td>0.20</td>
<td>2.92 ± 0.27</td>
</tr>
<tr>
<td>2001 Sept 17</td>
<td>2452170.0</td>
<td>0.18</td>
<td>2.43 ± 0.02</td>
</tr>
<tr>
<td>2001 Sept 19</td>
<td>2452172.0</td>
<td>0.42</td>
<td>2.70 ± 0.16</td>
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<tr>
<td>2001 Sept 20</td>
<td>2452173.0</td>
<td>0.83</td>
<td>2.76 ± 0.18</td>
</tr>
<tr>
<td>2001 Oct 13</td>
<td>2452196.0</td>
<td>0.39</td>
<td>2.72 ± 0.22</td>
</tr>
<tr>
<td>2001 Oct 14</td>
<td>2452197.0</td>
<td>0.42</td>
<td>2.82 ± 0.19</td>
</tr>
<tr>
<td>2001 Oct 15</td>
<td>2452198.0</td>
<td>0.14</td>
<td>2.89 ± 0.28</td>
</tr>
</tbody>
</table>
CMD of M52

CMD with overlaid theoretical isochrones from Cassisi et al. 2006.
Data Reduction

- Overscan correction and trimming
- Bias removal
- Flat fielding
- Correcting bad pixels
- Header corrections
Data Reduction

• Image Rejection
  – Bad seeing, bad tracking, bright satellite or meteor tracks
  – 746 images taken but only 423 were used
  – 165 images from September were analyzed separately
ISIS

- Image subtraction method of Alard & Lupton (1998) available in ISIS 2.1
- 6 Steps:
  - Transform all frames to a common grid
  - Construction of a reference image
  - Subtraction of each frame from reference image
  - Construction of median image of all subtracted images
  - Selection of stars to be photometered
  - Extraction of profile photometry from the subtracted images
# ISIS Parameters

## Table 4.1. ISIS Process Configuration File

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM_DIR</td>
<td>../images</td>
<td>Directory where the images are stored</td>
</tr>
<tr>
<td>MRJ_DIR</td>
<td>..</td>
<td>Installation directory</td>
</tr>
<tr>
<td>REFERENCE</td>
<td>a2m5213brzf.fits</td>
<td>Reference image for astrometry</td>
</tr>
<tr>
<td>REF_SUB</td>
<td>ref.fits</td>
<td>Reference image for subtraction</td>
</tr>
<tr>
<td>INFIL</td>
<td>../register/dates</td>
<td>Dates of the frames</td>
</tr>
<tr>
<td>VARIABLES</td>
<td>phot.data</td>
<td>Coordinates of objects to make light curves</td>
</tr>
<tr>
<td>DEGREE</td>
<td>2</td>
<td>Degree of the polynomial astrometric transform</td>
</tr>
<tr>
<td></td>
<td></td>
<td>between frames</td>
</tr>
<tr>
<td>CONFIG_DIR</td>
<td>../register2</td>
<td>Where to find the configuration files</td>
</tr>
<tr>
<td>SIG_THRESH</td>
<td>3.0</td>
<td>Threshold for variable detection in var.fits</td>
</tr>
<tr>
<td>COSMIC_THRESH</td>
<td>3</td>
<td>Parameter for cosmic ray rejection</td>
</tr>
<tr>
<td>REF_STACK</td>
<td>interp.a2m5213brzf.fits</td>
<td>Image for subtraction (only for _sub image)</td>
</tr>
<tr>
<td>N_REJECT</td>
<td>2</td>
<td>If Nth brightest value in series too large, reject it</td>
</tr>
<tr>
<td>MESH_SMOOTH</td>
<td>3</td>
<td>Size of smoothing mesh for var.fits</td>
</tr>
</tbody>
</table>

## Table 4.2. ISIS Default Configuration File

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>nstamps x</td>
<td>15</td>
<td>Number of stamps along X axis</td>
</tr>
<tr>
<td>nstamps y</td>
<td>15</td>
<td>Number of stamps along Y axis</td>
</tr>
<tr>
<td>sub x</td>
<td>1</td>
<td>Number of sub division of the image along X axis</td>
</tr>
<tr>
<td>sub y</td>
<td>1</td>
<td>Number of sub division of the image along Y axis</td>
</tr>
<tr>
<td>half.mesh.size</td>
<td>12</td>
<td>Half kernel size</td>
</tr>
<tr>
<td>half.stamp.size</td>
<td>15</td>
<td>Half stamp size</td>
</tr>
<tr>
<td>deg.bg</td>
<td>3</td>
<td>Degree to fit differential background variations</td>
</tr>
<tr>
<td>saturation</td>
<td>45000</td>
<td>Saturation value for eliminating pixels</td>
</tr>
<tr>
<td>pix.min</td>
<td>7</td>
<td>Minimum value for the pixels to fit</td>
</tr>
<tr>
<td>min.stamp.center</td>
<td>100</td>
<td>Minimum value for objects to enter kernel fit</td>
</tr>
<tr>
<td>ngauss</td>
<td>3</td>
<td>Number of Gaussians</td>
</tr>
<tr>
<td>deg.gauss1</td>
<td>8</td>
<td>Degree associated with 1st Gaussian</td>
</tr>
<tr>
<td>deg.gauss2</td>
<td>6</td>
<td>Degree associated with 2nd Gaussian</td>
</tr>
<tr>
<td>deg.gauss3</td>
<td>4</td>
<td>Degree associated with 3rd Gaussian</td>
</tr>
<tr>
<td>sigma.gauss1</td>
<td>0.8</td>
<td>Sigma of 1st Gaussian</td>
</tr>
<tr>
<td>sigma.gauss2</td>
<td>1.67</td>
<td>Sigma of 2nd Gaussian</td>
</tr>
<tr>
<td>sigma.gauss3</td>
<td>4</td>
<td>Sigma of 3rd Gaussian</td>
</tr>
<tr>
<td>deg.spatial</td>
<td>3</td>
<td>Degree of the fit of the spatial variations</td>
</tr>
</tbody>
</table>

