
Available from: [http://dx.doi.org/10.1111/j.1365-2966.2005.09104.x](http://dx.doi.org/10.1111/j.1365-2966.2005.09104.x)

Copyright © 2005 Royal Astronomical Society.

This is the author’s version of the work, posted here with the permission of the publisher for your personal use. No further distribution is permitted. You may also be able to access the published version from your library. The definitive version is available at [www.interscience.wiley.com](http://www.interscience.wiley.com).
A Dearth of Planetary Transits in the direction of NGC 6940

Ben Hood\textsuperscript{1}, Andrew Collier Cameron\textsuperscript{1}, Stephen R. Kane\textsuperscript{1}, D.M. Bramich\textsuperscript{1,3}, Keith Horne\textsuperscript{1}, Rachel A. Street\textsuperscript{2}, I. A. Bond\textsuperscript{4}, A. J. Penny\textsuperscript{5}, Y. Tsapras\textsuperscript{6}, A. Quirrenbach\textsuperscript{6}, N. Safizadeh\textsuperscript{7}, D. Mitchell\textsuperscript{7}, J. Cooke\textsuperscript{7}

\textsuperscript{1}School of Physics \& Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS, Scotland
\textsuperscript{2}APS Division, Department of Pure and Applied Physics, Queen's University, Belfast, University Road, Belfast, BT7 1NN, Northern Ireland
\textsuperscript{3}Instituto de Astrofisica de Canarias, C/ Via Lactea s/n, E-38200, La Laguna, Tenerife, Spain
\textsuperscript{4}Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK
\textsuperscript{5}SETI Institute, USA
\textsuperscript{6}School of Mathematical Sciences, Queen Mary University of London, Mile End Road, London, E1 4NS, UK
\textsuperscript{7}Center for Astrophysics \& Space Sciences (CASS), University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92037-0424, USA

ABSTRACT

We present results of our survey for planetary transits in the field of NGC 6940. We think nearly all of our observed stars are field stars. We have obtained high precision ($\sim$3-10 millimags at the bright end) photometric observations of $\sim$50,000 stars spanning 18 nights in an attempt to identify low amplitude and short period transit events. We have used a matched filter analysis to identify 14 stars that show multiple events, and four stars that show single transits. Of these 18 candidates, we have identified two that should be further researched. However, none of the candidates are convincing hot Jupiters.

Key words: methods: data analysis – stars: variables – open clusters and associations: individual (NGC 6940) – planetary systems

1 INTRODUCTION

Charbonneau et al. (2000) opened a new chapter in the science of extrasolar planets when they recorded the first transit of a planet around its parent star. The transit produced a 1.5% dip in the star's light. Until then, the only evidence of planets around main sequence stars had been radial velocity measurements of stellar reflex motions. Though the RV method has been the most successful method of finding planets heretofore, the transit method of searching for planets is complementary, because it provides different information than RV. Measuring a transiting planet can provide the actual mass of the planet by determining the orbital inclination of the system and provide the radius of the planet. Also, in some situations, transiting planets can be probed for atmospheric spectra, as with HD 209458 (Brown et al. 2001). Finally, the transit method can find planets to kiloparsec distances, much farther than RV.

However, the strength of the transiting method of discovery, that it shows us the orbital inclination, is also its weakness, because that orbital inclination must be close to 90 degrees for us to see the transit. Radial velocity measurements have shown that approximately 1-2\% of Sun-like stars in the solar neighborhood have hot Jupiters, giant planets with orbital distances of 0.035-0.4 AU (Lineweaver \& Grether 2003). Assuming that orbital inclinations are random, approximately 10\% of stars with hot Jupiters should have transits visible to us. Therefore, approximately one of a thousand Sun-like stars should show an eclipse, if the stars we observe have the same planetary abundance as the solar neighborhood.

Janes (1996) suggested that open clusters would be good fields in which to look for planetary transits. Open clusters contain hundreds of stars of a similar distance and metallicity. The field is crowded enough to be able to observe a sufficient number of stars, but not crowded enough to make reduction exceptionally difficult. The high number of stars is essential, since perhaps only one in a thousand stars will exhibit the characteristic dip (a shallow flat-bottomed eclipse) of a planet transiting the parent star. Unfortunately, though this is the reason we observed in the direction of NGC 6940, we don't think we have observed any significant number of
Table 1. Parameters of open cluster NGC 6940

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (J2000.0)</td>
<td>20 34 26</td>
</tr>
<tr>
<td>Dec(J2000.0)</td>
<td>+28 17 00</td>
</tr>
<tr>
<td>l</td>
<td>69.90</td>
</tr>
<tr>
<td>b</td>
<td>-7.17</td>
</tr>
<tr>
<td>Distance(pc)</td>
<td>770</td>
</tr>
<tr>
<td>Distance modulus (mag)</td>
<td>10.10</td>
</tr>
<tr>
<td>Age(log 10)</td>
<td>8.858</td>
</tr>
<tr>
<td>Age(Gyr)</td>
<td>0.72</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>+0.01</td>
</tr>
<tr>
<td>E(B-V)</td>
<td>0.214</td>
</tr>
</tbody>
</table>

