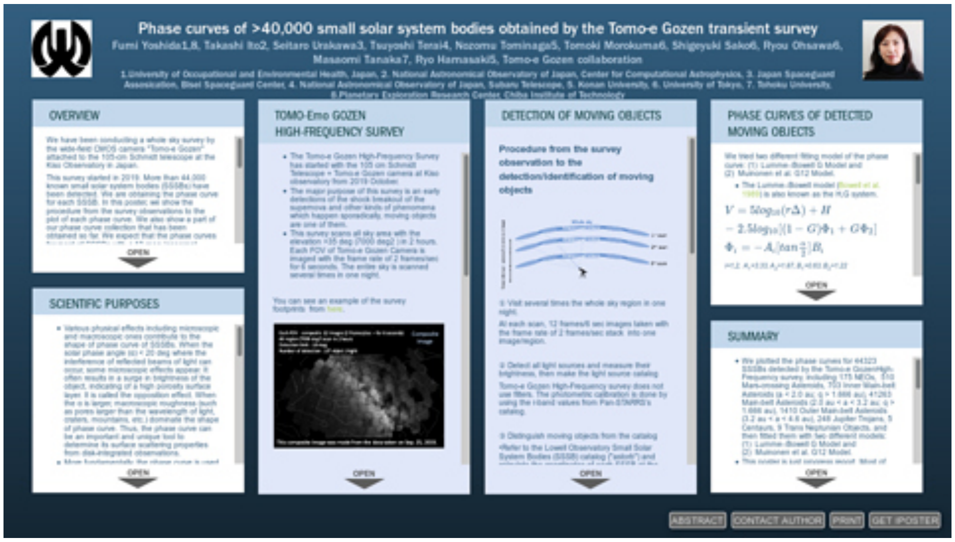
Phase curves of >40,000 small solar system bodies obtained by the Tomo-e Gozen transient survey



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PRESENTED AT:

OVERVIEW

We have been conducting a whole sky survey by the wide-field CMOS camera "Tomo-e Gozen" attached to the 105-cm Schmidt telescope at the Kiso Observatory in Japan.

This survey started in 2019. More than 44,000 known small solar system bodies (SSSBs) have been detected. We are obtaining the phase curve for each SSSB. In this poster, we show the procedure from the survey observations to the plot of each phase curve. We also show a part of our phase curve collection that has been obtained so far. We expect that the phase curves for most of SSSBs with < 18 mag (apparent magnitude) can be obtained by the end of the Tomo-e GozenHigh-Frequency survey.

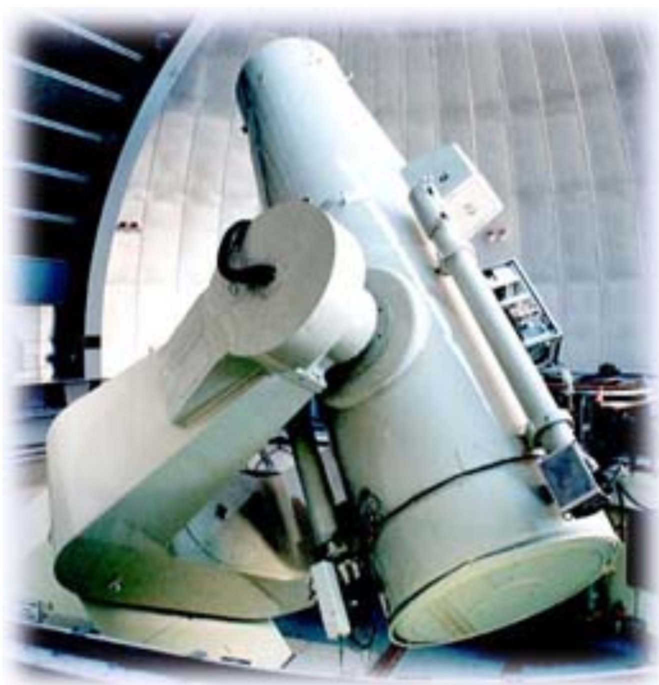
Instruments

The Tomo-e Gozen High-Frequency Survey (Tomo-e Gozen transient survey on the title was renamed) started from 2018 November at the 105 cm Schmidt Telescope + Tomo-e Gozen at Kiso observatory (Institute of Astronomy, School of Science, The University of Tokyo, 10762-30, Mitake, Kiso-machi, Kiso-gun, Nagano 397-0101, Japan).

