Investigation of Small Bodies in the Solar System with the Zwicky Transient Facility

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1. Scientific Motivation

Small solar system bodies are remnants of the formation stage of solar system. They encompass all comets and asteroids, including the Trojans, the centaurs, near-Earth objects (NEOs) and trans-Neptunian objects. Studies of small bodies contribute to the understanding of several fundamental questions in planetary science, such as the composition of the proto-planetary disk, the evolutionary history of solar system, as well as the transportation and distribution of water and organic materials in the solar system.

Since the 1990s, systematic surveys have dramatically increased our knowledge of Near Earth Objects (NEOs) . As of Nov 2016, more than 15,000 near-Earth asteroids (NEAs) and 100 near-Earth comets (NECs) are known; 92% km-sized NEOs have been cataloged (Granvik et al. 2016, Nature, 530, 303). These results have raised new questions, many related to transient events, such as the detection of small, fast-moving NEOs (due to the short visibility window of these NEOs), long-term activity trends and short-lived outburst events of comets and active asteroids, and super-fast rotating asteroids. Most of these events require sampling at cadences much higher than the coverage frequency of the current global NEO network (about 2 weeks). Therefore, facilities with broader and faster coverage are needed.

Once commissioned in late 2017, the Zwicky Transient Facility will be the telescope with largest sky coverage among meter-sized facilities, hence providing the deepest survey with the highest cadence. With ZTF, we will be able to systematically explore time domain studies of small bodies in the solar system . We will focus at the questions that are not primary goals for other solar system surveys. These include:

1.1 Small NEOs

It is estimated that the coverage of small NEOs (<200 m) is only 10% completed (L. Johnson 2016, SBAG 15). The 2013 Chelyabinsk event has demonstrated the hazard posed by small asteroids. Such asteroids are very faint and can only observed when they are closest to the Earth.They usually have a high motion rate and leave streaks on typical survey exposures (~30-60 s), presenting a challenge for any detection algorithm. Assuming an albedo of 0.05, a 100-m asteroid will reach V=16 at 10 lunar distance (LD) but will move at a rate of 15 deg/day (e.g. Veres et al. 2012, PASP, 124, 1197), leaving a streak of 20” at 30 s exposure. Moreover, ephemeris uncertainties of close approaching NEOs grow quickly. To secure a discovery, it is critical to attempt follow-up observations within the order of several hours.

ZTF will make use of a streak detection pipeline originally developed and tested for PTF (Waszczak et al. 2016, PASP, in press). Streak candidates need vetting by a human operator and are reported to the Minor Planet Center in a timely manner (usually within an hour). The follow-up assets of ZTF, such as the robotic low-resolution spectrometer attached to the Palomar 1.5 m telescope (the SED Machine) and the GROWTH network (Global Relay of Observatories Watching Transients Happen), will contribute to timely follow-up and classification of the detected NEOs. Waszczak et al. estimated that ZTF will be as powerful as the Pan-STARRS NEO survey or the upgraded Catalina Sky Survey, two of the most successful NEO surveys which have found 80% of the newly-discovered NEOs in the recent years.

1.2 Twilight survey

The twilight region (solar elongation <90 deg) is difficult to observe but is known to contain a number of interesting phenomena: sungrazing and sun-skirting comets such as the Kreutz comet family and Comet ISON, the classic cases of cometary fragmentation (e.g. Knight et al. 2010, AJ, 139, 926); an asteroid population that is predicted to be thermally disrupted (Granvik et al. 2016, Nature, 530, 303); the poorly understood population of Earth Trojans (Connors et al. 2011, Nature, 475, 7357); and NEOs approaching the Earth from the direction of the Sun, like the Chelyabinsk event (Brown et al. 2013, Nature, 503, 238). A fast-and-wide strategy is critical for the success of such a survey. This region is not usually patrolled by the current NEO network, and there has been limited attempt to make use of the short twilight hours to survey this region (e.g. Ye et al. 2014, ApJ, 796, 83, D. Tholen personal comm).

The ZTF twilight survey will make use of the twilight hours (between 12-18 deg twilight) to repeatedly scan the small elongation region, a 1200 square degree region (approximately 50-70 deg elongation at a declination of 0 to +60 deg) at both the evening and the morning direction. An existing discovery routine, developed for PTF, the Moving Object Detection Engine (MODE), will be used for data processing. Possible detections need to be vetted by human operator within the same night so any interesting events can be followed up in a timely manner.

1.3 Long-term Orbital Activity Trends

Cometary activity changes as active areas on the surface rotate in and out of sunlight. This variability is caused by changes in the distribution of sunlight as the comet rotates (diurnal variation) and orbits the sun (seasonal variation). Temporal variability in the activity thus provides a means of exploring heterogeneities of comet nuclei. Variability can thus be used to constrain rotation frequency, pole orientation, shape, the density, and the distribution of active sources on their nuclei. Thus far, only space missions have provided both dense temporal coverage (Deep Impact, Rosetta) and/or long- term monitoring of comets (Rosetta).

The rise of all-sky surveys with robotic telescopes now makes it possible to do this from the ground. We predict that ZTF can detect at least 20 to 30 comets per night. Using photometry marshalls developed for the iPTF, we will acquire and make available photometry for all known comets. Depending on sky conditions, comet brightness, and background, we anticipate a photometric accuracy of 0.1 mag. ZTF will thus produce systematic and much more accurate comet light-curves than that are currently available with a sample of comets not biased by brightness or distance to the Sun. ZTF will use Sloan *r′* and *g′* filters for its all-sky monitoring. The *r′* filter is commonly used for dust observations, as its bandpass is mostly free of the emission of comet gases. The *g'* filters includes the emission of C_2 and we will use the photometry in this filter this as a proxy for the comet's gas production rate.

