TAOS: THE TAIWANESE–AMERICAN OCCULTATION SURVEY

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Abstract. The Taiwanese–American Occultation Survey (TAOS) seeks to determine the number and size spectrum for small ($\sim$ 3 km) bodies in the Kuiper Belt. This will be accomplished by searching for the brief occultations of bright stars ($R \sim 14$) 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 $\times$ 2048 pixel CCD camera, in a compact array located in the central highlands of Taiwan. TAOS will monitor up to 3, 000 stars at 5 Hz. The system will go into scientific operation at the end of 2003.

1. Introduction

The discovery of the Edgeworth–Kuiper belt (Jewitt and Luu, 1993) opened up a new frontier in solar system astronomy. The flood of discoveries which followed and the fascinating theoretical challenges raised have been described and celebrated at this meeting, and are ably described elsewhere in this volume.

Note that the observed frontier of the Solar System has progressed only from $\sim$10 AU when Kepler deduced his laws of planetary motion in the early 1600's, to $\sim$50 AU today.* Progress is especially challenging beyond Neptune, because the objects are small, and the brightness in reflected sunlight declines $\propto r^{-4}$. The CCD

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

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revolution led to the discovery of the first Kuiper Belt Object and has the potential to detect objects as faint as $R \sim 28.5$ (e.g. the deep survey with the Advanced Camera for Surveys on the *Hubble Space Telescope*, see Holman's article in this volume). 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.

2. Occultations of Stars by KBOs

An occultation survey is conceptually straightforward (Bailey, 1976; Axelrod et al., 1998; Roques and Moncuquet, 2000). One monitors the light from a sample of stars that have angular sizes smaller than the expected angular sizes of small 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. (Diffraction also sets a minimum occultation duration, given by the Fresnel length scale.) 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.

Figure 1 shows occultations by two spherical KBOs at 43 AU. The smaller object, diameter 1.0 km, is smaller than the Fresnel scale $a \sim (r\lambda)^{1/2}$, and the larger, diameter 3.0 km, is just larger than the Fresnel scale. Strong diffraction effects are evident in both lightcurves, but the larger object shows very strong photometric modulation. The top panels show *static* (star, object, and observer in fixed locations) lightcurves, for monochromatic light. The bottom panels show show the same events for light from an A0 star, the broad (400–800 nm) bandpass of the TAOS system, observed at opposition (relative velocity $\sim$25 km/s), smoothed by a “boxcar" window of length 200 msec (corresponding to the TAOS exposure time).⋆ Note that data points will sample these curves at 200 msec intervals.

We expect TAOS will be able to detect occultations due to objects with diameters $\gtrsim$3 km, but will be able to detect events due to objects with diameters $\lesssim$1 km only when the target star is relatively bright and hot. 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 and Moncuquet (2000).

⋆ 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.