The 105 cm Schmidt Telescope (http://www.ioa.s.u-tokyo.ac.jp/kisohp/TELS/tels_e.html)

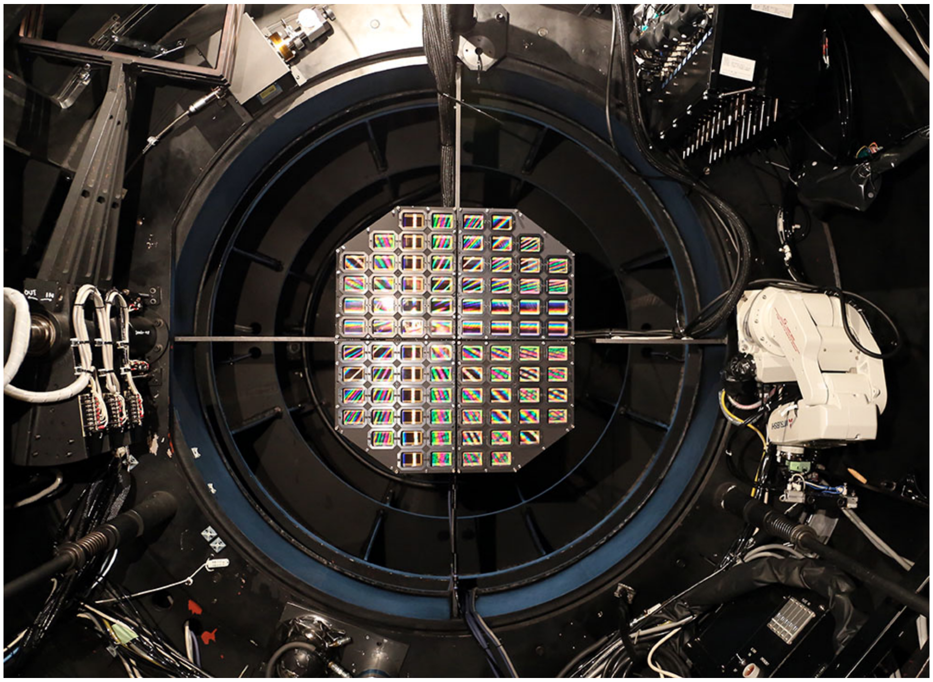
[Location] 137d37m31.5s E, 35d47m50.0s N, Altitude: 1132m

Operated by Institute of Astronomy, School of Science, The University of Tokyo (10762-30, Mitake, Kiso-machi, Kiso-gun, Nagano 397-0101, Japan).



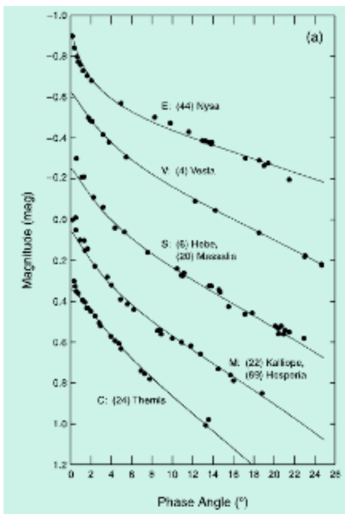
Tomo-e Gozen Camera (http://www.ioa.s.u-tokyo.ac.jp/kisohp/NEWS/tomoe_fm_firstlight.html)

First astronomical wide-field video camera. FOV: 20 square degrees covered with 84 chips 35mm full HD CMOS image sensor with 190 Mpixels. It can take a video in 2 frames/sec (Sako et al. 2018 (https://ui.adsabs.harvard.edu/abs/2018SPIE10702E..0JS /abstract)).