1.4 Comet Outbursts

Comet outburst can be spectacular, turning a modestly active comet into a naked eye object (e.g. 17P/Holmes in 2007). Possible mechanisms include rotational breakup, internal ice phase transitions, and thermal stress. Rosetta observations suggest mini-outbursts may occur on a daily basis. Most outbursts are discovered by chance by amateur observers and little is known about their frequency and intensity distribution, and thus about the mechanism that drives them. ZTF will focus on outbursts with brightness changes between 1-5 magnitude, where we anticipate the greatest discovery potential.

The aim of our ZTF outburst monitoring program is two-fold: first, provide an early warning system that flags outbursts within a day of their onset, and two, provide a baseline of the activity before and after the outburst. The close collaboration of ZTF and the GROWTH network (Global Relay of Observatories Watching Transients Happen) and the *Swift* space telescope will enable us to perform fast follow-up observations of outbursts.

1.5 Cometary ion tails

Since the 1950s, cometary ion tails have been studied as natural probes of the interplanetary magnetic field. The appearance, structure, and orientation of a comet's ion tail are primarily controlled by local solar wind conditions. When the observing geometry is ideal, the direction of the ion tail can offer clues to the local temporal and spatial variations in the solar wind flow. The ion tail may contain bundled features, or folding rays, which are tail-ward extensions of ion pileup regions and are observed to fold back along the tail. The ion tail could be further affected by disconnection or deviations events. Such phenomena can generally be directly related to changes in the localized solar wind.

1.6 Super-fast rotators (SFRs)

Most asteroids are gravitationally bounded aggregations ("rubble-piles"). It is thought that rubble-pile asteroids cannot have rotation periods less than a critical limit or they will disintegrate. However, it has been found that a small number of asteroids have rotation periods shorter than this limit, implying that they may be monolithic. PTF has discovered 3 of 6 super-fast rotators (SFRs) known to date (Chang et al. 2014, ApJ, 788, 17). However, the detection rate is still too low to place a meaningful constraint to the SFR population. With its large sky coverage, ZTF can improve our knowledge to the SFR population.

1.7 Asteroid rotation periods and phase functions

From asteroid light curve, we can measure several fundamental properties for asteroids, such as shape, spin status and taxonomy. We expect to collect ~100,000 asteroid light curves within a year using ZTF. from which we will be able to derive several tens of thousands of rotation periods and phase functions. The statistics of asteroid rotations can help to understand how its evolution is affected by mutual collisions, gravitational perturbations of planets, and the YORP effect. Phase functions can be used to determine asteroid taxonomy. Combining rotation period and taxonomy, we are also able to study the spin-rate limits for different type asteroids, which is a proxy of asteroid bulk density.

1.8 Binary asteroids

Several mechanisms have been proposed for binary asteroid formation, such as catastrophic impact, mutual capture, tidal disruption, and rotational fission. However, the fraction of binary asteroids would depend on how and where they were formed. Therefore, the binary fractions in different asteroid systems, such as NEAs and main belt, can help to understand their formation. Although Pravec and Harris (2007) suggested that binary fractions in NEA and Main-belt are similar, the surveys were conducted with very limited samples. One way to discover binary asteroids is to to identify eclipsing features on asteroid light curves (i.e., inverse U shape light curve). With numerous asteroid light curves collected by the ZTF, the binary fraction will be derived in a more statistical way.

1.9 Tumbling asteroids

Tumbling asteroids are non-principal axis rotating asteroids, which either have long damping time-scale (i.e., billion years) or were just excited recently due to collision or approaching to critical spin-rate limit by the YORP effect (Warner et al., 2009). With ZTF, the sample size will be increased dramatically and so does the chance of discovering tumbling asteroids. Therefore, we will be able to have a more comprehensive understanding on the initiation of tumbling rotation.

1.10 Asteroid shape models

With ZTF, we are able to collect multiple-year asteroid light curves with ~1 day cadence. This will be very useful in derive asteroid shape models and spin status (i.e., spin rate and spin axis orientation). The shape model is important in a detailed study of an asteroid, such as thermal inertia derivation, calculation for spin status evolution, and orbital evolution due to thermal effect. Moreover, this will be the first project to conduct survey on asteroid shapes, which is a relatively unexplored but yet important field in asteroid study. With detailed study on asteroid shapes, we will be able to tell the relationship between size and shape, which can help to understand how collision and impact effect on shaping asteroids.

1.11 Asteroid phase function

The solar phase angle of an asteroid is defined as the angle of Sun-asteroid-Earth. The asteroid brightness differs at different solar phase angle. The relationship between the phase angle and the asteroid brightness is named as the photometric phase curve. The steep gradient is usually seen near zero solar phase angle, and it is named as the opposition effect. The opposition effect is well described by the coherent backscattering mechanism, and it suggests the existence of particulate particles on the surface of the asteroid. The degree of the opposition effect depends on the albedo of the surface. The shallower slope at larger phase angle is understood by the shadow hiding of the rough surface. Thus, the photometric phase curves can be used to study the surface roughness, geometric albedo, taxonomic classification, and the existence of regolith on the asteroid surface.

2. Proposed programs

The ZTF solar system science working group has developed the following draft survey strategies, optimized for specific science objectives.

While the individual survey plans have significant commonality, as well as significant overlap with surveys suggested for other ZTF science areas, the objective here is to clearly state the optimal survey strategies for each science area so that an assessment can begin to be made of what various compromises would imply for the stated science objectives.

The order below does not imply the priority of each program.

