A Search for Transiting Hot Planets as Small as Neptune in the Open Cluster M37

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**Abstract.** We are conducting a transit survey of the open cluster M37 using the Megacam instrument on the 6.5 m Multiple-Mirror Telescope. We have obtained $\sim 4500$ images of this cluster over 18.5 nights and have achieved the precision necessary to detect planets smaller than Saturn. In this presentation we provide an overview of the project, describe the ongoing data reduction/analysis and present some of our preliminary results.

1. Introduction

One can separate surveys for transiting planets along two axes: surveys of bright stars vs. surveys of faint stars and galactic field surveys vs. surveys of stellar clusters. Each type of survey has its own advantages and disadvantages so that there are a wide range of possible transit survey strategies each with different scientific goals in mind (Charbonneau et al. 2006). This presentation describes a deep survey of an open cluster: M37 (NGC 2099).
The advantage of surveying a stellar cluster is that the stellar population in the survey can be well characterized. As a result, it is straightforward to determine the planet frequency (or an upper limit) as functions of stellar and planetary mass and orbital period from the number of transiting planets that are discovered. Knowing this frequency would provide a fundamental constraint for theories of the formation and evolution of planetary systems. Moreover, knowing the properties of the stars in the survey has the advantage of lessening the probability of spending valuable time following-up false positive transit detections, a problem which has plagued field surveys. For these reasons there have been a number of surveys for transiting planets in stellar clusters. This includes surveys of globular clusters (Gilliland et al. 2000; Weldrake et al. 2005) and open clusters. The latter includes UStAPS (Street et al. 2003; Bramich et al. 2005; Hood et al. 2005), EXPLORE-OC (von Braun et al. 2005), PISCES (Mochejska et al. 2005, 2006), STEPSS (Burke et al. 2006) and MONITOR (Aigrain et al. 2006).

Despite a large number of surveys, to date no confirmed transiting planet has been discovered in a stellar cluster. So far the open cluster surveys have only provided upper limits on the planet frequency, all of which lie above the frequency inferred from the other surveys. The fundamental problem facing an open cluster survey is that very few rich open clusters exist. Moreover, the richest clusters, which have at most a few thousand members, all lie more than a kilo-parsec away. Surveys of open clusters are necessarily deep surveys for which the expected number of planet discoveries is low (typically one or two planets).

Pepper & Gaudi (2005) developed a formalism for estimating the expected yield of a cluster survey. This work has given the insight that the minimum radius planet that can be detected around a cluster star is approximately constant for all stars that have a photometric precision limited by source shot noise. For stars with light curves that do not have correlated noise the minimum detectable radius is inversely proportional to the square root of the telescope diameter. Pepper & Gaudi (2006) have noted that it may be possible to find planets as small as Neptune, or even Super Earths using existing ground based telescopes and instruments. While radial velocity and micro-lensing surveys have recently uncovered several planets in this regime (Butler et al. 2004; Santos et al. 2004; McArthur et al. 2004; Beaulieu et al. 2006; Lovis et al. 2006) there is a substantial motivation to discover one that transits its host star. Moreover, the frequency of planets in this regime is essentially unknown, thus even an upper limit on this frequency would represent a significant improvement in our knowledge of these planets. Finally, the discovery of even a single transiting planet in a stellar cluster would provide a unique opportunity to determine the mass and radius of the planet with a precision that is not limited by uncertainties in the mass and radius of the star.

Following this motivation we have undertaken an ambitious twenty night survey of the open cluster M37 (NGC 2099) using the Megacam wide-field mosaic CCD camera on the 6.5m Multiple-Mirror Telescope (MMT). By using a significantly larger telescope than has heretofore been utilized for a transit survey we are able to achieve a precision that should in principle allow us to detect planets as small as Neptune. This survey also provides a unique opportunity to study low-amplitude variability in an intermediate age open cluster. In §2 we
describe the planning, observations and data reduction. We briefly describe a few preliminary results in §3.

2. The Survey

2.1. Planning

To demonstrate the feasibility of a full scale transit survey with the MMT we conducted a preliminary three night survey of the open cluster NGC 6791 (Hartman et al. 2005). We were able to achieve a point-to-point precision of better than 1 mmag for the brightest stars; the noise was not dominated by systematics. These results suggested that for a closer open cluster we could achieve the precision necessary to detect planets as small as Neptune which would provide a 1 mmag deep transit around a solar radius star (with a deeper transit for smaller stars).

To select the open cluster for a transit survey we applied the formalism of Pepper & Gaudi (2005) to all open clusters visible from the MMT in December/January. We chose this timing constraint so that observations could be obtained continuously over two trimesters during the long winter nights. Data for the open clusters was obtained from WEBDA where available with a literature survey to determine the cluster mass function for the most promising candidates. Besides maximizing the formal expected number of detections, we also considered the age, metallicity, angular size and presence of additional data for the clusters. Among the top choices we chose M37 (05:52:19, +32:33:12) for its solar metallicity ([Fe/H] = +0.09, Mermilliod et al. (1996)) and intermediate age (520 Myr, Kalirai et al. (2001)).

2.2. Observations

The observations were obtained over twenty four nights (eight of which were half nights) between December 21, 2005 and January 21, 2006. We obtained a total of ~ 4500 images. We used the Megacam instrument (McLeod et al. 2000) which is a 24′ × 24′ mosaic consisting of 36 2k×4k, thinned, backside-illuminated CCDs that are each read out by two amplifiers. We used an r′ filter to maximize the sensitivity to smaller stars while avoiding fringing that would occur at longer wavelengths. The mosaic has a pixel scale of 0.08″ which allows for a well sampled point-spread-function (PSF) even under the best seeing conditions. This camera provides a field of view large enough to contain the cluster without dithering. And, because of its fine sampling, one can obtain 2 × 10⁷ photons in 1″ seeing from a single star prior to saturation setting the photon limit for the precision in a single exposure to 0.25 mmag.