We present results from a deep search for planetary transits in the field of NGC 6940. We describe the observation and data reduction methods used in order to extract light curves for each of these stars. We show that using these methods we can achieve the accuracy necessary to detect planetary transits of a Jupiter-radius object. We describe our transit finding algorithm and show with simulations that we can recover injected transits using that algorithm. Finally, we describe several transit candidates: 14 stars that show multiple low amplitude short duration events and four stars that show single events. We have rejected all but two as poor transit candidates, and recommend them for further study.

2 OBSERVATIONS AND REDUCTION

2.1 Observation

Observations were taken over June and July of 1999 using the 2.5 metre Isaac Newton Telescope at La Palma, Canary Islands. Usable observations were taken on 18 nights between 22-30 June and 22-31 July. Images were taken with the Wide Field Camera, a mosaic consisting of four 2048 x 4096 pixel E2V CCDs, mounted at the prime focus of the INT. The mosaic created a 0.29 square degree field of view with 0.33 arcsec per pixel (see Fig. 1).

Three open clusters were observed in rotation during the observing run, NGC 6819 (Street et al. 2003), NGC 6940, and NGC 7789 (Bramich et al. 2004). This paper reports on the analysis of NGC 6940 (see Table 1) observations. Each image was exposed for 300 seconds, taken in pairs to help remove/identify cosmic rays. This resulted in approximately 2 observations per hour per cluster. We obtained 251, 278, 267 and 249 usable frames of NGC 6940 for each of the four CCDs, respectively. The observing routine was designed to maximize the number of stars observed, in order to maximize the possibility of a transit detection. The 300 second exposure setting was mainly in order to capture enough cluster member stars of NGC 6819 and NGC 7789, which are 1900 and 2400 parsecs distant, respectively. This setting has caused some minor problems with the observation of NGC 6940, discussed below in the section on colours. In retrospect, a shorter exposure time would have been better for NGC 6940, to avoid saturating cluster stars at 770 pc.

2.2 Data Reduction

After standard CCD processing, the individual science frames were reduced with differential image analysis, based on code developed by Bond et al. (2001). The process is described in more detail by Bramich (Bramich et al. 2004) and summarized here.

We used an automated script and IRAF tools to build a 3-sigma clipped mean masterbias and 3-sigma clipped mean masterflat frame. From each of the science frames we then subtracted the masterbias frame and divided the masterflat. For the reduction procedure, we considered each of the CCDs separately. However, unlike Bramich, we considered all the observations as one run, over June and July 1999, instead of considering them as separate runs.

Following the standard processing, we reduced the photometry on the science frames using differential image analysis (DIA) (Alard & Lupton 1998; Alard 2000). Our implementation of DIA code was written for the MOA project (Bond et al. 2001). All of the processes are automated into scripts which call on C code developed by Bond and Bramich.

Differential Image Analysis (DIA) is excellent for accurately measuring variable stars within a somewhat crowded field. The idea of differential image analysis is that constant stars are removed from the observations, leaving only those stars in which we are interested, because they contain variability induced possibly by a transiting planet. We first used a script to build a reference frame that is a combination of the best seeing frames in the entire run. Alard (2000) showed that using several good seeing science frames generated better results than just using one, best frame as the reference.

We subtracted this reference frame from each of the science frames to create residual images. In order for the subtraction to be successful, we had to convolve the reference frame to the same seeing as each of the science frames. The science frames $I(x, y)$ are related to the reference frame $R(x, y)$ with the convolution equation:

$$I(x, y) = R(x, y) * d(x, y),$$

where $*$ denotes convolution and $d(x, y)$ is the difference between the science frames.

Figure 1. CCD Mosaic of NGC 6940.
A Dearth of Planetary Transits in the direction of NGC 6940

2.3 Photometric Precision

We find that with the above processing, we can achieve an rms scatter of 0.004 – 0.006 mag at the bright end of our observations; good enough to detect planetary transits (see Fig. 2). However, only a very small number of our stars have precision near this limit. Only ∼4400 stars of the ∼50,000 have rms scatter better than 1%.