2.1 Detection and follow-up of small NEOs

Survey area	Cadence	Interval	Hours per night	Filters
10140	2/night	1 h	6	*r'*

The goal is to find as many NEOs as possible and to provide sufficient information that they can be followed-up by other facilities; therefore, it is desirable to have the largest coverage possible every night. Two visits are necessary to determine the direction of the streaks as well as to increase the observed orbital arc. The interval between the visits is flexible but should be around 1 hour (asteroids will move no less than 0.6 deg/hr), because a longer arc will reduce the growth of positional uncertainty and will help the follow-up effort; and shorter intervals will prevent complications such as asteroids moving between sensors/fields. Experience shows that streaks with 1 hour arc are usually recoverable (i.e. the size of the uncertainty ellipse is reasonable) for another 12-24 hours (M. Micheli, private comm) depending on the motion and magnitude of the initial detection. In PTF, target-of-opportunity (ToO) observations were required to ensure at least two streak detections during a night. This will likely not be required if the time interval between successive observations is short enough (e.g. ~1 hr). However, if typical revisit times are larger, then ToOs may be needed. This evaluation can only be done once the overall cadence for both public and collaboration time is determined.

Small bodies tend to appear slightly redder than the Sun (*g'*-*r'*=0.7; e.g. DeMeo and Binzel, 2008, Icarus, 194, 436), therefore the observation should preferably be conducted in *r'*, though *g'* observations can be accommodated at the expense of decreased sensitivity. The loss in sensitivity in *g'* band is likely <0.5 mag assuming similar depth to iPTF in respective band. On the other hand, i' band observation will negatively impact NEO detection at a much more significant level, as the CCD is much less sensitive in i' band.

2.2 Long-term monitoring of comets

Survey area	Cadence	Interval	Hours per night	Filters
10140	1/week	n/a	6	*g'*+*r'*

The goal is to regularly monitor all observable comets on a long-term basis to measure their gas/dust ratio (represented by the ratio between *g'*-band and *r'*-band flux) over a long period of time. As such, only a low, weekly cadence is required.

It is possible to derive gas/dust ratio from *g′*+*i′* band observations at the cost of reduced sensitivity. *i′* band will come with a small benefit of reduced contamination from the gaseous species, though such contamination at *r′* band is already nearly negligible.

2.3 Cometary outbursts/fragmentation, morphology, nuclei rotation

Survey area	Cadence	Interval	Hours per night	Filters
10140	1/night	n/a	1.5 in evening 1.5 in morning	*r′*

The goal is to patrol the largest possible observable sky on a daily basis to look for abnormal cometary activity (outbursts, fragmentation, etc.) and to monitor the evolution of cometary morphology. A few outbursts are serendipitously discovered by amateurs per year, therefore we expect several discoveries with ZTF. As such, a 1-night cadence is required, to be split into 1.5 hour in the early evening and 1.5 hour in the early morning, to cover the largest number of comets . The observations should be conducted in *r′*-band only to prevent contamination from the gaseous species which fall in the *g′*-band. Similar to comet monitoring project, observation at *i′* band will negatively impact the sensitivity of the survey and is therefore not preferred. We expect to be able to detect cometary outbursts/fragmentation <24 hour after they take place.

2.4 Twilight survey

Survey area	Cadence	Interval	Hours per night	Filters
845	4/session	5 min	0.5 in evening 0.5 in morning	*r′*

We will make use of the twilight hours (time between 12-18 deg twilight; approximately 0.5 hour for the evening and 0.5 hour for the morning) to look for NEOs and comets at small solar elongation (45-60 deg elongation, declination 0 to +60 deg). Since the window is short and the sky is bright, a 5 min. cadence and 4 visits (to suppress the number of false-positives) are needed. Observation should be conducted in *r′* band as both *g′* and *i′* band have issue with the bright skylight/OH emission.

2.5 Search for super-fast rotators

Survey area	Cadence	Interval	Hours per night	Filters
423	48/night	10 min	6	*r′*

The goal is to measure the rotational light-curves of a large number of asteroids near the opposition direction. The target area is a 25x25 deg region around the opposition point where the asteroids are brightest. Observations should preferably be conducted in *r′*-band to maximize the detection efficiency, but *g′*-band is also acceptable. The main interest for the rotational light-curve project is to search for super-fast rotators (rotation period < 2 hour). To ensure sufficient sampling along the light-curve, a 10-min cadence is requested.

2.6 Asteroid light curve collection and rotational fission detections

Survey area	Cadence	Interval	Hours per night	Filters
10140	1/night	n/a	n/a	*r′*

The goal is to measure asteroid rotational periods, detect binary asteroids and tumbling asteroids, and derive asteroid shapes from asteroid light-curves obtained from archived data. In order to ensure simultaneous fits to the phase function and rotation period, we require >100 detections within a single apparition. This could be achieved if the observable sky can be surveyed every night (i.e. with a cadence of 1/night). We expect to obtain rotation periods for several tens of thousands of asteroids in the first two years of the ZTF project. Such a large number of rotation periods will enable a statistically confident spin-rate distribution, and therefore, providing insight to spin-status altering mechanisms. In addition, with constant monitoring of the ZTF fast rotators using Robo-AO, we might witness a fragmentation event due to the exceedingly fast rotation. Moreover, comparing rotation periods before and after the fragmentation event would secure the rotation fission scenario, and the ZTF has the ability to provide rotation period measurement before the event. In addition, with multiple-year asteroid light curves, we will be able to derive asteroid shapes using light-curve inversion method.

2.7 Asteroid phase function

Survey area	Cadence	Interval	Hours per night	Filters
10140	every 5 nights	n/a	n/a	*r′*

The supernovae cadence of PTF has a typical re-visit time scale of five days, and the data have the time-span of 2-3 months every year. Although the data acquired by this cadence is too sparse to construct the rotational lightcurve, the dataset is suitable for photometric phase curve study. Because of single band survey and shorter re-visit time scale of PTF, phase curves generated using PTF data have much more data points in general than the one generated by other survey programs. The photometric phase curve of (1943) Anteros constructed from PTF data is shown in Fig. 1. (1943) Anteros is a near-Earth asteroid, and the coverage of the solar phase angle is wide. The curve is fitted by IAU's H-G magnitude system. The slope parameter G is indicative of taxonomic type of the asteroid. Primitive low-albedo C-type asteroids typically have G ~ 0.1. On the other hand, igneous moderate-albedo S-type asteroids exhibit G ~ 0.2. The taxonomic classification of an asteroid may be carried out using a high quality phase curve.

