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TAOS – The Taiwanese-American Occultation Survey

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The Taiwanese-American Occultation Survey (TAOS) seeks to determine the number and size spectrum for small (∼3 km) bodies in the Kuiper Belt. This will be accomplished by searching for the brief occultations of bright stars (R ∼14) by these objects. We have designed and built a special purpose photometric monitoring system for this purpose. TAOS comprises four 50 cm telescopes, each equipped with a 2048×2048 pixel CCD camera, in a compact array located in the central highlands of Taiwan. TAOS will monitor up to 2 000 stars at 5 Hz. The system went into scientific operation in the autumn of 2005.

1 Introduction

The discovery of the Edgeworth-Kuiper belt (Jewitt & Luu 1993) opened up a new frontier in solar system astronomy. Note that the observed frontier of the Solar System has progressed only from 10 AU when Kepler deduced his laws of planetary motion in the early 1600's, to 50 AU today[1]. Progress is especially challenging beyond Neptune, because the objects are small, and the brightness in reflected sunlight declines r^{-4}. Objects as faint as R ∼28.5 (Bernstein et al. 2004) have been detected, but further progress requires the use of a technique to probe objects which are much fainter than this. The most promising technique for this purpose is an occultation survey of the outer solar system, because it can probe objects which are smaller and/or more distant than those probed by surveys in reflected sunlight.

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[1] If objects are listed by semi-major axis, instead of location at discovery, this outer limit expands by a factor of four.

2 Occultations of stars by Kuiper Belt Objects

An occultation survey is conceptually straightforward (Bailey 1976; Axelrod et al. 1992; Roques & Moncuquet 2000). One monitors the light from a sample of stars that have angular sizes smaller than the expected angular sizes of small Kuiper Belt Objects (KBOs). An occultation is manifested by detecting the reduction in the flux from one of the stars for a brief interval. The rate of occultations is recorded over the time span of the observations. The measured rate is proportional to the number of objects, and the measured durations and depths of the occultations give size information. The implementation of this idea is complicated by the short expected duration of an occultation event, by the very low event rate, and by diffraction diluting the depths of the occultations[2]. Furthermore, the selection of stars with small angular sizes means that relatively faint stars are used; this increases the probability of false events due to shot noise in the photons.

[2] Diffraction also sets a minimum occultation duration, given by the Fresnel length scale.

Fig. 1 The diffraction pattern produced by a 3 km KBO at 42 AU projected onto the surface of the Earth. The figure comprises a 10 km × 10 km area. An A0V target star is assumed, and the diffraction pattern is integrated over the stellar spectrum convolved with the TAOS filter.

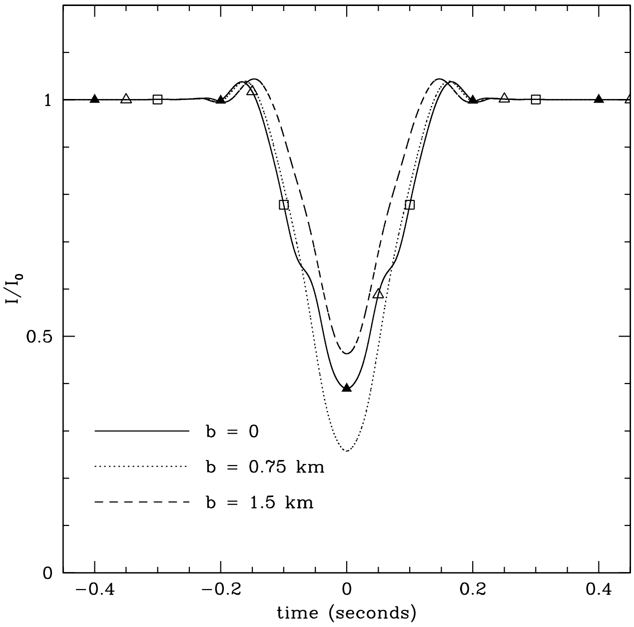

Fig. 2 Lightcurves that would actually be measured from the diffraction pattern shown in Fig. 1. Lightcurves for three different impact parameters are shown. A rolling boxcar average of width 130 ms was applied to each lightcurve to account for the sampling time of the TAOS system. Images will be readout at 200 ms intervals, so the measured lightcurve will be points at 200 ms intervals on the curves shown. For example, a lightcurve comprising either the solid triangles, open triangles, or open squares could be measured.

Figure 1 shows the diffraction pattern produced by a 3 km object at 43 AU. The object is just larger than the Fresnel scale, and strong diffraction effects are evident. Possible lightcurves for such an event are shown in Fig. 2. We assume that the object is at opposition (with relative velocity 25 km/s), smoothed by a "boxcar" window of length 130 ms, corresponding to the TAOS exposure time. The TAOS exposure time is a compromise between CCD performance for high speed operation and anticipated strength of the events. It is approximately the Fresnel scale divided by the transverse velocity at opposition. Note that these curves will be sampled at 200 ms intervals.