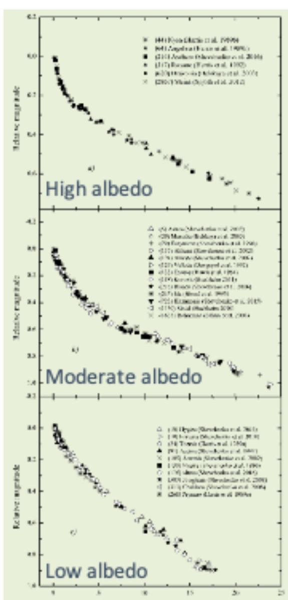


SCIENTIFIC PURPOSES

- Various physical effects including microscopic and macroscopic ones contribute to the shape of phase curve of SSSBs. When the solar phase angle (α) < 20 deg where the interference of reflected beams of light can occur, some microscopic effects appear. It often results in a surge in brightness of the object, indicating of a high porosity surface layer. It is called the opposition effect. When the α is larger, macroscopic roughness (such as pores larger than the wavelength of light, craters, mountains, etc.) dominate the shape of phase curve. Thus, the phase curve can be an important and unique tool to determine its surface scattering properties from disk-integrated observations.
- More fundamentally, the phase curve is used to estimate the absolute magnitude (H) of each object, which is one of essential parameter to determine asteroid's size. The brightness of an SSSB at α = 0 deg corresponds to its H. Since the brightness of SSSB cannot always be measured at α = 0, multiple observations are required to estimate the brightness at α = 0 by fitting each data point obtained at different α. Such observations take usually long time, because of the following reasons (1) we must obtain lightcurves at each α to reduce an influence of brightness variation due to its rotation, (2) we must wait the phase angle of the object changes. Therefore, the H of most asteroids in the catalog would be estimated under assumption that a typical slope parameter (G) is 0.15.
- On the other hand, it is well known that the G value depends on asteroid’s type or albedo (see right figures).
- Under these situations, we think that re-estimating "precise H" based on its phase curve is very important/essential task.



Muinonen et al. in Asteroid III p.124 (2002) (https://ui.adsabs.harvard.edu/abs/2002aste.book..123M/abstract)

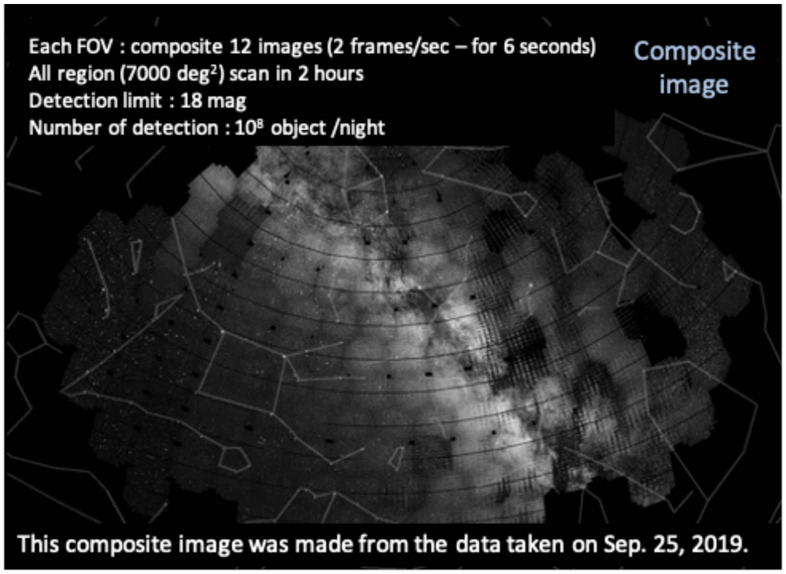


Shevchenko et al. A&A 626, A87 (2019) (https://ui.adsabs.harvard.edu/abs/2019A%26A...626A..87S/abstract)

TOMO-EMO GOZEN HIGH-FREQUENCY SURVEY

- The Tomo-e Gozen High-Frequency Survey has started with the 105 cm Schmidt Telescope + Tomo-e Gozen camera at Kiso observatory from 2019 October.
- The major purpose of this survey is an early detections of the shock breakout of the supernova and other kinds of phenomena which happen sporadically, moving objects are one of them.
- This survey scans all sky area with the elevation >35 deg (7000 deg2) in 2 hours. Each FOV of Tomo-e Gozen Camera is imaged with the frame rate of 2 frames/sec for 6 seconds. The entire sky is scanned several times in one night.