3. Supporting observations

The surveying projects (small NEOs, twilight survey) require about 2 hour per week per telescope for follow-up observations. Presently, we have access to the Lulin 1-m telescope (represented by Chow-Choong Ngeow in this white paper) as part of the GROWTH collaboration, and Xingming 0.5-m telescope in China (represented by Quan-Zhi Ye in this white paper). Other GROWTH partners are expected to participate as well (e.g. Los Alamos). The cadence is TBD depending on the situation of each target. We also expect to make modest use of the SEDM for prompt characterization of small NEOs. Prototype tests will be undertaken during the first year of ZTF to demonstrate feasibility and effectiveness of follow-up with SEDM.

Dennis Bodewits is leading a long-running program with the Swift telescope. He has developed observing routines and data reduction packages for comet observations using its UV-optical telescope. Swift's rapid follow-up capabilities, UV sensitivity, and relatively large field of view (15 x 15 arcmin) make it uniquely suited for comet and asteroid activity studies. This was demonstrated with our observations of asteroid (596) Scheila. When the Catalina all sky survey detected large brightness increase of the asteroid, Bodewits et al used Swift observations to rule out cometary-like activity drive by the sublimation of volatiles. Instead, the outburst was the first confirmed collision between two asteroids (Bodewits et al. 2011, ApJL, 733, L3).

In the event that the on-sky uncertainty area has grown too large, we may request a ToO session using ZTF. For the ToO sessions, only a pair of back-to-back observations is needed, since we only need to track down the asteroid again. This was standard practice in PTF/iPTF.
We request 2 hour per week on SEDM for the classification of detected objects. For the purpose of asteroid classification, low-resolution spectrum will suffice.

4. Expertise to undertake projects

(Names below are ordered alphabetically)

Drs. Dennis Bodewits, Michael Kelley and Matthew Knight (UMD) will lead the science activities related to long-term monitoring of comets, including orbital activity trend of comets and cometary outbursts. Dr. Bodewits will also lead the effort to develop the necessitate tools to reach the science goals. Dr. Quan-Zhi Ye (Caltech/IPAC) will participate science activities of both programs.

Drs. James Bauer (JPL) and Yu-Chi Cheng (NCU) will participate the science activities focused on the long-term monitoring of comets.

Drs. Chan-Kao Chang and Hsing-Wen Lin (NCU) are experienced in using iPTF data to study asteroid rotation and have developed the required tools to analyze asteroid light-curves. They will lead the science activities related to the study of SFRs and rotational fission detections.

Prof. Xiao-Ping Lu, Drs. Chan-Kao Chang and Hsing-Wen Lin will work on asteroid shape determination using light-curve inversion method.

Prof. Wing-Huen Ip (NCU) and Dr. Quan-Zhi Ye (Caltech/IPAC) will lead the science activities related to the twilight survey. Dr. Ye will oversee the operation of the survey. The twilight survey will make use of the MOPS package developed by Dr. Frank Masci.

Dr. Zhong-Yi Lin (NCU) will lead the science activities related to the cometary ion tails and does not require specific tool to be developed within the collaboration.

Prof. Chow-Choong Ngeow (NCU) represents the follow-up partner at NCU and will lead the follow-up effort on any object of interest at the Lulin Observatory in Taiwan. He does not require specific tool to be developed within the collaboration.

Dr. Frank Masci (Caltech/IPAC) is the architect and development lead of the ZTF data reduction pipeline including the MODE pipeline. He will oversee the software development and operation of the pipeline and consult on algorithmic matters related to the solar system science.

Prof. Thomas Prince (Caltech) will oversee the small NEO survey and participate in science activities. Drs. Carolyn Nugent (Caltech/IPAC), Quan-Zhi Ye, and Mr. Ben DeMario (Caltech) will participate in operations and science activities related to the small NEO survey. The small NEO survey will make use of the streak finding tool of the standard ZTF data handling pipeline.

Besides participate science activities in his area of expertise, Dr. Quan-Zhi Ye (Caltech/IPAC) will act as liaison to the collaborating partners for all solar system programs.

5. Personnel and time-line

The small NEO survey is overseen by Prof. Thomas Prince. The participants include Chan-Kao Chang, Ben DeMario, George Helou, Wing-Huen Ip, Hsing-Wen Lin, Frank Masci, Chow-Choong Ngeow, and Quan-Zhi Ye. The plan is to process the data in the same night and report any potential new NEOs to the Minor Planet Center in a timely manner. We plan to submit and initial paper describing survey results after the first year of observation (including follow-up). We expect a survey strategy paper discussing the characteristics of the population of small NEOs near the end of the 3rd year of the survey in addition to any papers that may result from discovery of particularly significant small NEOs. This project is one of the possible thesis directions for Ben DeMario.

The long-term monitoring of comets is overseen by Dr. Dennis Bodewits. The participants include James Bauer, Yu-Chi Cheng, Michael Kelley, Matthew Knight, Zhong-Yi Lin, and Quan-Zhi Ye. The plan is to immediately follow-up and study comets of particular interests. In addition to papers on individual objects, we expect a paper focused on the population characteristics of all observed comets at the end of the 3-year survey.

The cometary ion tail project is led by Dr. Zhong-Yi Lin. The plan is to study comets with significant ion tail that warrants the use of ZTF.

The twilight survey is led by Dr. Quan-Zhi Ye. The participant includes Prof. Wing-Huen Ip. The plan is to process the data in the same night and report any potential new NEOs to the Minor Planet Center in a timely manner. We expect a survey strategy paper at the end of the 3-year survey.

