Asteroids: New Observations, New Models
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DEEP-South: Network Construction, Test Runs and Early Results

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Abstract. Korea Microlensing Telescope Network (KMTNet) which consists of three identical 1.6 m wide-field telescopes with 18k × 18k CCDs, is the first optical survey system of its kind. The combination of fast optics and the mosaic CCD delivers seeing limited images over a 4 square degrees field of view. The main science goal of KMTNet is the discovery and characterization of exoplanets, yet it also offers various other science applications including DEep Ecliptic Patrol of SOUTHern sky (DEEP-South). The aim of DEEP-South is to discover and characterize asteroids and comets, including Near Earth Objects (NEOs). We started test runs last February after commissioning, and will return to normal operations in October 2015. A summary of early results from the test runs will be presented.

Keywords. minor planets, asteroids, surveys

1. Introduction

Demand for Physical Characterization As of August 31st 2015, more than 13,000 Near Earth Objects (NEOs) have been catalogued; however, the physical properties are only known for a tiny fraction of them. For instance, the percentage of NEOs with a known rotational period (P_{rot}) is 6.3%, yet the fraction for which we know P_{rot} and B-V simultaneously is less than 1%. This is why physical characterization of the population has been an important problem for decades. We note that a timely and economical solution to this long-pending question is time-series broadband photometry with medium-sized telescopes.

Demand for Global Sky Coverage The lack of a meter-class telescope for NEO research in the southern hemisphere has been an issue for several decades. For this reason, there is a growing need for systematic survey and characterization of NEOs on the other side of the ecliptic, and to bridge gaps, there has been a higher demand for the coordinated use of telescopes (Chapman *et al.* 2001) in the southern hemisphere.

Korea Microlensing Telescope Network In 2009, Korea Astronomy and Space Science Institute (KASI) started to design and build KMTNet, which consists of three identical 1.6 m prime focus telescopes with 18k × 18k CCD camera, an array of four chips with 9600 × 9600 pixels (Fig. 1). This wide-field optics and the CCD provides seeing limited images over a 4 square degrees field of view, with a plate scale of 0".4/pixel (Kim *et al.* 2010). They started telescope and CCD installation in May 2014 at Cerro Tololo Interamerican Observatory (CTIO), South African Astronomical Observatory (SAAO), and Siding Spring Observatory (SSO) (Fig. 2). Construction and commissioning was

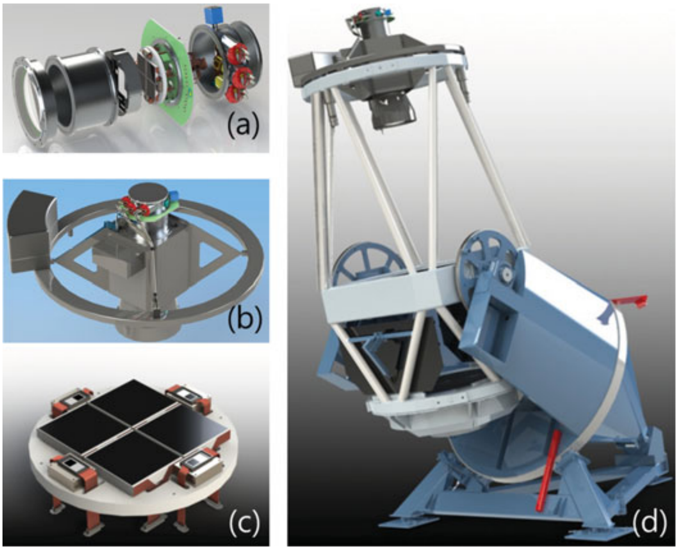

Figure 1. (a) Corrective lens/CCD camera assembly, (b) top ring, (c) 18k × 18k mosaic CCD and (d) 1.6 m KMTNet telescope

Figure 2. KMTNet observatories at CTIO, SAAO and SSO

successfully completed in May 2015, and fine-tuning is in progress. As its name implies, KMTNet aims to find extrasolar planets using gravitational microlensing events towards Galactic bulge when it lies above the horizon (Park *et al.* 2012). In the rest of the year, this network of telescopes is devoted to other key science projects such as studies of asteroids and comets, variable stars, supernovae (SNe) and galaxies.

Deep Ecliptic Patrol of the Southern Sky The three KMTNet observatories are longitudinally well separated, and thus will have the benefit of 24-hour continuous monitoring of the southern sky. The wide-field and round-the-clock operation capabilities of this network facility are ideal for the discovery and physical characterization of asteroids and comets, such as orbits, absolute magnitudes (H) shapes and spin states. Their approximate surface mineralogy will also be discriminated based on broadband colors (Carvano *et al.* 2010). The automated observation scheduler, the data pipeline, the cloud computing facility, related research activity and the team members are collectively called 'DEEP-South'.