You can see an example of the survey footprints from here (http://www.ioa.s.u-tokyo.ac.jp/kisohp/NEWS/pr20190930/skymap20190925_x3000.mp4).



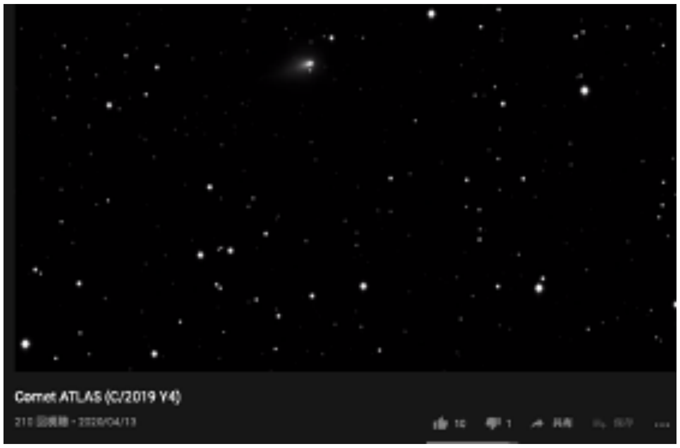
- The detection limit is ~ 18 mag.
- The data amount is ~30 TB/night.
- About 100 nights/year are used for this survey.
- The survey is planned to continue more than 10 years.


(http://www.ioa.s.u-tokyo.ac.jp/kisohp/NEWS/pr20190930/trail_20151214_2fps.mp4)

Tomo-e caught a meteor in its frame.

A meteor came in from the right top and then disappeared, its trail remained for a while. Continuous imaging with 2 frame /sec exposure. FOV is one of 84 CMOS sensors, 5x speed playback.

You can watch some videos taken by Tomo-e Gozen camera on Youtube (https://www.youtube.com/channel/UCb716QkXJ0hLaa3c2reytdw?fs=1&modestbranding=1&rel=0&showinfo=0?fs=1&modestbranding=1&rel=0&showinfo=0).

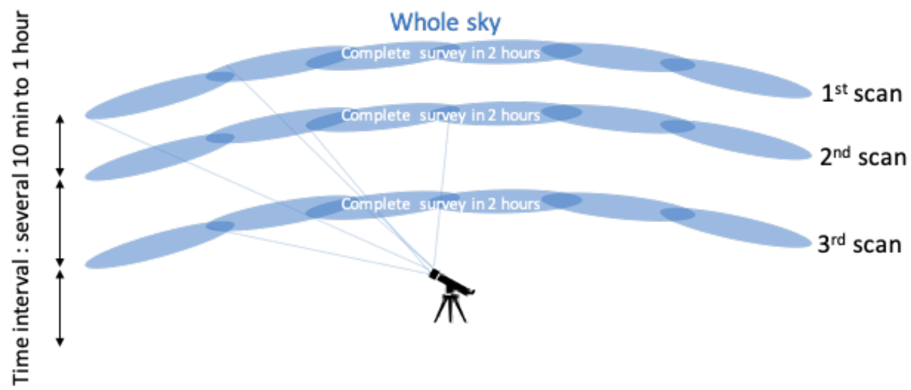


Comet ATLAS (C/2019 Y4)

If you want to see a movie of this comet, please visit Tomo-e Gozen camera on Youtube (https://www.youtube.com/channel/UCb716QkXJ0hLaa3c2reytdw?fs=1&modestbranding=1&rel=0&showinfo=0?fs=1&modestbranding=1&rel=0&showinfo=0).

DETECTION OF MOVING OBJECTS

Procedure from the survey observation to the detection/identification of moving objects



① Visit several times the whole sky region in one night.

At each scan, 12 frames/6 sec images taken with the frame rate of 2 frames/sec stack into one image/region.