## Table 4.3. ISIS Phot Configuration File

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>sub_x</td>
<td>1</td>
<td>Number of sub division of the image along X axis</td>
</tr>
<tr>
<td>sub_y</td>
<td>1</td>
<td>Number of sub division of the image along Y axis</td>
</tr>
<tr>
<td>rad1.bg.size</td>
<td>15</td>
<td>Inner radius of annulus for background</td>
</tr>
<tr>
<td>rad2.bg.size</td>
<td>20</td>
<td>Outer radius</td>
</tr>
<tr>
<td>nstars</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>mesh</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>saturation</td>
<td>45000</td>
<td>Saturation value for eliminating pixels</td>
</tr>
<tr>
<td>min</td>
<td>7</td>
<td>Minimum value for the pixels to fit</td>
</tr>
<tr>
<td>psf.width</td>
<td>100</td>
<td>Minimum value for objects to enter kernel fit</td>
</tr>
<tr>
<td>ngauss</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>radphot</td>
<td>5</td>
<td>Radius of circle within the pixels will be fitted to estimate flux</td>
</tr>
<tr>
<td>nstars.max</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>nb.adu.e</td>
<td>0.5</td>
<td>Gain in units of ADU/electrons</td>
</tr>
<tr>
<td>rmax</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>first</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>keep</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
Step 1

- Image registration and interpolation

“Template” Image

Interp_Image
Step 2

- Build a composite reference frame to transform all images to the same seeing and background level

\textit{ref.fits}
Step 3

- Subtraction of each frame from reference image
Step 3

According to Alard & Lupton (1998) the kernel satisfies the following equation with x and y as coordinates:

\[
Reference(x, y) \otimes Kernel(u, v) = I(x, y)
\]

\[
Kernel(u, v) = \sum_i a_i B_i(u, v)
\]

- The \(a_i\) term is the contribution of the different basis functions describing the kernel(u,v)
- \(B_i\) are the basis functions used to model the seeing differences with the form:

\[
B(u, v) = e^{-\frac{(u^2+v^2)}{2\sigma_n^2}} u^{d_n x} v^{d_n y}
\]
ISIS

• Step 4
  – Construction of median image of all subtracted images

var.fits
ISIS

• Step 5
  – Selection of stars to be photometered

• Step 6
  – Extraction of profile photometry from subtracted images
Flux to Magnitude Conversion

- Using the method described by Mochejska et al. (2003)

\[ c_i = c_{tpl} + \Delta c_{tpl} - \Delta c_i \]

\[ m_i = 2.5 \times \log \left( 10^{m_o-m_{tpl}/2.5} + \Delta c_{tpl} - \Delta c_i \right) + m_o \]

\[ \sigma_i^m = 2.5 \times \log \left( \frac{c_i}{c_i + \sigma_i^c} \right) \]
Variability

• 22 variable stars (19 newly discovered)
  – 10 eclipsing-type W Ursa Majoris contact binaries
  – 5 detached binaries of Algol type
  – 1 slowly pulsating B star
  – 6 irregular/unclassified
Variability
Light Curves

Figure 6.12. Light curve of ID 1834. Major time-axis tick marks are spaced by 2.4 hours. The time-axis is defined as the Heliocentric Julian Date (HJD(1)) subtracted from the Heliocentric Julian Date of the first observation (HJD(1)) taken on August 24th.

Figure 6.21. Light curve of ID 4109. Major time-axis tick marks are spaced by 2.4 hours. The time-axis is defined as the Heliocentric Julian Date (HJD(1)) subtracted from the Heliocentric Julian Date of the first observation (HJD(1)) taken on August 24th.
Period Determination

• Lomb-Scargle
  – Fitting of sine and cosine terms of various frequencies that correspond to possible periodicities

• Lafler-Kinnman
  – For time series data folded on the correct period there will be a minimization of brightness differences between observations of adjacent phases

Figure 6.4. ID 0533 Lomb-Scargle period analysis. The peak of maximum power corresponds to a $P = 0.607$ days.

