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FAST CCD PHOTOMETRY IN THE TAIWAN-AMERICA OCCULTATION SURVEY

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Abstract. We describe the efforts of the Taiwan-America Occultation Survey (TAOS) project to develop a data acquisition and analysis scheme for fast CCD imaging photometry. The TAOS project aims to conduct a census of the Kuiper-belt objects (KBOs) by detecting chance stellar occultation events by these small bodies in the outer reach of the solar system. An array of telescopes, each with fast optics (f/2) of 0.5 m aperture and equipped with a 2K CCD camera (3 square degrees FOV), have been set up in central Taiwan to monitor a couple thousand stars simultaneously. By reading out the CCD chip sequentially a few rows of pixels at a time (pause-and-shift), it is possible to achieve stellar photometry with a sampling rate up to several hertz. Here we report how such a setup has been used to observe the SX Phoenicis type variable CY Aqr to illustrate the potential usefulness of the TAOS database in stellar variability studies.

Key words: solar system: Kuiper belt objects – methods: observational – techniques: photometric

1. THE KUIPER-BELT OBJECTS

The solar system is believed to have condensed out of an interstellar cloud of gas and dust, in which the hot, central part contracted to form what later became the Sun, whereas in a surrounding rotating disk, solid grain particles continued to grow, and eventually coagulated to form planets (and satellites). Surplus material from star and planet formation, particularly the bombardment of planetesimals, played an important role in the early evolutionary history of the planets. At the outer reach of the protoplanetary disk, the density was low, so there was not sufficient time to condense to make giant planets. A large population of planetesimals may still exist in their pristine state, distributed in a ring- or disk-like structure extending along the plane of the ecliptic, known as the Kuiper belt (Edgeworth 1949, Kuiper 1951). It is possible that the Kuiper belt extends to ~1000 AU (Stern 2003). Such a cometary belt may be ubiquitous, manifested as circumstellar disks around nearby stars (Aumann et al. 1984, Macintosh et al. 2003).

Since 1992 (Jewitt & Luu 1993), several hundred Kuiper-belt Objects (KBOs) have been found that lie beyond the orbit of Neptune, including Pluto (see http://www.boulder.swri.edu/ekonews/ for the latest statistics and relevant research information.) These small objects might have been influenced by the migration of giant planets during early evolution (Gomez 2003, Morbidelli & Levison 2003), experienced thermal, radiation, and collisional processes (Stern 2003), and hence a variety of distinct subclasses may exist (Horner et al. 2003).

The KBOs, also known as Trans-Neptunian Objects (TNOs), are seen in reflected sunlight, so only the largest (sizes greater than tens of kilometers) or those relatively near the Sun (heliocentric distances less than about 50 AU at discovery, i.e., only at the near edge of the Kuiper belt) could be detected by large telescopes. Even smaller objects, expected to be much more numerous on theoretical grounds, still cannot be seen even by the presently most sensitive instruments. Imaging survey observations suggest a possible depletion of faint (small) KBO population (Chiang & Brown 1999), perhaps as a result of the evacuation due to gravitational perturbation after the giant planets formed, and to collisions among planetesimals (Stern 1996). Does the Kuiper belt terminate at 50 AU? Are KBOs concentrated on the ecliptic plane? How many of them are there anyway? A complete census of the KBOs (total number, size and spatial distributions) will shed crucial light on the dynamical evolution of planetesimals, and of early history of planetary formation (Luu & Jewitt 2002). To detect the small KBOs, we would need techniques other than direct imaging.

2. THE TAIWAN-AMERICA OCCULTATION SURVEY

The Taiwan-America Occultation Survey (TAOS) is a collaboration among institutions in Taiwan, U.S.A. and Korea, aiming to detect chance stellar occultation events by KBOs (Chen 1999). Such an occultation will cast a shadow on the Earth's surface, so an Earth-bound observer should detect a disappearing blink of the starlight in a fraction of a second. The concept has been studied (Cooray 2003) and sporadic observations have been attempted (Roques et al. 2003). The frequency of the events gives a statistical estimate of the total number of the KBOs. Essentially it is like "*guessing the number of mosquitoes at night by seeing them silhouetted against park light*".