② Detect all light sources and measure their brightness, then make the light source catalog

Tomo-e Gozen High-Frequency survey does not use filters. The photometric calibration is done by using the r-band values from Pan-STARRS's catalog.

③ Distinguish moving objects from the catalog

•Refer to the Lowell Observatory Small Solar System Bodies (SSSB) catalog ("astorb") and calculate the coordinates of each SSSB at the detected time.

•If there is an object that falls in the range of 6″ x 6″ centered on the expected coordinates, the object is regarded as the known asteroid listed in "astob".

•Such objects' RA and DEC, MJD, apparent mag, mag errors, expected mag derived from "astorb", and SSSB's name are automatically added to the survey database table.

④ Obtain the solar phase angle (α), the heliocentric and geocentric distances at the detected time by JPL Horizons (https://ssd.jpl.nasa.gov/horizons.cgi), and then calculate the reduced magnitude at the α.

⑤ Plot α vs. reduced magnitude

⑥ Fit the phase curves by several models and then obtain H and G

Number of moving objects detected in each category

Asteroid category	Total number of detected asteroids
Aten [NEO, PHA]	5
Aten [NEO]	11
Amor [NEO, PHA]	4
Amor [NEO]	68
Apollo [NEO, PHA]	33
Apollo [NEO]	54
Mars-crossing	510
Inner main belt	703
Main belt asteroids	41263
Outer main belt	1410
Jupiter Trojans	248
Centaur	5
Trans Neptunian	9

In total 44323 as of April 11, 2020

As for the categorization, please refer here (https://ssd.jpl.nasa.gov/sbdb_query.cgi?obj_group=all;obj_kind=all;
obj_numbered=num;ast_orbit_class=AMO;OBJ_field=0;ORB_field=0;table_format=HTML;max_rows=200;
format_option=comp;c_fields=BgBhBiBjBnBsChAcCq;
c_sort=AcA;.cgifields=format_option;.cgifields=ast_orbit_class;.cgifields=table_format;.cgifields=obj_kind;.cgifields=obj_group;.cgifields=obj_numbered;.cgifields

Considering the detection limit of 18 mag in this survey, most of moving objects found in this survey can be known SSSBs.

PHASE CURVES OF DETECTED MOVING OBJECTS

We tried two different fitting model of the phase curve: (1) Lumme–Bowell G Model and (2) Muinonen et al. G12 Model.

- The Lumme–Bowell model (Bowell et al. 1989 (https://ui.adsabs.harvard.edu/abs/1989aste.conf..524B/abstract)) is also known as the H,G system.

$$V = 5log_{10}(r\Delta) + H - 2.5log_{10}[(1-G)\Phi_1 + G\Phi_2]$$

$$\Phi_i = -A_i[tan\frac{\alpha}{2}]B_i$$

i=1,2, A_1=3.33, A_2=1.87, B_1=0.63, B_2=1.22

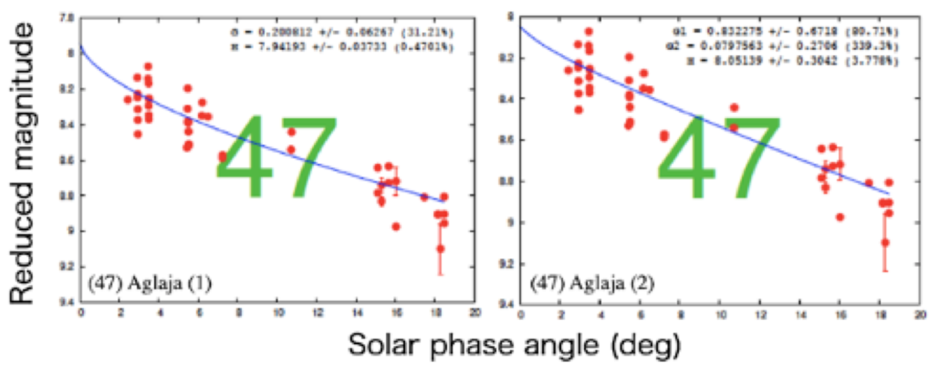
- Muinonen et al. G12 Model (Muinonen et al. 2010 (https://ui.adsabs.harvard.edu/abs/2010Icar..209..542M/abstract)) is another phase-function model, which includes a second free parameter and a third basis function:

$$V = 5log_{10}(r\Delta) + H - 2.5log_{10}[G_1\Phi_1 + G_2\Phi_2 + (1 - G_1 - G_2)\Phi_3]$$