Our instrumental magnitude saturation limit for each of our CCDs was approximately 17. Beyond that limit, saturated stars, bad columns, and CCD defects were identified as stars. We also see that CCD three (Fig. 2 c) has a much tighter curve than the other three CCDs. This is because we were able to combine 12 best seeing frames in order to make the reference frame for CCD three. The constituent frames of the reference frame need to be roughly sequential, or at least occur on the same night, and only CCD three had such a run of sequential, good seeing frames, without defects. The other CCDs only had four to six sequential frames with good

\[
I(x, y) = K(u, v, x, y) \otimes R(x, y) + B(x, y)
\]  

where \(K(u, v, x, y)\) is the convolution kernel and \(B(x, y)\) represents the sky background. Thus, the residual images should have only random noise at the positions of constant stars, while the variable stars will create a dark or light spot on the residual, depending on whether or not the star was dimmer or brighter (relative to the reference frame) in the working image. This method generally performs much better than PSF fitting, particularly with blended stars (Alard & Lupton 1998).

Finally, we measure the flux on the residual images using an optimal PSF scaling at the position of each star. Stars have already been identified using PSF fitting on the reference image, using IRAF’s DAOPhot package.
Figure 3. Colour magnitude diagrams. Colour magnitude diagrams for each of the four CCDs, with the colours and magnitudes converted to standard values. The highlighted stars are our transit candidates. The line represents a theoretical main sequence for a cluster 770 parsecs away, but only K and M stars would be represented by the line. The main dark ridge in each of the graphs, with $R - I$ colour indices of 0.5-0.75 are spectral type K3-K8.

We found $\sim$350 photometric standard stars for the field of NGC 6940 from the Canadian Astronomy Data Centre (Stetson 2000). Of these standard stars, we were able to use $\sim$240 stars to calibrate the observations ($\sim$110 of the standard stars were saturated in our data). To change our observations from the instrumental CCD magnitudes into standard $R$ and $I$ magnitudes, we made a linear regression to put CCD one into the standard observations, then corrected each of the other CCDs to conform roughly to CCD one’s values.

We began by computing a linear regression between the instrumental $r$ and $i$ values and the standard (Johnson-Cousins) observed $R$ and $I$ values of our 240 stars:

$$R_{JC} = r_{CCD} \times 0.977 + 0.192$$

and

$$I_{JC} = i_{CCD} \times 0.985 - 0.702$$

Unfortunately, the photometric standard stars observed were in the center of the cluster, so they only appear on CCD one. Thus, offsets were inferred for the remaining three CCDs by assuming that the mean magnitude in $r$ and the colour $r - i$ of all the stars (to magnitude 20, when we have large errors) would be approximately equal. We found that the following offsets correct the biases of the other CCDs:

$$(r - i)_{CCD2} = (R - I) + 0.064$$

and

$r_{CCD2} = R - 0.105$
A Dearth of Planetary Transits in the direction of NGC 6940

2.6 Stellar Radii

are of K0 spectral type or later. We can determine
radius for each of the stars in our data set. We did this by
roughly the stars that have sufficient precision by comparing
the rms of the star with the depth of a theoretical tran-
sit of a Jupiter-sized object. Figure 4 shows the scatter of
each of our stars compared to the stellar radii. The lines
represent 0.5 $R_{Jup}$, 1 $R_{Jup}$, and 2$R_{Jup}$ transits in front of
stars with the appropriate stellar radii. Almost none of our
stars have precision good enough to view the transit of a 0.5
$R_{Jup}$ planet, however, about 19% of our stars have enough
precision to measure a one $R_{Jup}$ transit, while nearly 56%
have precision to measure a two $R_{Jup}$ transit. We have not
provided a rigorous treatment of extinction and reddening,
which will affect the computed size of the stars, because we
are observing field stars, with varying distances.

\[ \frac{r - i}{CCD_3} = (R - I) - 0.338 \]  
\[ R_{CCD_3} = R - 0.177 \]  
\[ \frac{r - i}{CCD_4} = (R - I) - 0.073 \]  
\[ R_{CCD_4} = R - 0.148 \]

2.5 Colour Magnitude

Using the calibrations above, we computed the $R - I$ colour
index for each star and produced a colour-magnitude dia-
gram (Figure 3). We were unable to find a significant main
sequence in the observations of NGC 6940. The 300 s ex-
posures have saturated the members of our cluster, which
This correlates very well with the observed
estimates that 94.5% of our observable
stars should be K0 spectral type or later (Robin et al. 2003).
Besançon model for our direction of the galaxy and our ob-
observations, which suggest that 94.3% of our stars
main sequence stars are K and M type. We can determine

\[ \frac{R}{131} = 0.3501(R-I)^3 \]

\[ R = 0.473(1.5) \]

3 TRANSIT DETECTION ALGORITHM

The final step in our data reduction is the search for plan-
etary transits from the stellar light curves. We used a
matched filter algorithm which compares theoretical transit
lightcurves with the observed lightcurves from our ~50,000
reduced stars.

