KELT: The Kilodegree Extremely Little Telescope

Joshua Pepper, Andrew Gould and D. L. DePoy

Department of Astronomy, Ohio State University, Columbus, Ohio 43210

pepper@astronomy.ohio-state.edu, gould@astronomy.ohio-state.edu, depoy@astronomy.ohio-state.edu

ABSTRACT

Transits of bright stars offer a unique opportunity to study detailed properties of extrasolar planets that cannot be determined through radial-velocity observations. We propose a technique to find such systems using all-sky small-aperture transit surveys. The optimal telescope design for finding transits of bright stars is a 5 cm “telescope” with a $4k \times 4k$ camera. We are currently building such a system and expect to detect $\sim 10$ bright star transits after one year of operation.

1. Introduction

Transit surveys are widely believed to provide the best means to discover large number of extrasolar planets. At the moment, all ongoing transit surveys are carried out in relatively narrow pencil beams. They make up for their small angular area with relatively deep exposures. These surveys are potentially capable of establishing the frequency of planets in various environments, but they are unlikely to find the kinds of transits of bright stars that would be most useful for intensive follow-up analysis. Although some of the surveys of field stars are considered ”wide field”, their total survey areas are small compared to $4\pi$ sr.

2. Optimal Telescope Design

It can be demonstrated that the best way to find HD209458b - type transits is with an all-sky photometric survey. According to Pepper, Gould & DePoy Pepper, Gould, and DePoy (2001) (hereafter PGD),

$$
\frac{dN_t}{dM_V} = \frac{5}{4\pi} \frac{\Omega}{4\pi} F(M_V, r, a) \left( \frac{a}{a_0} \right)^{-5/2} \left( \frac{r}{r_0} \right)^6 \left( \frac{\gamma}{\gamma_0} \right)^{3/2} \left( \frac{\Delta \chi^2_{\text{min}}}{36} \right)^{-3/2}
$$

(1)
where $\gamma$ is the number of photons collected from a fiducial $V = 10$ mag star during the entire experiment, $\Delta \chi^2_{\text{min}}$ is the minimum difference in $\chi^2$ between a transit lightcurve and a flat lightcurve required for candidate detection, and $F(M_V)$ is the function:

$$F(M_V) = \left[ \frac{n(M_V)}{n_0} \right] \left[ \frac{L(M_V)}{L_0} \right]^{3/2} \left[ \frac{R(M_V)}{R_0} \right]^{-7/2} \tag{2}$$

In equation (1) we have adopted $\gamma_0 = 1.0 \times 10^7$, $a_0 = 10 R_\odot$, $r_0 = 0.10 R_\odot$, and in equation (2) we have made our evaluation at $M_V = 5$ mag (i.e. $R_0 = 0.97 R_\odot$, $L_0 = 0.86 L_\odot$, and $n_0 = 0.0025 \text{ pc}^{-3}$). Note that $\gamma_0 = 1.0 \times 10^7$ corresponds to approximately 500 20-second exposures with a 5 cm telescope and a broadened (V+R) type filter for one $V = 10$ mag fiducial star. Since $N_t$ depends on the characteristics of the survey primarily through the total photon counts, $\gamma$, and only logarithmically (through $\Delta \chi^2_{\text{min}}$) on the sampling strategy and the size of the explored parameter space (see PGD), telescope design must focus on maximizing $\gamma$, which is given by

$$\gamma = \frac{K E L^2 T}{\Omega F^2} \tag{3}$$

where $E$ is the fraction of the time actually spent exposing, $L$ is the linear size of the detector, $T$ is the duration of the experiment, $F$ is the focal ratio of the optics, and $K$ is a constant that depends on the telescope, filter, and detector throughput. (For these calculations, we will assume $K = 40 \text{ e}^{-\text{cm}^{-2}\text{s}^{-1}}$, which is appropriate for a broad V+R filter and the fiducial $V = 10$ mag star.) Interestingly, almost regardless of other characteristics of the system, the camera should be made as fast as possible. We will adopt $F = 1.8$, beyond which it becomes substantially more difficult to design the optics. A more remarkable feature of equation (3) is that all explicit dependence on the size of the primary optic has vanished: a 1 cm telescope and an 8 m telescope would appear equally good.

PGD shows that two additional considerations (read-out time, scintillation noise) drive one toward smaller apertures, while two others (sky noise and focal-plane distortion) prohibit going beyond a certain minimal size. Combined, these four effects imply a sweet spot,

$$D \approx (5\text{ cm})10^{0.2(V_{\text{max}}-10)} \tag{4}$$

where $V_{\text{max}}$ is the targeted magnitude limit of the survey.