The SFR survey is in charged by Drs. Chan-Kao Chang and Hsing-Wen Lin. The plan is to immediately follow-up and study possible SFRs. In addition to papers on individual objects, we expect a paper focused on the population characteristics of all observed comets at the end of the 3-year survey.

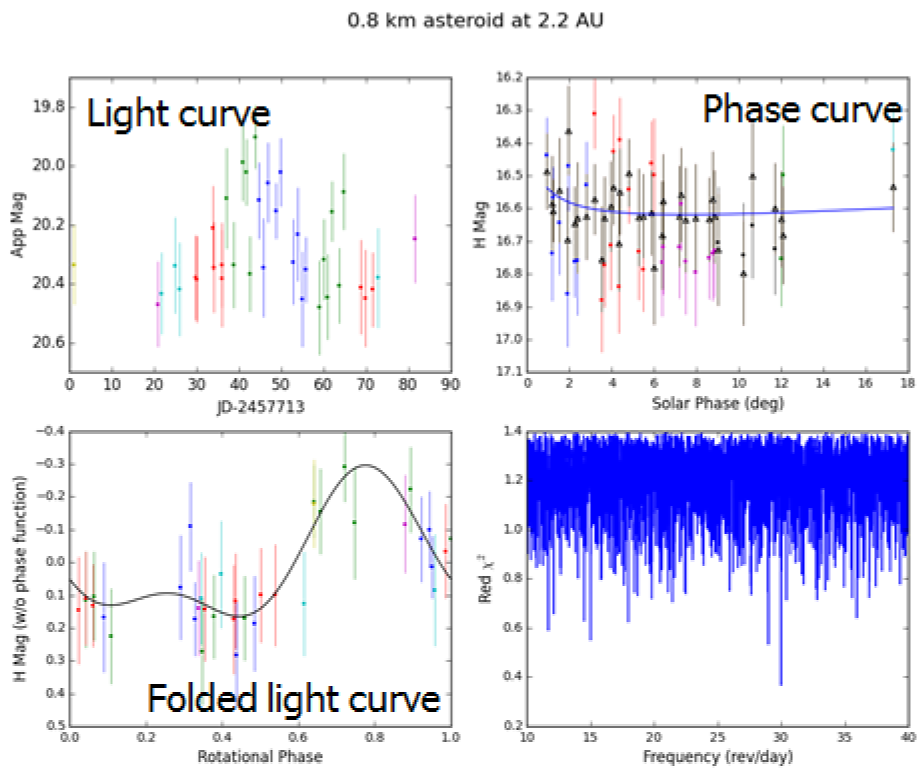
The asteroid light curve study is in charged by Drs. Chan-Kao Chang, Hsing-Wen Lin and Xiao-Ping Lu. With the archived asteroid light curves, they plan to derive rotation periods, detect binary asteroids and tumbling asteroids, and determine asteroid shape.

The asteroid phase function study is led by Prof. Daisuke Kinoshita. He plans to derive phase function for a large number of main-belt asteroids.

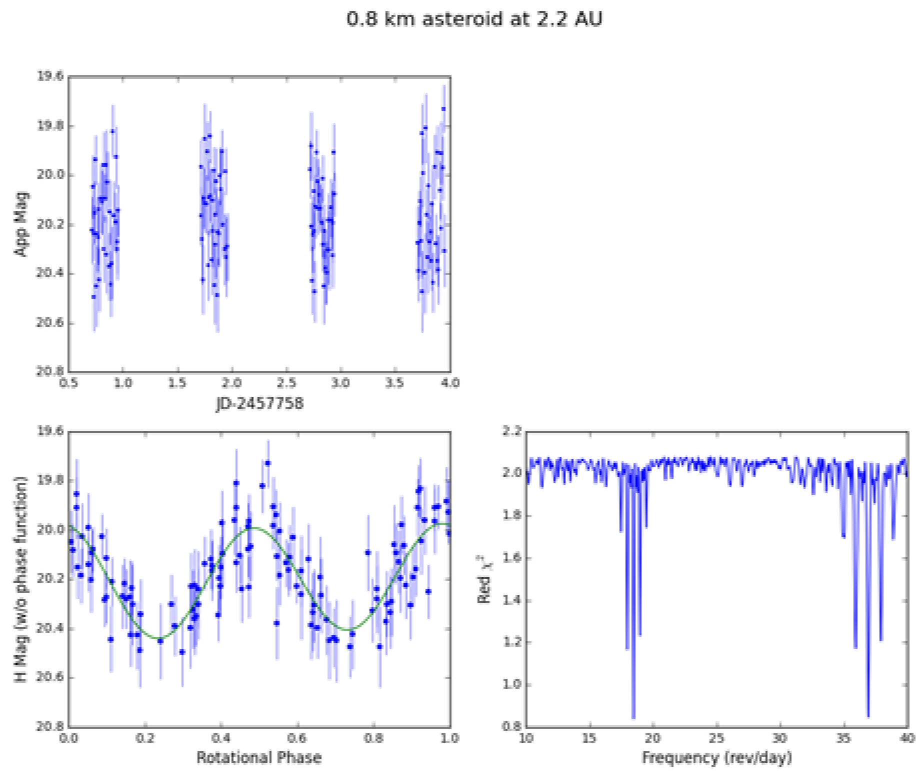
A1. Detecting simulations for SFR hunting

SFRs are of sub-kilometer asteroids and therefore would be observable only when they around oppositions. The following simulation shows the light curve of one-year observation with 1-day cadence (case a) vs. that of high-cadence (5-, 10-,and 20-min) observation within 4-night (case b). The light curve was simulated for an asteroid of D ~0.8 km with axis ratio of (1, 0.6, 0.6). A linear phase function was employed. The result shows that (1) case a won't help to find SFRs due to only ~10-20 detections available in the light curve; (2) instead, the high cadence observations can recover the super-fast rotation period, and the higher the cadence is, the higher the confidence in detecting SFR.