This search uses a truncated cosine approximation with
two parameters: period, duration, depth, and the time of
midpoint. We first used a period sweep from 1.5 d to
7 d with a fixed transit duration of 3 h. The stars with mul-
tiple transit-like events are naturally weighted much higher
with this method. The fixed-transit duration allows a pri-
mary sweep on all stars, which would be too computa-
tionally expensive if we varied the duration. A 1.5 $R_{Jup}$ planet
with a one day period would create a 1.3–2.0 h transit du-
ration, for stars of spectral type M5-K0. The same planet
with a seven day period would create a 2.5–3.8 h duration.
We have found that as long as the observed duration does
not differ by a factor of two from the fixed duration, our
algorithm can identify the transit.

From this first period sweep, we compute the transit signal-to-noise for each star. The transit S/N is calculated
from the fit of the data to a constant light curve as compared
to a transit light curve.

Following the first sweep, stars with a significantly bet-
ter transit fit (~400 stars, S/N > 8.0) are subjected to an-
other period and duration sweep, which refines the possi-
bile transit parameters. Finally, the stars are then analyzed
individually (in folded form and unfolded) to consider the
possibility of a transit. Stars which have single faint points
are rejected, as well as suspicious transits which occur only
on nights with known problems.

4 DETECTION SIMULATIONS

In order to estimate how many stars might yield planetary
transit detections, we used Monte Carlo simulations on two
CCDs to estimate how many transit-like events we could re-
cover if every star had a hot-Jupiter sized planet. We ran the
simulations on CCDs one and two, and found very similar
results. We assume that the other CCDs will show similar
results, because all CCDs have similar magnitude distribu-
tions.

We began by randomly assigning each star a planetary
inclination, planetary period, and planetary transit epoch.
The inclinations were uniform in $\cos i$, the random period was uniform in $\log p$ from $3 - 5.2$ d, and the epoch of mid-transit was a random date between zero and the period. The planet was assumed to be $1.5 R_{Jup}$ and the stellar radius was computed using the colour information for each of the stars using equation 10. We then tested each of the systems to determine if the inclination allowed for a transit to be observed, and we compared the transit timing for each of the stars with our actual timings of our observations to see if the simulated transits would occur during our observations. Finally, we injected the transit into the data set using a simple box transit: if an observation was taken during the planet crossing the limb of the star, then the brightness of the star was decreased by half the full transit depth; if it was taken during the full transit, then the magnitude would be offset by the amount computed for a star that size being eclipsed by a $1.5 R_{Jup}$ planet.

After running this simulation on $\sim 12,500$ stars that were recorded on CCD one, we found $\sim 720$ stars ($5.8\%$) that should have transits observable based on inclination and eclipse timing. Similarly, on CCD two we ran $14,000$ stars and found $\sim 800$ ($5.7\%$) that would transit. We then inserted these injected transits into our data set and loaded them into OPTPHOT, our transit search algorithm. We searched over 3 – 5.2 d periods for 3 h transits. We were able to recover $\sim 370$ of the $\sim 1520$ stars with known transits ($\sim 25\%$). However, this does not suggest that our algorithm is missing well-defined transits. All stars were given a planet, and over $\sim 55\%$ of our stars are magnitude 21 or fainter, with an average precision of 0.05 magnitudes. This precision at faint magnitudes prevents the detection of transits that would only produce shallow dips, especially since it would require many transits during our observing windows, an unlikely event.

We are able to see a distinct differentiation between stars with injected transits and normal observed stars in our transit search. Figure 5 shows that the stars with an injected transit rise significantly above the stars without such a transit. This makes us confident that we would be able to find well defined transits in our brighter stars.

## 5 RESULTS

Presented in this section are the results from the observations of NGC 6940. Similar results for NGC 7789 or NGC 6819 can be found in [Bramich et al. (2004)] and [Street et al. (2004)], respectively.

### 5.1 Multiple Transit-like Events and Variable Stars

Our transit search algorithm has discovered 14 stars in the field of NGC 6940 that have multiple short duration eclipses. Using the transit depth and stellar radii computed from their colour indices, we have determined a possible radius of each of the stellar companions. Every stellar companion is smaller than 35\% the Sun’s radius, and six are smaller than 25\% of the Sun’s radius. Folded lightcurves can be found in Fig. 6 while the parameters of each system are found in Table 2. The authors may be contacted for the complete data on each of the candidates to facilitate follow-up work.

**Star 6405**: Our eclipse depth of 8.9\% appears to be too conservative, so the assigned companion radius of $2.1 R_{Jup}$ is probably too small. However, the most damning feature of this eclipse (in terms of it being a planet) is the shallow secondary eclipse that occurs at half the orbital phase. This is definitely a binary system.

**Star 16016**: This is one of our best sampled transits, with 4 transits observed. The noise amplitude of the lightcurve is consistent with other 20th magnitude stars in our sample. The eclipse bottom does not look particularly sharp, though sparse time sampling could have hidden that feature. We have computed a companion radius of $2.1 R_{Jup}$. If possible, this star should be measured using RV.