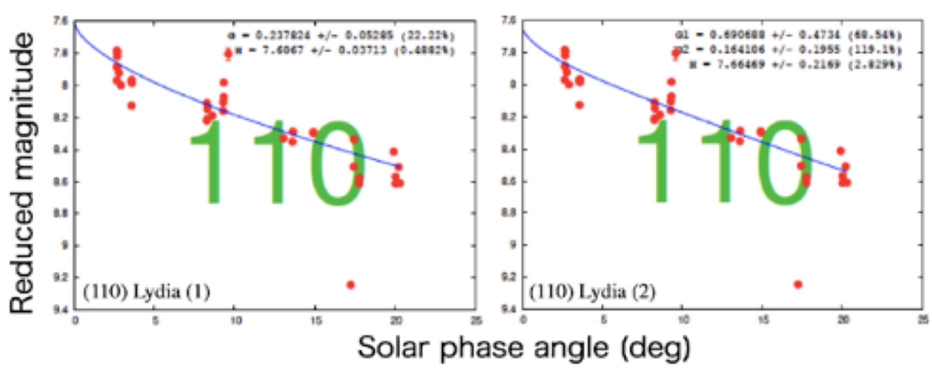
We show a part of our phase curve collection with the fitting by (1) Lumme–Bowell G Model (https://drive.google.com/file/d/1gg2YcocR0EDXm6NGODgSp5Xn6eRGFAw1/view?usp=sharing) and (2) Muinonen et al. G12 Model (https://drive.google.com/file/d/1BfcHA_wo6FPgbBxwl712pPledo3aO2Ai/view?usp=sharing). (Please click these links to see the plots.)

The α range of detected SSSBs is from 0 deg to a few 10 degrees, corresponding to the range where microscopic effects appear. Most of detected SSSBs do not have enough data points yet. However, the Tomo-e Gozen high-frequency survey will be continued for 10 years. During the 10 years, we keep obtaining the phase curves of SSSBs. Once dense data points are given, its phase curve provides information on H and surface properties.

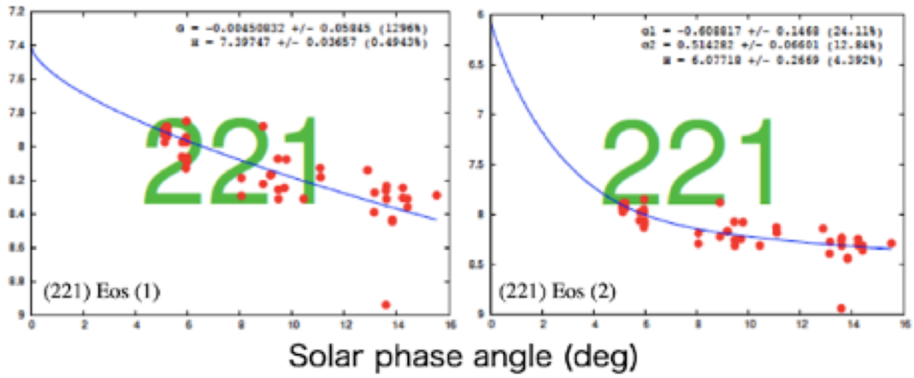
Some comparison between (1) Lumme-Bowell G Model and (2) Muinonen et al. G12 Model