Figure 6.5. ID 0533 Lafler-Kinman period analysis. Two of the lower $r$ values corresponds to a period $P = 0.607$ days and $P = 1.214$ days.
W UMa Variables
Detached Eclipsing Variables
Cluster Membership
BLS Theory

• Searches over a range of periods & transit phases to find the greatest likelihood of a transit

• BLS returns:
  • Period
  • Depth
  • Fractional transit length
  • Bin index at the beginning and end of the transit

Kovacs et al. 2002
BLS Theory

- BLS searches for the non-sinusoidal periodic signal by minimizing the following equation:

$$D = \sum_{i=1}^{i_1-1} w_i(x_i - H)^2 + \sum_{i=i_2+1}^{n} w_i(x_i - H)^2 + \sum_{i=i_1}^{i_2} w_i(x_i - L)^2$$

Where,

$$L = \frac{s}{r}$$

$$H = -\frac{s}{1 - r}$$

$$r = \sum_{i=i_1}^{i_2} w_i$$

$$s = \sum_{i=i_1}^{i_2} w_i x_i$$

Minimization equation reduces to:

$$D = \sum_{i=1}^{n} w_i x_i^2 - \frac{s^2}{r(1-r)}$$
BLS Theory

• Kovacs defines the SR as:

\[ SR = \text{MAX} \left\{ \frac{s^2(i_1, i_2)}{r(i_1, i_2)(1 - r(i_1, i_2))} \right\}^{\frac{1}{2}} \]

SR global max corresponds to the period yielding the highest probability of an observed transit

• The SDE is defined as:

\[ SDE = \frac{SR_{\text{peak}} - \langle SR \rangle}{sd(SR)} \]

“Significance” of the peak to help determine the likelihood of a planetary transit

• The SNR(\(\alpha\)) is defined as:

\[ \alpha = \frac{\delta}{\sigma \sqrt{nq}}, \]

Used as a measure of the detectability of the transit

Kovacs et al. 2002
BLS Implementation

Top panel shows the RMS of the 4128 stars which appear on our *var.fits*. The middle panel shows the RMS of the 3935 stars remaining after filters have been applied. The bottom panel shows the 1238 stars remaining which are suitable for BLS study after filters were applied including RMS < 0.015 mag cutoff.
BLS Transit Selection Criteria

• SDE > 4
• $\alpha > 9$
• Periods between 1.05 - 10 days
• Transit depth < 0.08 mag
• Transit must be in > 1 transit phase bin
• Two discrete levels in their binned phased plots
• Points in transit are from more than 1 night
BLS Results

- 21 planetary candidates that required further investigation
- 4 planetary candidates with box shaped light curves characteristic of a planetary transit and have points in transit from multiple nights

**Table 5.3. BLS Final Results**

<table>
<thead>
<tr>
<th>Star ID</th>
<th>Coords. (x, y)</th>
<th>SDE</th>
<th>SR(α)</th>
<th>Period(days)</th>
<th>N_t</th>
<th>Depth</th>
<th>Qtran</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>994,781</td>
<td>6.269</td>
<td>11.524</td>
<td>1.0972</td>
<td>16</td>
<td>-0.013</td>
<td>0.0378</td>
<td>0.005</td>
</tr>
<tr>
<td>2563</td>
<td>1524, 997</td>
<td>5.295</td>
<td>10.308</td>
<td>1.5096</td>
<td>13</td>
<td>-0.024</td>
<td>0.0307</td>
<td>0.009</td>
</tr>
<tr>
<td>1347</td>
<td>1344,566</td>
<td>5.236</td>
<td>19.141</td>
<td>1.4552</td>
<td>13</td>
<td>-0.025</td>
<td>0.0307</td>
<td>0.005</td>
</tr>
<tr>
<td>1267</td>
<td>1806,535</td>
<td>5.149</td>
<td>16.867</td>
<td>1.3598</td>
<td>10</td>
<td>-0.060</td>
<td>0.0236</td>
<td>0.1</td>
</tr>
</tbody>
</table>
BLS Results

Binned phase plot for candidate ID 1347
BLS Results

Phase vs. unbinned delta magnitude of the points in transit for candidate ID 1347
BLS Results

Normalized signal residue vs. trial frequency for candidate ID 1347. The SR peak corresponds to a period of 1.4552 days.
Open clusters provide an ideal environment for finding transits

Obtained lightcurves for 4,128 stars using ISIS

Using BLS no planetary transits were apparent

22 variables stars were discovered

CMD helped determine possible cluster membership

W UMa in cluster? Need radial velocity follow up observations

Exciting future for transiting extrasolar planets…
Contact ?
References

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• Cassisi, S., et al. 2006 Meorie della Societa Astronomica Italiana, 77,71
• Fischer, D.A & Valenti, J. 2005, APJ, 622,1102
• Mochejska,et al. 2005, APJ, 129,2856
• Udry, S. & Santos, N.C. 2007, ARAA,45,397