**Star 9939**: This has a fairly sharp eclipse, though it is only well sampled on egress, suggesting a grazing binary star. It is also fairly deep, with nearly a 25\% drop in magnitude. However, our colours suggest the parent is an M2 star, with a radius of a little under half a solar radii, giving the companion a radius of $\sim 2.4 R_{Jup}$.

**Star 13652**: This 18\% eclipse is not as sharp as some of our other obvious binary stars, though the faint magnitude has introduced enough noise to make it difficult to ascertain. The parent star is one of our brighter candidates, a K4. The estimated companion radius is 3.1 $R_{Jup}$, though that is a lower limit, as our eclipse may be deeper than our model suggests. Thus, it is probably a star.

**Star 1068**: If it were indeed a planetary transit, the companion radius would be around 2.2 $R_{Jup}$, orbiting the K5 parent star. However, the sharp eclipse suggests a grazing binary, though sparse time-sampling and few observed eclipses may have contributed to that perception.

**Star 1254**: We cannot really classify if the eclipse is sharp or round bottomed, due to few eclipses and sparse time-sampling, though we think this could be a grazing binary. If the eclipse is caused by a planetary companion to the K5 star, $R_e$ would be around 3 $R_{Jup}$.

**Star 2133**: Out-of-eclipse variation suggests that perhaps this is a binary star. However, it is one of our faintest eclipses, with a 3.9\% dip found with three observed eclipses. This would indicate a planetary companion of 1.5 $R_{Jup}$, which is well within the range for hot Jupiters. We suggest a follow up study of this star. It is also one of the brightest stars in our sample at 17.4 mags, which makes it a good candidate for further research.

**Star 11807**: This faint star seems to have a somewhat sharp eclipse, suggesting a grazing binary. The eclipse depth of 11.4\% may be too conservative, so the computed value of the companion at 3 $R_{Jup}$ is probably too small.

**Star 13180**: This star exhibits some significant out-of-eclipse sinusoidal variation. The sinusoidal period (4.46 days) appears to be slightly but significantly out of sync with the eclipse period (4.04 days). The variation may be star spot activity on the star. A sharp eclipse suggests that this is a binary star grazing its companion.

**Star 6716**: Sparse time-sampling prevents us from definitively saying this eclipse has a sharp bottom, but it appears so, suggesting a grazing binary star. The model suggestion of a 12.8\% dip is conservative, so the computed companion size of 2.7 $R_{Jup}$ is a minimum.

**Star 7350**: This somewhat deep transit could be sharp bottomed, but the time-sampling is too sparse to say for sure. Since the parent is a relatively bright K6 star, we
Table 2. System parameters of stars that show multiple transit-like events. Non-integer values of \( N_t \) mean that we observed partial eclipses.