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Table 1. DEEP-South observation modes

Mode	Region	Description
OC	opposition	targeted photometry for physical characterization
NW	opposition	follow-up photometry of NEOWISE objects
S1	sweet spots	blind survey in search for Atens and Atiras (IEOs)
S2	ecliptic	blind survey for MBAs and KBOs
TO	-	target of opportunity observation

2. Overview

Observation Modes DEEP-South observation is made during the off-season for exoplanet search, yet part of the time is shared during the period between when the Galactic bulge rises early in the morning and sets early in the evening. We were awarded 12.5% of the telescope time at each site every year between 2015 and 2019, corresponding to 135 full nights a year for the network. Most of the allocated time is devoted to targeted photometry of NEAs near opposition, called Opposition Census (OC). OC targets km-sized Potentially Hazardous Asteroids (PHAs) in early stage and goes down to sub-km PHAs when there are few objects within the observation window. Then we continue to extend to km-sized and sub-km NEAs in later stages. Johnson BVRI (mainly R-band) is used most of the time, yet SDSS *griz* filters will be applied at CTIO a couple of weeks a year. Typical exposure of 60 sec at sidereal tracking is employed so that streak length of an object does not exceed the size of a seeing disk. Fraction of the DEEP-South time is also assigned to measure spin states and colors of objects either in the main-belt or in the Kuiper belt, for 'Ecliptic Survey' (S2). At the same time, we will conduct 'NEOWISE (Mainzer *et al.* 2011) follow-up' (NW) and Target of Opportunity (TO) observations, the latter for unpredictable events and urgent follow-up alerted by the Minor Planet Center (MPC). Sweet spot survey (S1) is being planned to scan the sky at lower solar elongations for discovery and track of Atens and Atiras every early morning and in the evening (Table 1).

Data Mining Data mining of the KMTNet bulge and SNe archives for detection and characterization of moving objects will soon be accomplished. The Bulge monitoring was awarded 50% of the total telescope time while 17.5% of the time was scheduled for SNe search. We will take full advantage of the fact that each of these projects takes 60-sec exposure, similar to that of DEEP-South. As the exoplanet search team points the telescopes at a 4 degree by 4 degree selected crowded field towards the Galactic center (Park *et al.* 2012), the detection of mover candidates will be a good challenge.

Target Fields We defined 10,536 target fields (TFs) in equatorial coordinates and assigned a name to each TF with respect to ecliptic coordinates, and the size of each corresponds to 4 square degrees, exactly the same as that of the 18k $\times$ 18k CCD. TF offers several advantages: it enables (1) systematic debiasing of the main-belt asteroids for population studies and (2) the monitoring of the long-term variability of comparison stars in each CCD image. In addition, we could benefit from (3) convenience either in observation scheduling, telescope operations or data reduction and analysis.

Strategy We know little about the fraction of asteroids with lightcurves (LCs) spanning longer than 8-10 hours as it is very difficult to obtain non-aliased, photometrically

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calibrated data on longer time scales. Sparsely-sampled long-duration LCs covering periods longer than 8-10 hours can be presented by S1, while more densely-sampled LCs will be acquired with OC. We obtain the spin state and the three-dimensional shape model of an asteroid from LCs (Kassaleinen *et al.* 2002); while we can monitor color variations using BVRI colors to find any evidence for inhomogeneity or collisions in the recent past. It is critical that absolute magnitude H and slope parameter G are estimated to have been measured for less than 1% of the total population. This is why we plan to derive phase curves and optical albedos of asteroids over the course of this five year photometric survey.

Test Runs After the successful commissioning, we embarked on DEEP-South test runs during the autumn season in 2015 at KMTNet-CTIO, with observation time spanning from ~8 minutes to ~6 hours per night. Following an interruption by the bulge season in mid-winter, we resumed the test run in late July with three KMTNet telescopes. As of early August 2015, we reconstructed preliminary LCs of ten km-sized PHAs, three NHATS (Near Earth Object Human Accessible Target Study) objects, and three comets. In parallel, we surveyed seven S2 fields during the same period. The results of the test runs are presented in Kim *et al.* (2015). They acquired ~10 preliminary LCs of PHAs, including 5189 (1990 UQ), 53426 (1999 Sl5), 385186 (1994 AW1) and 436724 (2011 UW158) and derived their rotational periods.

Observation Scheduler and Data Pipeline We designed a highly automated observation scheduler and pipeline for data reduction and analysis called 'DEEP-South Scheduling and Data reduction System' (DS SDS) (Yim *et al.* 2015). A significant portion of this software subsystem has already been implemented and is being applied. For this purpose, we make use of a cloud computing facility called 'KAYROS' located at Korea Institute of Science and Technology Information (KISTI), with 280 virtual cores for scheduling, moving object detection, lightcurve analysis and management of either workflow or the virtual cluster.

3. Implications

With OC mode, the serendipitous discovery, astrometry and photometry of ~10-10^2 objects passing through each image is anticipated every night. They are either known or unknown objects, from near Earth space to the outer reaches of the Solar System. We also expect to obtain physical and mineralogical properties of >10^3 NEOs, and to discover and characterize ~10^4 main-belt asteroids and dozens of comets during the five-year mission. In the long run, it is expected that we will be able to provide the scientific community with a unique and homogeneous database on minor planets.

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