The average time between exposures (including read-out and time spent initializing for the next exposure) was 24 seconds. Ideally one would like to observe the same stars from exposure to exposure while spending as little time as necessary with the shutter closed. In other words, one would like to maximize the exposure times. There are, however, competing factors that limit how long one can expose. As the exposure time is increased more stars are lost to saturation, and, more importantly, the fraction of the image that is lost to saturated stars and artifacts (diffraction speaks and bleed columns) increases. Not only does
this decrease the number of stars that can be observed, it also compromises
the quality of the image and the ability to reduce the image to achieve high
precision photometry for any of the stars. To determine the optimal exposure
time we obtained a series of preliminary observations of M37 during a Megacam
engineering run on October 29, 2005. We found that in 1" seeing an exposure
time of sixty seconds was the longest we could go before saturation posed a
problem for image quality. To keep the same stars saturated in each image we
then varied the exposure time as the seeing and atmospheric extinction changed.

2.3. Data Reduction

When read out with 2×2 binning, a single mosaic image requires 189 megabytes
of storage. The entire run produced nearly a terabyte of data which presents
a challenge for data reduction. We analyze each chip independently, so there
are more than 160,000 images to reduce. To save i/o time we performed the
preliminary CCD corrections, including bias correction and flat-fielding, using
our own software. We constructed a single master flat-field from twilight sky
flats taken over the course of the run. This was done, in part, because conditions
were acceptable for flat-fielding on only a handful of evenings.

To perform photometry we used the image subtraction technique due to
Alard & Lupton (1998) and Alard (2000), using a slightly modified version of
Alard’s Isis 2.1 package. We constructed a reference image for each chip from ∼
100 of the best seeing images (the actual number used varied from chip to chip).
Stars are identified on the reference and each science image using
Sextractor 2.3.2 (Bertin & Arnouts 1996), we used Sextractor rather than the extract
routine in Isis as SEXTRACTOR appeared to handle blended stars better and
also performed better on poorer seeing images (we still run extract to remove
cosmic-rays). The reference star list is then matched to the image star list using
a third order polynomial, we then transform the higher signal to noise reference
image to the object image. For images with better than 1'' seeing we used a
Gaussian convolution kernel to broaden them before performing subtraction.
We then perform subtraction adjusting the FWHM of the Gaussians used in
the kernel according to the value expected from the difference in seeing between
the reference and object images. To determine the differential photometry on
the difference images we performed aperture photometry, scaling the result by
the aperture sum of the PSF convolved with the kernel. We performed PSF
fitting photometry on the reference images using DAOPHOT version 2 (Stetson
1987, 1992) to convert the differential light curves into magnitudes. To ensure
proper flux scaling we used the PSF from DAOPHOT as input to the differential
photometry routine.

The above procedure produced light curves for 24,000 sources with 14 <
r < 25. The light curves are then sent through the following pipeline to identify
transits:

1. Remove images from the light curves that are outliers in more than a given
   fraction of all the light curves. The cutoff is chosen for each chip based
   on a visual inspection of the histogram of the fraction of light curves that
   have a given image as a three-sigma outlier.
2. Remove 0.9972696 day period signals from the light curves. This is done to remove artifacts due to, for example, rotating diffraction spikes that have a period of exactly 1 sidereal day. The signal is removed by binning the light curves in phase and then adjusting the points in a bin by an offset so that the average of the bin is equal to the average of the light curve.

3. Find periodic signals in the light curves using the Lomb-Scargle algorithm [Lomb 1976; Scargle 1982; Press & Rybicki 1989], remove significant detections using a low-order Fourier series. This is done to remove continuous semi-periodic variations due to, for example, star spots.

4. Detrend the light curves using the TFA algorithm [Kovács, Bakos & Noyes 2005]. The trend list for each light curve consists of the other stars on the chip with root-mean-square (RMS) < 0.1 that are well outside the photometric radius of the star in question. There are typically ~ 250 stars in the trend list for each chip.

5. Search for transits using the BLS algorithm [Kovács, Zucker & Mazeh 2002].

3. Preliminary Results

As a demonstration of our photometric precision, Fig. 1 shows the RMS of the resulting light curves after detrending. We also show the RMS after applying a moving mean filter of two hour width to the light curves - it is apparent that the limit at which time-correlated noise begins to dominate the light curves is well below 1 mmag. As a further demonstration, Fig. 1 also shows light curves for injected transiting planets ranging in size from Neptune to Jupiter. While we have marginal detection capability for planets as small as Neptune, transiting planets smaller than Saturn should be easily detected if they exist. Using the above pipeline we have identified a number of candidate transiting planets, spectroscopic follow-up of these systems to rule out false positive scenarios is underway. Other results, including studies of the variability and rotation of stars in M37 will be presented elsewhere.

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Figure 1.: Left: RMS over the entire run as a function of magnitude for stars in M37. Dark points are after detrending with TFA. Light points are after detrending with TFA and applying a moving mean filter with a two hour time-scale. The stars show the expected binned RMS assuming the unfiltered light curves do not have time-correlated noise. Right: light curves of injected transiting planets ranging in size from Neptune (bottom) to Jupiter (top). We are marginally sensitive to planets as small as Neptune, but can easily detect larger planets.
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