<table>
<thead>
<tr>
<th>Star</th>
<th>( R ) (mag)</th>
<th>( R-I ) (mag)</th>
<th>( \delta m ) (mag)</th>
<th>( \delta t ) (h)</th>
<th>( R_e ) (( R_\odot ))</th>
<th>( R_c ) (( R_\odot ))</th>
<th>( P^1 ) (d)</th>
<th>( t_0 ) (HJD-2451300)</th>
<th>( N_t )</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD 1</td>
<td>6405</td>
<td>16.905(5)</td>
<td>0.692(7)</td>
<td>8.9%</td>
<td>1.4</td>
<td>0.688(3)</td>
<td>0.205(4)</td>
<td>1.42</td>
<td>51.461</td>
<td>3.5</td>
<td>20(^h)34(^m)4.17</td>
</tr>
<tr>
<td></td>
<td>16016</td>
<td>19.859(6)</td>
<td>0.544(24)</td>
<td>7.2%</td>
<td>3.0</td>
<td>0.770(15)</td>
<td>0.200(7)</td>
<td>2.17</td>
<td>54.464</td>
<td>4</td>
<td>20(^h)34(^m)56('')24</td>
</tr>
<tr>
<td>CCD 2</td>
<td>9939</td>
<td>20.136(9)</td>
<td>1.256(22)</td>
<td>24.4%</td>
<td>2.1</td>
<td>0.479(8)</td>
<td>0.237(6)</td>
<td>2.20</td>
<td>53.446</td>
<td>2.5</td>
<td>20(^h)35(^m)13('')37</td>
</tr>
<tr>
<td></td>
<td>13652</td>
<td>19.891(5)</td>
<td>0.576(21)</td>
<td>17.6%</td>
<td>4.0</td>
<td>0.750(12)</td>
<td>0.315(6)</td>
<td>2.22</td>
<td>55.499</td>
<td>3</td>
<td>20(^h)35(^m)27('')91</td>
</tr>
<tr>
<td>CCD 3</td>
<td>1068</td>
<td>19.127(5)</td>
<td>0.619(13)</td>
<td>8.7%</td>
<td>3.8</td>
<td>0.725(7)</td>
<td>0.214(5)</td>
<td>7.14</td>
<td>52.465</td>
<td>2</td>
<td>20(^h)33(^m)35('')10</td>
</tr>
<tr>
<td></td>
<td>1254</td>
<td>19.793(6)</td>
<td>0.641(23)</td>
<td>18.1%</td>
<td>2.4</td>
<td>0.714(12)</td>
<td>0.303(6)</td>
<td>4.90</td>
<td>52.597</td>
<td>2</td>
<td>20(^h)33(^m)36('')11</td>
</tr>
<tr>
<td></td>
<td>2133</td>
<td>17.413(5)</td>
<td>0.578(9)</td>
<td>3.9%</td>
<td>3.4</td>
<td>0.749(5)</td>
<td>0.148(10)</td>
<td>3.74</td>
<td>56.769</td>
<td>3</td>
<td>20(^h)33(^m)41('')07</td>
</tr>
<tr>
<td></td>
<td>11807</td>
<td>20.104(6)</td>
<td>0.396(36)</td>
<td>11.4%</td>
<td>2.6</td>
<td>0.876(29)</td>
<td>0.296(10)</td>
<td>5.82</td>
<td>54.513</td>
<td>2</td>
<td>20(^h)34(^m)34('')71</td>
</tr>
<tr>
<td></td>
<td>13180</td>
<td>18.062(5)</td>
<td>0.591(10)</td>
<td>7.7%</td>
<td>2.4</td>
<td>0.741(6)</td>
<td>0.205(5)</td>
<td>4.04</td>
<td>83.596</td>
<td>3</td>
<td>20(^h)34(^m)41('')92</td>
</tr>
<tr>
<td>CCD 4</td>
<td>6716</td>
<td>17.564(6)</td>
<td>0.609(10)</td>
<td>12.8%</td>
<td>4.6</td>
<td>0.731(5)</td>
<td>0.262(6)</td>
<td>3.65</td>
<td>53.628</td>
<td>1.5</td>
<td>20(^h)34(^m)6('')28</td>
</tr>
<tr>
<td></td>
<td>7350</td>
<td>17.738(6)</td>
<td>0.609(9)</td>
<td>16.6%</td>
<td>3.0</td>
<td>0.699(5)</td>
<td>0.284(5)</td>
<td>1.77</td>
<td>55.585</td>
<td>2</td>
<td>20(^h)34(^m)9('')78</td>
</tr>
<tr>
<td></td>
<td>8837</td>
<td>18.549(6)</td>
<td>0.708(11)</td>
<td>21.3%</td>
<td>3.5</td>
<td>0.680(5)</td>
<td>0.314(4)</td>
<td>3.54</td>
<td>53.486</td>
<td>2</td>
<td>20(^h)34(^m)18('')74</td>
</tr>
<tr>
<td></td>
<td>12900</td>
<td>20.183(11)</td>
<td>0.523(25)</td>
<td>11.5%</td>
<td>3.2</td>
<td>0.783(16)</td>
<td>0.265(6)</td>
<td>2.67</td>
<td>51.638</td>
<td>4</td>
<td>20(^h)34(^m)42('')05</td>
</tr>
<tr>
<td></td>
<td>15028</td>
<td>18.609(5)</td>
<td>0.689(13)</td>
<td>26.3%</td>
<td>3.3</td>
<td>0.689(6)</td>
<td>0.353(4)</td>
<td>3.45</td>
<td>57.568</td>
<td>2</td>
<td>20(^h)34(^m)54('')87</td>
</tr>
</tbody>
</table>

Table 3. System parameters of stars that show single transit-like events.

<table>
<thead>
<tr>
<th>Star</th>
<th>( R ) (mag)</th>
<th>( R-I ) (mag)</th>
<th>( \delta m ) (mag)</th>
<th>( \delta t ) (h)</th>
<th>( R_e ) (( R_\odot ))</th>
<th>( R_c ) (( R_\odot ))</th>
<th>( \text{epoch} ) (HJD-2451300)</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD 1</td>
<td>1995</td>
<td>19.786(8)</td>
<td>0.956(21)</td>
<td>20.5%</td>
<td>2.8</td>
<td>0.581(7)</td>
<td>0.263(12)</td>
<td>51.653</td>
<td>20(^h)33(^m)40('')32</td>
</tr>
<tr>
<td></td>
<td>11284</td>
<td>19.190(7)</td>
<td>0.631(15)</td>
<td>10.6%</td>
<td>3.2</td>
<td>0.719(8)</td>
<td>0.234(19)</td>
<td>91.573</td>
<td>20(^h)34(^m)31('')69</td>
</tr>
<tr>
<td></td>
<td>1533</td>
<td>19.706(8)</td>
<td>0.626(21)</td>
<td>27.4%</td>
<td>3.5</td>
<td>0.722(11)</td>
<td>0.376(16)</td>
<td>88.596</td>
<td>20(^h)33(^m)36('')75</td>
</tr>
<tr>
<td></td>
<td>2510</td>
<td>19.693(10)</td>
<td>0.771(42)</td>
<td>15.7%</td>
<td>3.8</td>
<td>0.652(18)</td>
<td>0.258(29)</td>
<td>59.603</td>
<td>20(^h)33(^m)42('')35</td>
</tr>
</tbody>
</table>