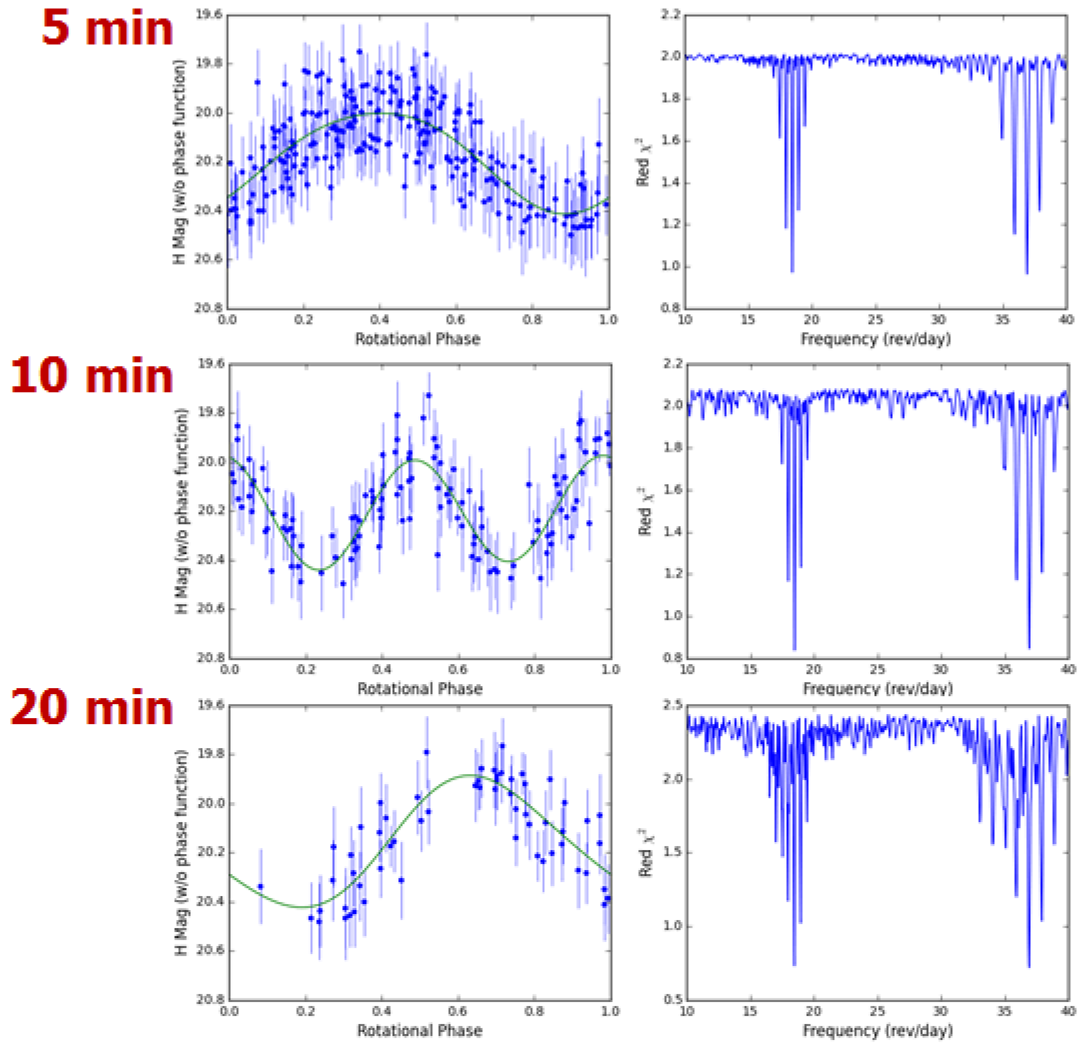
Case a: light curve of one-year observation with 1-day cadence



Case b: light curve of high-cadence (10 min) observation within 4-night



Difference in confidence level of detecting SFR with 5-, 10-, and 20-min cadence



5 min
10 min
20 min
H Mag (w/o phase function)
Rotational Phase
Red χ^2
Frequency (rev/day)

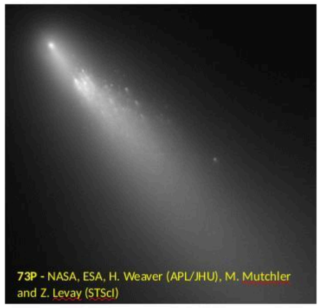
A2. Focus of the ZTF comet outburst program

Outbursts

Focus of our ZTF Outburst Program

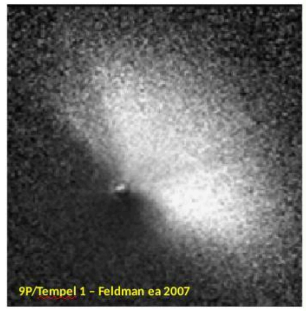
1. Large, >5 mag

- Sustained for weeks or longer
- Gas and dust increase
- Sometimes fragments
- ZTF will characterize baseline behavior



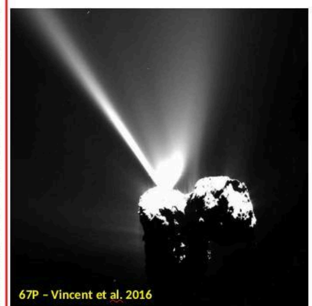
2. Medium, 2-5 mag

- Most common
- Target of this project
- Rise few days
- May include short-lived fragments
- Requires early warning (<days) for follow up