Because the detection of an event relies on the signal-to-noise of the target *background star*, rather than on that of the KBO itself, the distance of the KBO is irrelevant as long as geometric optics prevails (i.e., the KBO is not too far away so appears too small compared to the angular size of the star and diffraction effect sets in.) The occultation technique, sensitive to KBOs with heliocentric distances up to several hundred AUs and diameters down to 1–2 km, provides an innovative and so far the only means to complete the inventory of small objects out to the edge of the solar system.

An array of telescopes, each with fast optics (f/2) of 0.5 m aperture (by Torus, U.S.A.) and equipped with an SI-800 2K CCD camera (by Spectral Instruments, U.S.A.) have been set up in central Taiwan. The imaging system, with 3" pixels, gives an FOV of three square degrees to monitor simultaneously a few thousand stars. Three telescopes have already been installed and the fourth will be ready in early 2004, after which the survey shall commence. All telescopes will operate synchronously on the same target field at any given moment. Any possible event is subjected to a coincidence check of data from all telescopes.

The TAOS experiment is being carried out at Lulin Observatory. The site – elevated at 2880 m above sea level amid the mountain ranges in central Taiwan – came to full operation in the fall of 2002, after a decade of astroclimate evaluation, site preparation and infrastructure development, led by National Central University. It is adjacent to Jade Mountain National Park, and is reasonably dark, $V \approx 20.7$ mag arcsec^{-2} and $B \approx 21.2$ mag arcsec^{-2}, with good sky transparency. Typical seeing is 1.3–2.0". There are about 180–200 usable nights per year, mostly in late fall and winter.

In addition to the TAOS facilities, there is the Lulin 1 meter telescope (LOT) for general-purpose CCD imaging observations. Its western Pacific and subtropical location (E120° 52" 25′, N23° 28" 07′, very near the Tropical of Cancer) renders Lulin Observatory a vantage site in terms of longitudinal and sky coverage, particularly as part of a global telescope network. The TAOS telescopes particularly are geographically well positioned to observe the ecliptic – where perhaps the majority of KBOs reside – all year round.

Occultations by KBOs are expectedly extremely rare. Furthermore each event would last for less a second. These impose stringent challenges on hardware and software, e.g., low false rate, fast sampling and efficient event detection, etc. Photometric measurements should be as frequent and for as many stars as possible.

3. FAST CCD IMAGING PHOTOMETRY

To achieve sampling in less a second, the camera continuously reads out a sequential block of rows (e.g., 32 or 64 rows at a time) of the CCD chip after each pause (integration), while the shutter remains open and the telescope keeps tracking on the same target field. This electronic 'pause-and-shift' scheme essentially produces a sequence of snapshots for each star, i.e., a light curve, in the field with very high time resolutions. The image at any time will be filled with stars each of which, as time goes on, trails like a zipper (Figure 1), hence the name 'zipper' image. The readout continues until the CCD computer RAM buffer is full. Such a 'zipper' image will then be divided into row-blocks, each of 32 × 2048 pixels, for stellar photometry. The duration of the pause-and-shift cycles, i.e., the sampling time and the integration time are both adjustable.

Each row-block image is folded from, and hence crowded with all the stars in, the original sky image. Furthermore, the flux next to a star, be it another star or sky, in general is not a true neighbor, but instead may come from a different patch of the sky and from different time. This unusual feature in the TAOS data needs to be taken into account in stellar photometry.