We expect TAOS will be able to detect occultations due to objects with diameters $\sim$3 km, but will be able to detect events due to objects with diameters $\sim$1 km only when the target star is relatively bright and hot (i.e. small). A more capable (and expensive) survey would be able to detect much smaller objects. A space based Kuiper Belt occultation survey has been proposed by Roques & Moncuquet (2000).

Figure 3 shows the location of the diffraction limit in a plot of object diameter versus distance. Also shown are lines of constant R magnitude for reflected sunlight (assumed albedo 0.04), and the locations of most of the known KBOs. It is clear that strong occultation events can be produced by objects much smaller than are accessible to direct imaging, and further that occultations perform well at greater distances. Also shown on Fig. 3 are lines of constant projected diameter of a typical A0V target star. If the projected size of the star exceeds the size of the object, the strength of the photometric event will be diluted. TAOS will be mostly limited by diffraction since the majority of our target stars will have magnitudes $13 < R < 15$, a range that yields enough stars on the focal plane ($\sim$2000) to ensure an adequate event rate.

The occultation rate has been estimated by Cooray & Farmer (2003), and it depends sensitively on the assumed size distribution of small bodies in the Kuiper Belt. A break in the size distribution was recently reported (Bernstein et al. 2004), and we estimate that the actual TAOS event rate will thus be $\sim$10 events per year, significantly less than the rate estimated by Cooray & Farmer (2003).

3 The TAOS Robotic Observatory System

The TAOS system was designed to meet the following criteria: (1) make photometric measurements rapidly (5 Hz); (2) follow enough stars to obtain a significant event rate ($\sim$2 000 stars); (3) low false positive rate (0.1 false positive event per year); (4) moderate cost; and (5) credible result when program is complete.

The rapid photometry is be achieved by means of an unconventional use of an otherwise conventional CCD camera. An adequate number of stars can be imaged onto a modern CCD camera mounted on a small (50 cm), wide field-of-view (f/1.9) telescope. Moderate cost can be achieved by

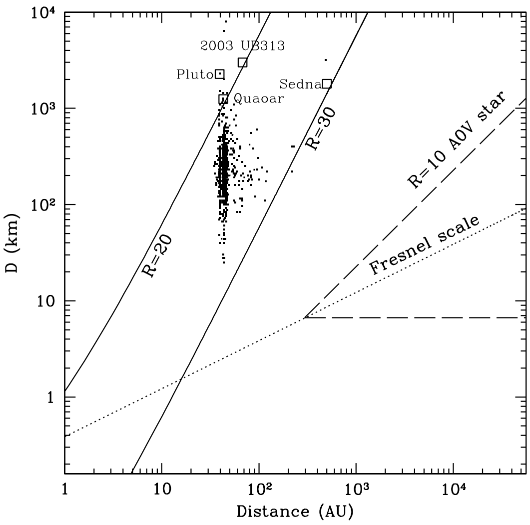

Fig. 3 Diameter of KBO versus heliocentric distance. Known KBOs are plotted as dots (at their semi-major axes), and some of the more well known outer Solar System objects are plotted with the open squares. The division between geometric optics and strong diffraction is shown (dotted line). Lines of constant R magnitude in reflected light are shown (solid lines, albedo 0.04). The top dashed line shows where the angular size of an A0V star is equal to the angular size of a KBO. The bottom dashed line shows where diffraction effects go away, and below this line the occultation event effectively becomes a transit event.

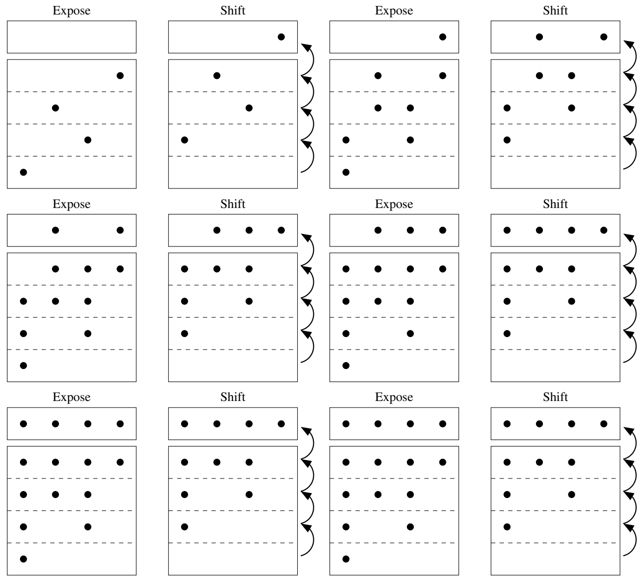

Fig. 4 Illustration of zipper mode operation with the focal plane divided into four row blocks. Note that after the fourth sequence of expose and shift operations that flux from all four stars is read out in each subsequent shift (steady state).