3. Small, 1-2 mag

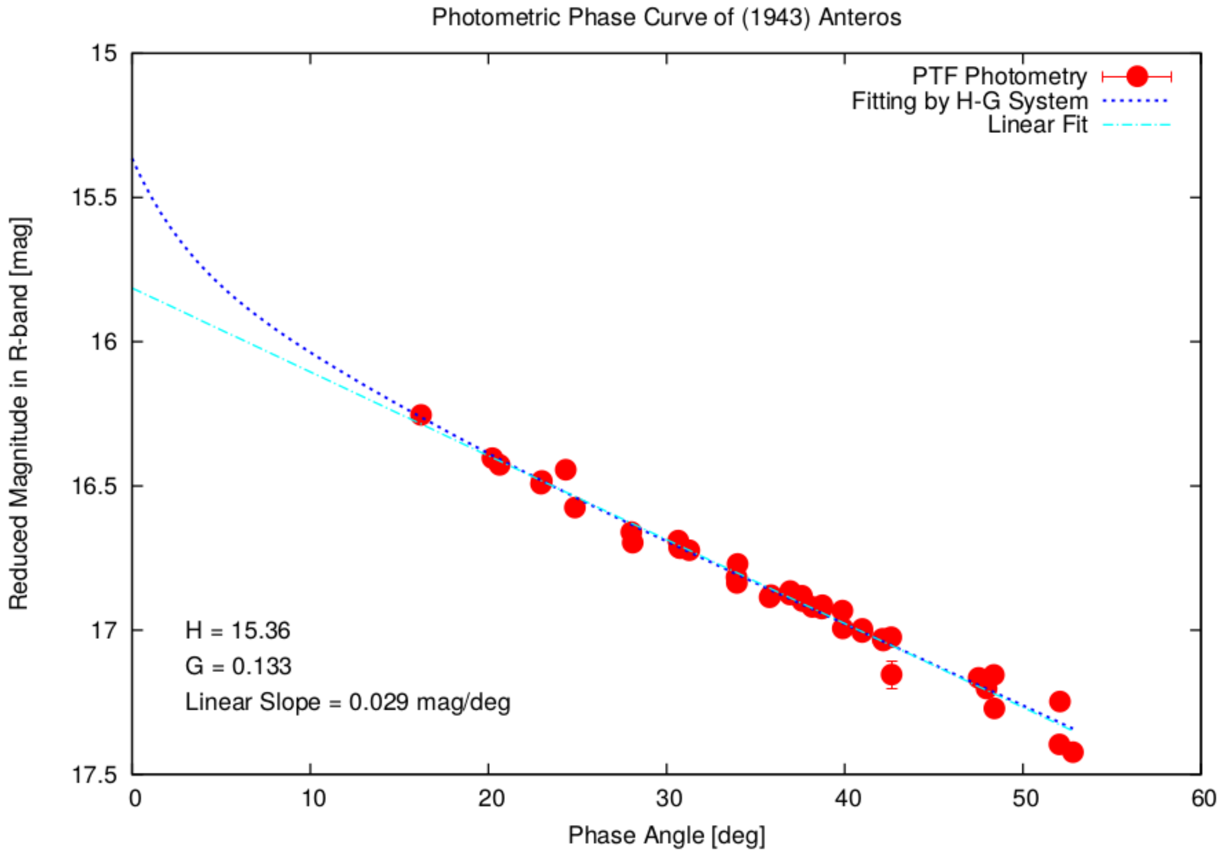
- Less often discovered, but likely more common
- Greatest discovery potential!
- Target of this project