### 3. The Kilo-square-degree Extremely Little Telescope (KELT)

Motivated by the logic of the “KELT equation” (3), we have begun building the Kilo-degree Extremely Little Telescope (KELT). As suggested by equation (4), KELT has a $D =$
4.2 cm, f/1.9 lens (a Mamiya medium-format photographic lens) mounted on a 4096 × 4096 CCD with 9µm pixels (an Apogee Instruments AP16e camera using a Kodak KAF-16801E detector). The images are Nyquist sampled over the entire field, as required to simultaneously minimize the problems of sky noise and intra-pixel variations. Field tests show that the focal-plane distortions are manageable even in the corners of the 26° × 26° field. Test images were taken with this initial KELT system in June 2003 in Ohio. The images are roughly as expected for the optical performance of the Mamiya medium-format camera lens used. Figure 3 shows representative light curves for several of the stars. In general, we achieve 1-4% photometric accuracy for stars with $V = 6 – 10$ mag. These estimates are based on simple aperture photometry against a $V = 19$ mag arcsec$^{-2}$ sky, and we expect a factor of 2-4 improvement using DoPhot data reductions of photometry at Kitt Peak.

### 3.1. Data Acquisition

We plan to install KELT at a host site in New Mexico, where the telescope will be in an enclosure that will be opened every night. The telescope will execute a standard cycle of observations in fixed terrestrial (alt-az) coordinates, covering the areas of the sky within about 45° of the zenith. Each 30 s exposure will be tracked, and pointing to the next field will be executed during the 30 s read-out time. The region within 45° of zenith could be covered in 10 separate pointings, but the two most southerly ones will be duplicated and one of the two most northerly deleted in order to equalize sky coverage over the long term. That is, each cycle will require 11 minutes, after which it will be repeated on the same section of the terrestrial sky (which has now moved 3.75° to the east in celestial coordinates). In this way, the observations will (over the course of entire year) obtain roughly uniform coverage of about $2\pi$ of the sky, roughly the northern hemisphere.

We anticipate $E = 50% × 20% = 10%$, where the first factor accounts for read-out time and the second for time lost to daylight, weather, and instrument problems. We will employ a broad (V + R) filter for which we expect $K = K_0 = 40$ e$^{-cm^{-2}s^{-1}}$. Hence, according to equation (3), during one year of observations, $\gamma = 7 × 10^7$ photons will be collected from each $V = 10$ mag star. That is $\gamma = 7 × \gamma_0$. Recall from equation (1) that $\gamma_0$ photons were required to probe $V_{\text{max}} = 10$ mag stars for the transit of Jupiter-sized planets.

However, equation (1) is based on source-photon statistics alone. According to PGD, the photon requirements should be increased by a factor $1^2 + (4.2/5)^{2/3} + 0.75(4.2/5)^{-2}(1.9/1.8)^{-2} = 2.8$. Hence, in 1 year, there is a ”margin of safety” (to allow for unanticipated and/or un-modeled problems) of a factor 2.5 in photon counts, corresponding to a factor 1.6 in S/N. For three years of operation, the margin of safety is about a factor 2.7 in S/N. We believe
Fig. 1.— Relative light curves of 7 stars located near the center of the field. This data was taken at a site in Ohio in June 2003. The approximate visual magnitudes are given in each panel. In general, we achieve 1-4% photometric accuracy for stars with $V = 6 - 10$ mag. These estimates are based on simple aperture photometry against a $V = 19$ mag arcsec$^{-2}$ sky. We expect a factor of at least 2-4 improvement using DoPhot data reductions of photometry at Kitt Peak.
that this is adequate to ensure success.

3.2. Data Analysis

Photometry of each image will be carried out using a modified DoPhot package that is already well tested on microlensing data. The positions and magnitudes of all target stars brighter than 10 mag (and indeed several mag fainter) are already known from Tycho-2. Where necessary, this can be supplemented with USNO-A data to fainter mags. Thus, DoPhot can operate in its more efficient fixed-position mode. The main modification required will be to take account of clouds. In traditional ”small-field” (< 30 arcmin) monitoring, accurate relative photometry is not seriously affected by clouds because the clouds dim all stars by approximately the same amount. This will certainly not be the case for our ∼ 25° field. We will attempt to mitigate this problem by measuring star brightnesses only relative to nearby stars. In the final analysis, however, we expect to lose more time to clouds than is lost in smaller-field monitoring.

Identification of transit candidates should be fairly straightforward. At V = 10 mag, there will be 1% errors (allowing for both scintillation and sky noise). Of course, this is in itself not good enough to plausibly identify the 1% transits due to Jupiter-sized planets. However, a 2-hr transit should yield 11 such measurements and hence a 3σ signal. Hence, it is not necessary to test all possible folds of the lightcurve to search the very large (period/phase) parameter space: one can focus first on the restricted space consistent with all subsets of the 2σ individual transit detections.

In the Northern sky, there are approximately 153,000 stars with V ≤ 10 mag. Gould & Morgan Gould and Morgan (2003) showed that about 104,000 of these can be identified as being significantly evolved or early type (and so too large to be useful for planetary transits) using a Tycho-2 reduced proper motion (RPM) diagram. Rejection of evolved stars will not only speed up the data processing, it will also remove one of the major sources of false candidates, namely K giants blended with eclipsing binaries (whether forming an associated triple or not). Vetting of the remaining candidates by follow up photometry during predicted transits using larger telescopes and by RV measurements will be much easier than for transit candidates from other surveys, simply because the KELT candidates will be extremely bright.
REFERENCES

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