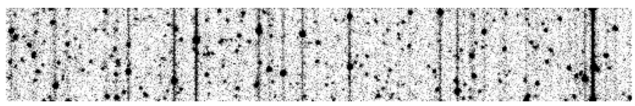

Fig. 5 Zipper mode image comprising a 512×64 subsection of a 2048×64 row block.

using components that are readily available with the minimum of customizing.

Four 50 cm telescopes are employed for this project instead of one 100 cm telescope in order to allow sensitive detection of true occultations and robust rejection of false positive events. The four identical telescopes were manufactured by Torus Technologies of Iowa City, Iowa. The aperture is 50 cm, imaging to a corrected Cassegrain focus at f/1.9. The corrected field-of-view comprises 3 square degrees. Four complete telescope/camera systems are installed at the Lu-Lin Observatory (longitude $120^\circ\ 50'\ 28''$ E; latitude $23^\circ\ 30'$ N, elevation 2850 m), in the Yu Shan (Jade Mountain) area of Taiwan. Three telescopes are currently operational. The fourth telescope was shipped with a defective primary mirror. The mirror has been repolished and reinstalled, and we expect to have the telescope operational by the autumn of 2006.

Each telescope is equipped with a Spectral Instruments Series 800 CCD camera employing a thinned, backside-illuminated 2048 2048 E2V 42-40 CCD chip. The CCD chip is thermoelectrically cooled and has peak quantum efficiency of $> 97\%$, and mean quantum efficiency over the spectral range we will employ ($400\,\mathrm{nm} < \lambda < 720\,\mathrm{nm}$) of $> 90\%$. There are two read channels, which work comfortably at a combined speed of 2 MHz.

The telescopes are fully robotic. Each clear night, the enclosure lids open automatically, and observations commence. Each enclosure is equipped with weather sensors, and the lids will automatically close when bad weather conditions occur. A control daemon schedules zipper mode observations on preselected fields. A field is observed for a period of $\sim$2 hours, then a different field is selected, such that we only observe at high elevations.

The observation and data handling system is designed to use the CCD area efficiently, and to allow photometric monitoring at 5 Hz without excessive read noise generation on the CCD. This is achieved with a mode of CCD operation that we call "zipper mode" (Liang et al. 2002). Zipper mode differs from conventional operation in the manner in which the CCD is read out. The telescope tracks the sky, and stars are imaged onto the focal plane. In a typical zipper mode operation, every 200 ms a "row block" of 64 rows will be read out at 2×10^6 pixels per second, which takes $\sim$70 ms. The remaining 130 ms "hold" is then repeated, followed by another read. This cycle may be repeated for extended periods of time, up to hours. This is illustrated in Fig. 4, and a sample image is shown in Fig. 5. The analysis must combine the photometry from the telescopes to optimally detect true events and reject false positives, and to allow rigorous determination of the statistical significance of accepted events

(Liang 2001; Liang et al. 2002). Examples of non-Poisson errors which might give rise to false occultation events are extreme atmospheric scintillation events, and transient objects such as birds, bats, or airplanes. We suspect that the atmospheric events will be the most troublesome. A true occultation will be detected in all four telescopes, while the false events mentioned above will typically be manifested in one or possibly two. We set our acceptable rate of false positives to 0.1/y, which will allow us to detect events which show a reduction in flux of 40% in stars with $R \sim 14$.

The system is connected to the GCN and will automatically respond to Gamma Ray Burst (GRB) events. The system has been listening on the GCN since autumn of 2005 and has responded to several alerts, but to date all of the alerts have been false alarms. All three of the currently operating telescopes are available for alert follow-up, and the fourth will be available as well. We currently plan on modifying our response strategy to have each of the telescopes operate in different modes. For example, one telescope may read out in zipper mode to get high frequency coverage of possible bright events. Two of the telescopes could take 2.5 second images synchronized such that one camera reads out while the other is exposing, providing constant coverage. Meanwhile, the fourth telescope could take 10 or 20 second exposures to search for faint afterglows. The TAOS system could also be set up to respond to other targets of opportunity. Decisions in this regard will be made by the TAOS science team on a case by case basis.

4 Summary

TAOS is the first occultation survey to target KBOs with sizes in the kilometer range. This is the only technique that can plausibly investigate objects this small. The TAOS system will make photometric measurements at the high rate needed to detect these very rare events. Data collection has begun with three telescopes. The fourth telescope will come online in the autumn of 2006, and an initial version of the analysis pipeline is expected to be completed by the end of 2006.

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