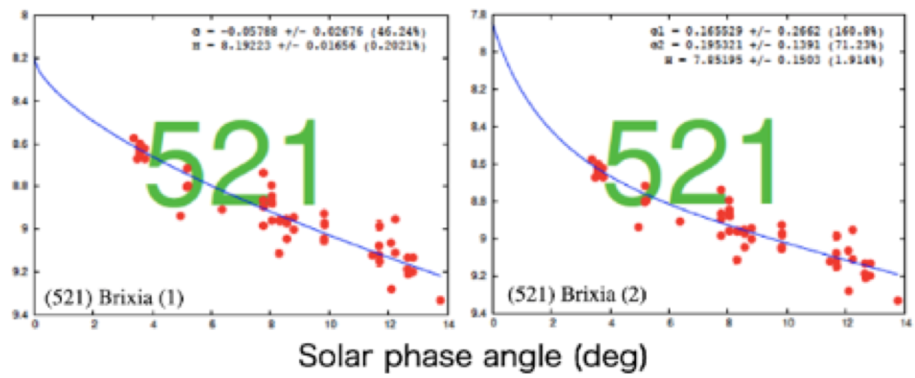
JPL	H=8.1	G=0.16	(1)	H=7.94	G=0.20	(2)	H=8.05



JPL	H=7.9	G=0.20	(1)	H=7.61	G=0.24	(2)	H=7.66



JPL	H=7.7	G=0.13	(1)	H=7.40	G=-0.00	(2)	H=6.08



JPL	H=8.5	G=-0.06	(1)	H=8.19	G=-0.06	(2)	H=7.85

SUMMARY

- We plotted the phase curves for 44323 SSSBs detected by the Tomo-e GozenHigh-Frequency survey, including 175 NEOs, 510 Mars-crossing Asteroids, 703 Inner Main-belt Asteroids (a < 2.0 au; q > 1.666 au), 41263 Main-belt Asteroids (2.0 au < a < 3.2 au; q > 1.666 au), 1410 Outer Main-belt Asteroids (3.2 au < a < 4.6 au), 248 Jupiter Trojans, 5 Centaurs, 9 Trans Neptunian Objects, and then fitted them with two different models: (1) Lumme–Bowell G Model and (2) Muinonen et al. G12 Model.
- This poster is just progress report. Most of SSSBs have not enough data points so far. However, once dense phase curve of each object is obtained, this study provides promising information on absolute magnitude and surface properties for the object.
- Since the Tomo-e Gozen High-Frequency survey will continue for 10 years, we are sure to have denser phase curves for more objects.

References

- Bowell et al. 1989, in Asteroids II, ed. R. P. Binzel, T. Gehrels, & M. Shapley Matthews (Tucson, AZ: Univ. Arizona Press), 524
- Muinonen et al. 2002, in Asteroid III, ed. W. Bottke, A. Cellino, P. Paolicchi, & R. P. Binzel (Tucson, AZ: Univ. Arizona Press), 124
- Muinonen et al. 2010, Icarus, 209, 542
- Sako et al. 2018, Proceedings of the SPIE, Volume 10702, id. 107020J 17 pp.
- Shevchenko et al. 2019, A&A 626, A87

ABSTRACT

The Tomo-e Gozen project conducts optical wide-field survey programs with a wide-field CMOS camera, Tomo-e Gozen, attached on the 105-cm Schmidt telescope at the Kiso Observatory, the University of Tokyo. Tomo-e Gozen is the world's first wide-field CMOS camera which covers 20 square degrees with 84 chips of 35 mm full HD CMOS image sensors. A wide-field and high-cadence survey in the optical wavelengths began in 2018 with the Tomo-e Gozen (hereafter referred to as the Tomo-e Gozen transient survey). The main purpose of this survey is to detect young supernovae. However, the survey simultaneously detects a large number of moving objects in their images. As one of the by-products of the survey, here we show our preliminary result about production of phase curves (solar phase angles versus absolute magnitude) of more than 40,000 (as of April 11, 2020) small solar system bodies including main-belt asteroids, near-Earth asteroids, Jupiter Trojans, Centaurs, and Transneptunian objects. Combining the moving object catalogue derived from the survey and the output ephemeris that the Horizons/JPL system provides, we are now able to obtain phase curves of these objects almost automatically. As the Kiso moving object catalogue is updated and being expanded on a daily basis, the number of the objects (small bodies) that we deal with goes up as well. Our result, when completed, will make a fair complement as well as a significant keystone to what is already published such as from the Pan-STARRS systematic survey on the knowledge of the surface characteristics of the small solar system bodies.