With the current setup, the effective integration time is the difference between the sampling interval, typical 200 ms or 300 ms, and the read/shift time, which amounts to about 1.25 ms per row. So for a 300 ms sampling, and 64 × 2048 row-blocks, the effective integration time would be 220 ms. Processing in almost real time of

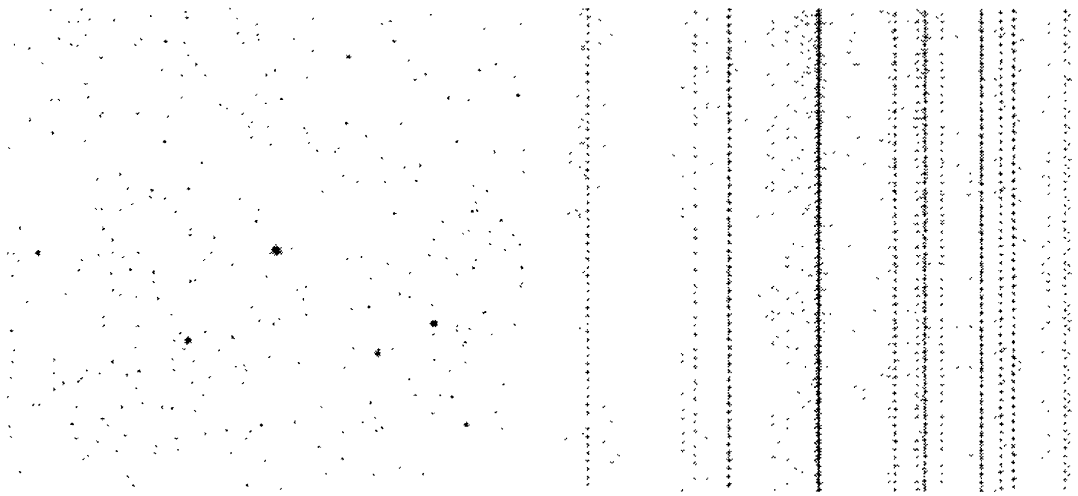

Fig. 1. An illustrated star field taken (left) by standard "star" imaging and (right) by the pause-and-shift ("zipper") procedure.

(e.g., 0.3 s) several thousand light curves is a daunting but rewarding task, as in addition to searching for possible KBO occultations, stellar variability or some transient phenomena can be studies with the database.

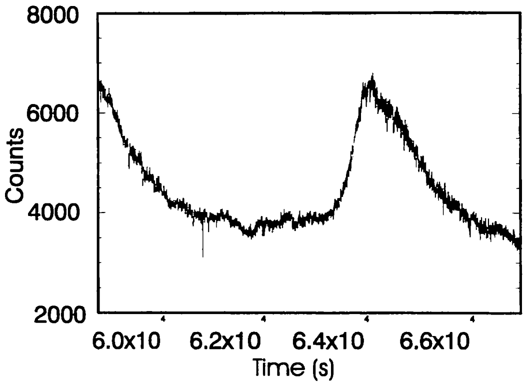

Fig. 2. The TAOS light curve of CY Aqr, estimated by the flux within a 3×3 aperture box, with the sky subtracted. The abscissa is time in s from UT=0^h September 16, 2003. The original 0.3 s data have been smoothed 10 times for illustration clarity.

Figure 2 shows the preliminary result of a known large-amplitude Delta Scuti star, CY Aquarii (BD+0°4900) observed on 16 September 2003 by one of the TAOS telescopes. No filter was used. CY Aquarii is an SX Phoenicis type variable with large amplitude (0.7 mag and 0.9 mag in V and B bands, respectively) and a short period (87.9 min). Additional periods have also been detected (e.g., Powell et al. 1995, Fu & Sterken 2003). The 88 min variation can be clearly seen, though the data run was not long enough to determine the period precisely. It is encouraging that even with only 0.22 s integrations, there is sufficient signal-to-noise to reveal the variation amplitude. Obviously further time-series analysis would be needed to uncover the possible wealth of variability information.

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