Figure 5. Results of transit injected on CCD one. The left panel shows the results of the \( \sim 700 \) stars which had injected transits. The bulge indicates the easily determined transit signals. The right panel includes all stars on CCD one, including the original stars and stars with an injected transit. Very few stars achieve our cutoff of a S/N of 8.
(a) 6405  (b) 16016  (c) 9939
(d) 13652  (e) 1068  (f) 1254
(g) 2133  (h) 11807  (i) 13180
(j) 6716  (k) 7350  (l) 8837
(m) 12930  (n) 15028
A Dearth of Planetary Transits in the direction of NGC 6940

have very little scatter in our data points, and the model fits relatively well.

**Star 8837**: This sharp eclipse has some scatter out of the primary eclipse, and could have a secondary eclipse that we have not yet found. Also, the companion is computed to be larger than $3 \, R_{\text{Jup}}$, so is probably another star.

**Star 12930**: Though this is one of the faintest stars in our list of candidates, we can find the periodicity because we have luckily observed four transits. However, the scatter does prevent us from saying if the eclipse is sharp or round bottomed.

**Star 15028**: Our models fit this eclipse exceptionally well, but it is fairly deep at 25%, and suggests a companion radius of $3.6 \, R_{\text{Jup}}$. Further observations would be necessary to determine the shape of the eclipse.

**5.2 Single transit events**

We have also discovered several single low amplitude transit-like events. We are unable to estimate a period for these events, but we can use the colour indices to compute the radii of the stars and the companions. Complete lightcurves are in Fig. 7 and the parameters are found in Table 3. The authors may be contacted for the complete data on each of the candidates.

**Star 1995**: Our models fit this eclipse well within the limited time-sampling, but it is fairly deep. However, our colours indicate a late type star with a radius of $0.581 \, R_{\odot}$ which suggests a companion radius of $2.7 \, R_{\text{Jup}}$.

**Star 11284**: Again, sparse time sampling makes it difficult to characterize the shape of the eclipse. Our computations suggest a companion size of $2.4 \, R_{\text{Jup}}$.

**Star 1533**: This is a fairly faint star, at nearly 20th magnitude, so there is some amount of scatter in our data points. However, the late type star (K5) can produce this fairly deep eclipse with companion $3.8 \, R_{\text{Jup}}$, which is a bit large for a planet, and is probably another star. At other points in the data, there could be secondary eclipses that are unresolved with our limited time-sampling, so this could be a faint binary.

**Star 2510**: This single transit eclipse could be sharp-bottomed, and scatter could obscure secondary eclipses. However, we have computed a companion radius of $2.6 \, R_{\text{Jup}}$.

**5.3 System Models: Checking Transit Duration**

Using the stellar parameters in Table 2, we attempted to compare our measured transit duration with a computed transit duration, based on the size of the star (derived from the colour index), the size of the companion (based on the measured transit depth), and the period. Table 4 reports these values of transit durations and the ratio between the two. This is not an absolutely rigorous check (because a missed transit could give us a spurious period), but it does give us some idea as to if the system which we describe is actually a possibility.

We find that four of our stars, 6405, 1068, 1254 and 13180, have observed values within $\pm 20\%$ of the computed value of the transit duration. We don’t feel that this is an endorsement of these candidates as planets (indeed, we know 6405 to be a binary system), but we feel it does probably eliminate the other systems from being planetary systems. Further, each of the four systems have companions computed to be between $2.0 - 3.0 \, R_{\text{Jup}}$, too large to be considered planets.
Our simulations suggest that if all our stars had a hot Jupiter, \( \sim 5.7\% \) of stars would show an eclipse. That is, the planet’s orbit and orbital inclination would allow us to record that transit with our observation regime. Our transit searching algorithm has shown that it can find \( \sim 25\% \) of these transits, if they are randomly distributed over the magnitude ranges we have in our data set. Finally, recent research by Fischer, et al. (2004) has quantified the relationship between metallicity and planet frequency, allowing us to quantify how many planets we would expect in our sample, if it mimics the solar neighborhood.