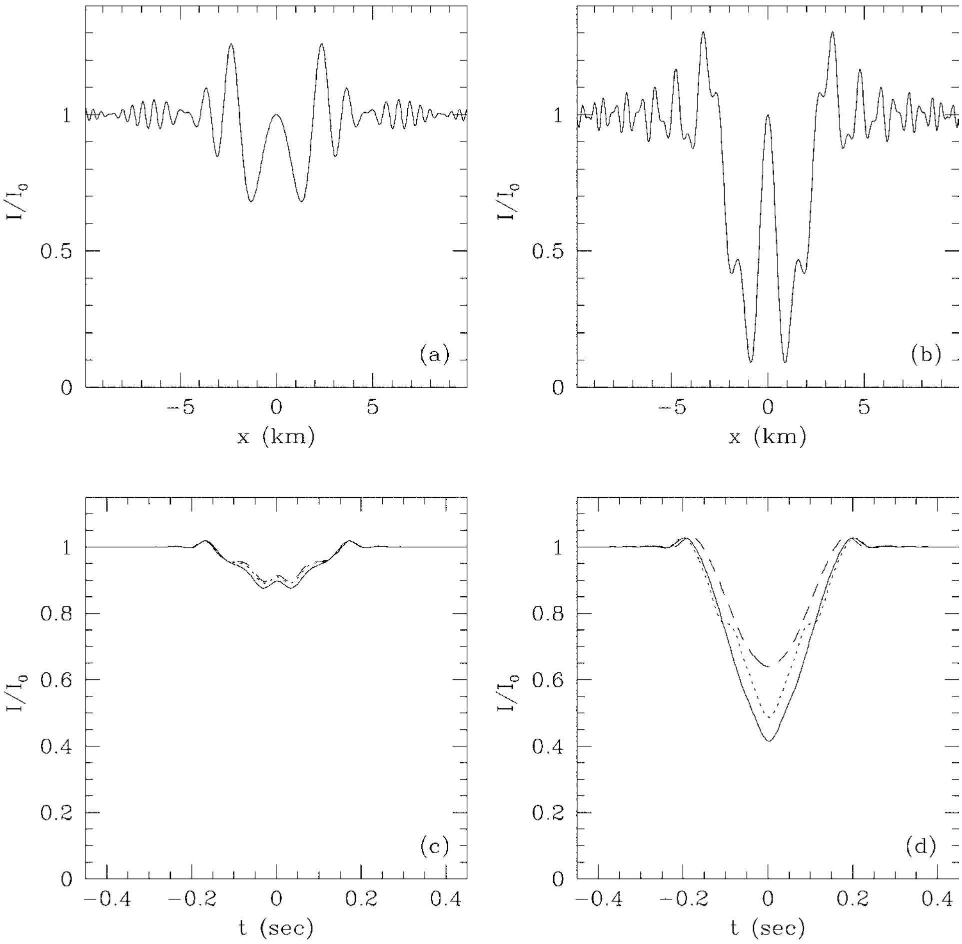

Figure 1. Occultations by small, spherical objects at 43 AU. (a) Relative intensity versus distance to center of shadow for object of diameter 1.0 km, light of wavelength $\lambda = 600$ nm. (b) As for (a), but diameter 3.0 km. (c) Lightcurve of occultation event for same geometry as (a), viewed at opposition (shadow moves at 25 km/s), light from an A0 star, bandpass 400–800 nm. Impact parameter of event 0.0 km (solid line), 0.25 km (dashed line), and 0.50 km (dotted line). (d) As for (c), but diameter 3.0 km, and impact parameter of event 0.0 km (solid line), 0.75 km (dotted line), and 1.50 km (dashed line).

Figure 2 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 Figure 2 are lines of constant projected diameter of the target stars. 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

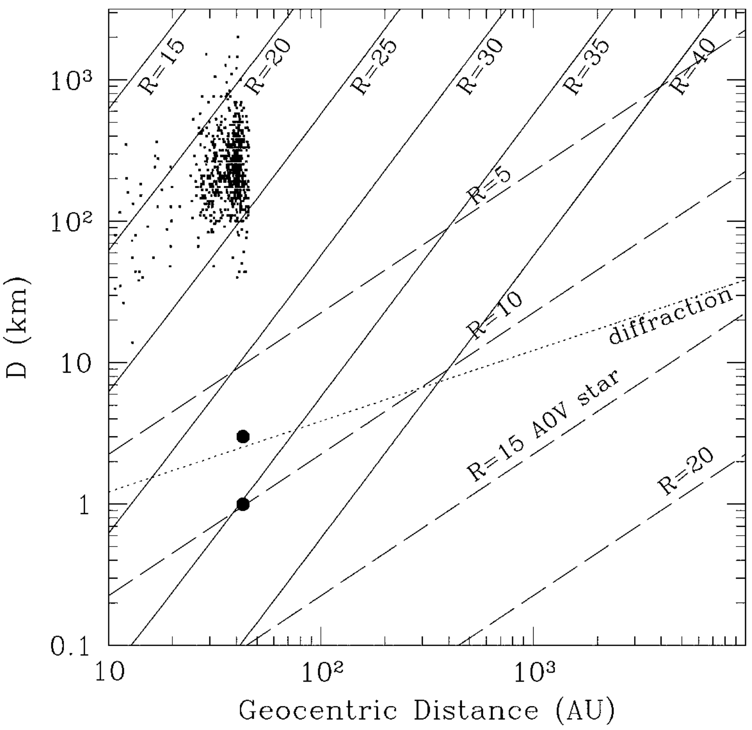

Figure 2. Diameter of KBO versus geocentric distance. Known KBOs are plotted as dots. The division between geometric optics and strong diffraction is shown (dotted line). Lines of constant R magnitude in reflected light are shown (solid lines, albedo 0.04). Stars with projected size equal to the size of the object are shown, labeled by their apparent R magnitude (dashed lines, A0 star). The two cases presented in Figure 1 are shown as filled circles.

limited by diffraction since the majority of our target stars will have magnitudes $13 \lesssim R \lesssim 15$, a range that yields enough stars on the focal plane ($\sim$ 3000) to ensure an adequate event rate.

The occultation rate has been estimated by Cooray and Farmer (2003), and it depends sensitively on the assumed size distribution of small bodies in the Kuiper Belt. We estimate that the actual TAOS event rate will be $\sim$20% of the Cooray and Farmer number, yielding $\sim$650 TAOS events per year.

3. The TAOS Robotic Observatory System

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

The rapid photometry will be achieved by means of the innovative 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 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. Two complete telescope/camera systems are installed at the Lu-Lin Observatory (longitude 120° 50' 28" E; latitude 23° 30' N, elevation 2850 meters), in the Yu Shan (Jade Mountain) area of Taiwan. Two more are in Taipei, Taiwan, and will be installed by the end of 2003.

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

The observation and data handling system is designed to use the CCD area efficiently, and to allow photometric monitoring at $\sim$5 Hz without excessive read noise generation on the CCD. This is achieved with a novel mode of CCD operation that we call "zipper mode". 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 msec a "row block" of 64 rows will be read out at 2×10^6 pixels per second, which takes $\sim$65 msec. The remaining $\sim$135 msec "hold" is then repeated, followed by another read. This cycle may be repeated for extended periods of time, up to hours.

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/year, which will allow us to detect events which show a reduction in flux of 40% in stars with $R \sim 14$.

4. Summary

TAOS will be 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. Scientific operation will commence at the end of 2003.

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