The Besançon model supplies us with metallicities for each star in the model, specific to our galactic coordinates. We use these metallicities because we are looking at mostly late type K and M stars, and not stellar systems with hot Jupiters. We recommend these stars for further study.

We have obtained high precision light curves for \( \sim 50,000 \) stars in the direction of the open cluster NGC 6940 using differential image analysis. We have used Monte Carlo simulations to estimate how many transiting planets we should expect to find, assuming planetary frequency of the solar neighborhood. We determined the sizes of the stars using radial velocity surveys have only discovered two M dwarfs harbouring planets, but that could be an observational bias against M dwarfs, which are often too faint for RV studies. Our results point to a lower incidence of hot Jupiters among late K and M dwarfs than among F or G dwarfs, regardless of the metallicity. Endl et al. (2004) have embarked on a study specifically aimed at finding if the formation history of M dwarfs prevents planetary companions, though they have not finished their surveys. Our results thus suggest that hot Jupiters are less common around M dwarfs, and the lack of planets is not an observational bias.

6 CONCLUSIONS

We have obtained high precision light curves for \( \sim 50,000 \) stars in the direction of the open cluster NGC 6940 using differential image analysis. We have used Monte Carlo simulations to estimate how many transiting planets we should expect to find, assuming planetary frequency of the solar neighborhood. We determined the sizes of the stars using radial velocity surveys have only discovered two M dwarfs harbouring planets, but that could be an observational bias against M dwarfs, which are often too faint for RV studies. Our results point to a lower incidence of hot Jupiters among late K and M dwarfs than among F or G dwarfs, regardless of the metallicity. Endl et al. (2004) have embarked on a study specifically aimed at finding if the formation history of M dwarfs prevents planetary companions, though they have not finished their surveys. Our results thus suggest that hot Jupiters are less common around M dwarfs, and the lack of planets is not an observational bias.

ACKNOWLEDGEMENTS

Ben Hood would like to thank the Marshall Commission for financial support. The authors would also like to thank Aleksander Schwarzenberg-Czerny for useful discussions regarding the transit detection algorithm. This research was (partially) based on data from the ING Archive. We thank the Canadian Astronomy Data Centre, which is operated by

### Table 4. Computed versus Observed Transit Duration

<table>
<thead>
<tr>
<th>star</th>
<th>p (d)</th>
<th>( \Delta t_c ) (h)</th>
<th>( \Delta t_o ) (h)</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>6405</td>
<td>1.42</td>
<td>1.1</td>
<td>1.4</td>
<td>0.79</td>
</tr>
<tr>
<td>16016</td>
<td>2.17</td>
<td>1.5</td>
<td>3.0</td>
<td>0.50</td>
</tr>
<tr>
<td>9939</td>
<td>2.20</td>
<td>1.3</td>
<td>2.1</td>
<td>0.62</td>
</tr>
<tr>
<td>13652</td>
<td>2.22</td>
<td>1.6</td>
<td>4.0</td>
<td>0.40</td>
</tr>
<tr>
<td>1068</td>
<td>7.14</td>
<td>3.2</td>
<td>3.8</td>
<td>0.84</td>
</tr>
<tr>
<td>1254</td>
<td>4.90</td>
<td>2.7</td>
<td>2.4</td>
<td>1.13</td>
</tr>
<tr>
<td>2133</td>
<td>3.74</td>
<td>2.0</td>
<td>3.4</td>
<td>0.59</td>
</tr>
<tr>
<td>11807</td>
<td>5.82</td>
<td>3.3</td>
<td>2.6</td>
<td>1.27</td>
</tr>
<tr>
<td>13180</td>
<td>4.04</td>
<td>2.2</td>
<td>2.4</td>
<td>0.92</td>
</tr>
<tr>
<td>6716</td>
<td>3.65</td>
<td>2.2</td>
<td>4.6</td>
<td>0.48</td>
</tr>
<tr>
<td>7350</td>
<td>1.77</td>
<td>1.3</td>
<td>3.0</td>
<td>0.43</td>
</tr>
<tr>
<td>8837</td>
<td>3.54</td>
<td>2.2</td>
<td>3.5</td>
<td>0.63</td>
</tr>
<tr>
<td>12930</td>
<td>2.67</td>
<td>1.8</td>
<td>3.2</td>
<td>0.56</td>
</tr>
<tr>
<td>15028</td>
<td>3.45</td>
<td>2.2</td>
<td>3.3</td>
<td>0.67</td>
</tr>
</tbody>
</table>

\[ f(x) = \sum e^{-a} \frac{a^x}{x!} \]
the Dominion Astrophysical Observatory for the National Research Council of Canada’s Herzberg Institute of Astrophysics. This paper was based on observations made with the Isaac Newton Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

REFERENCES

Janes, K., 1996, JGR, 101, 14853
Mayor, M., Queloz, D., 1995, Nat, 378, 355