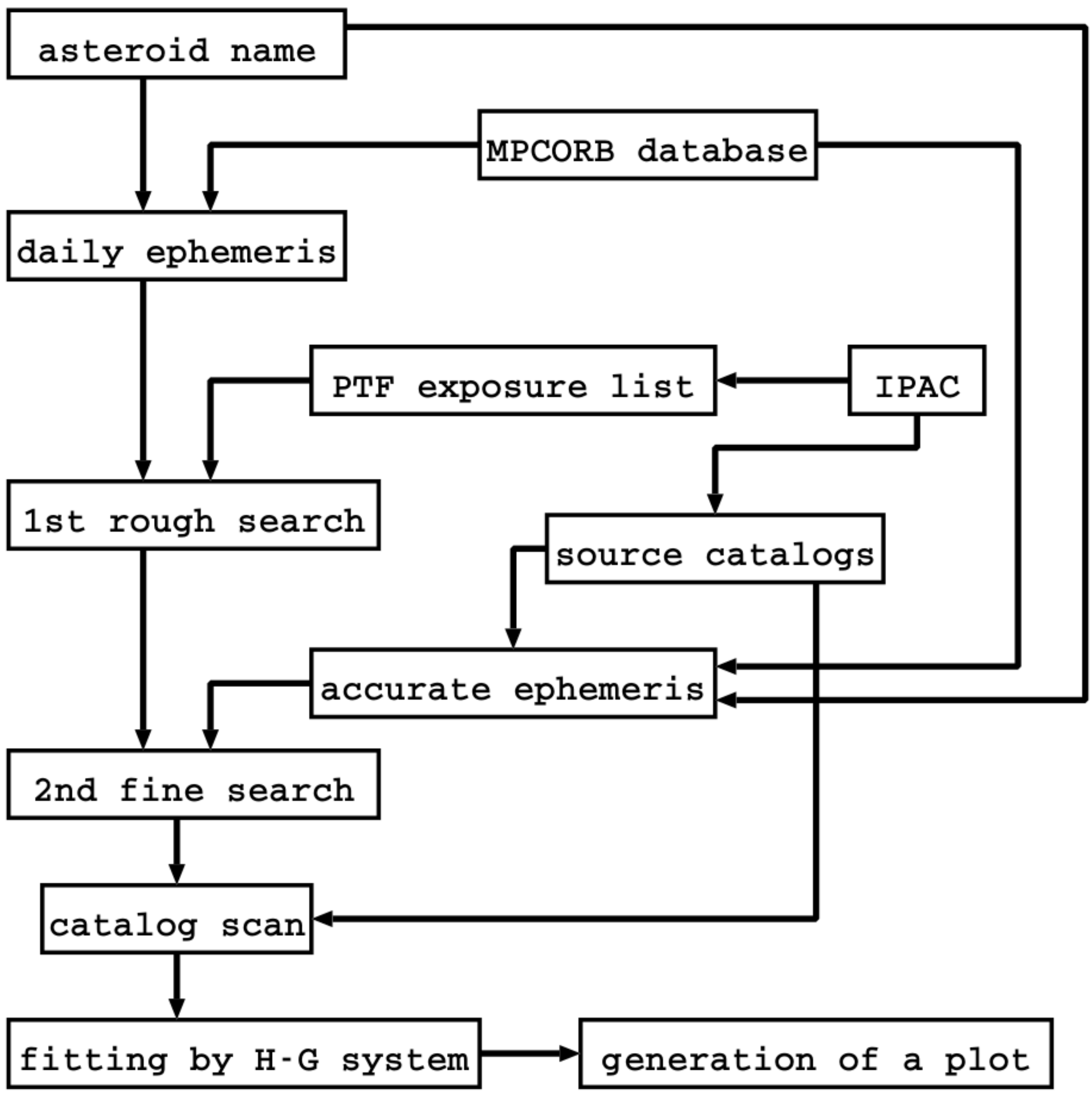
4. mini, <<1 mag

- Occur daily
- Very short lived (10s of minutes)
- Mostly discovered from spacecraft
- Require continuous dense sampling

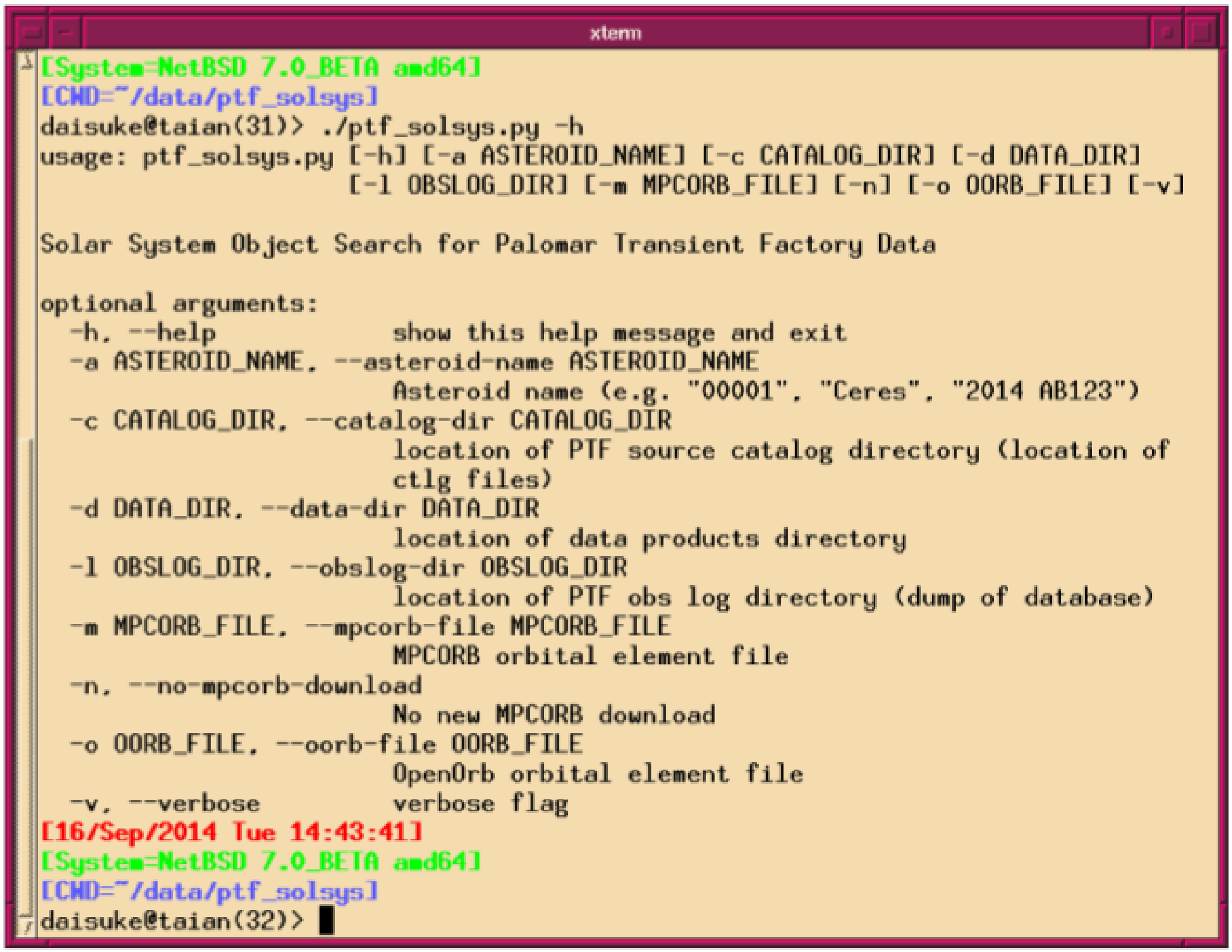
A3. Asteroid phase function



The photometric phase curve of a near-Earth asteroid (1943) Anteros. The data points are all from PTF photometric measurements. The data are fitted by both linear line and H-G magnitude system.



The flowchart of the phase curve generation program. 2-stage scan dramatically reduces the computing time required for the search. This version of the program achieves the full automation of the asteroid phase curve generation from PTF data.

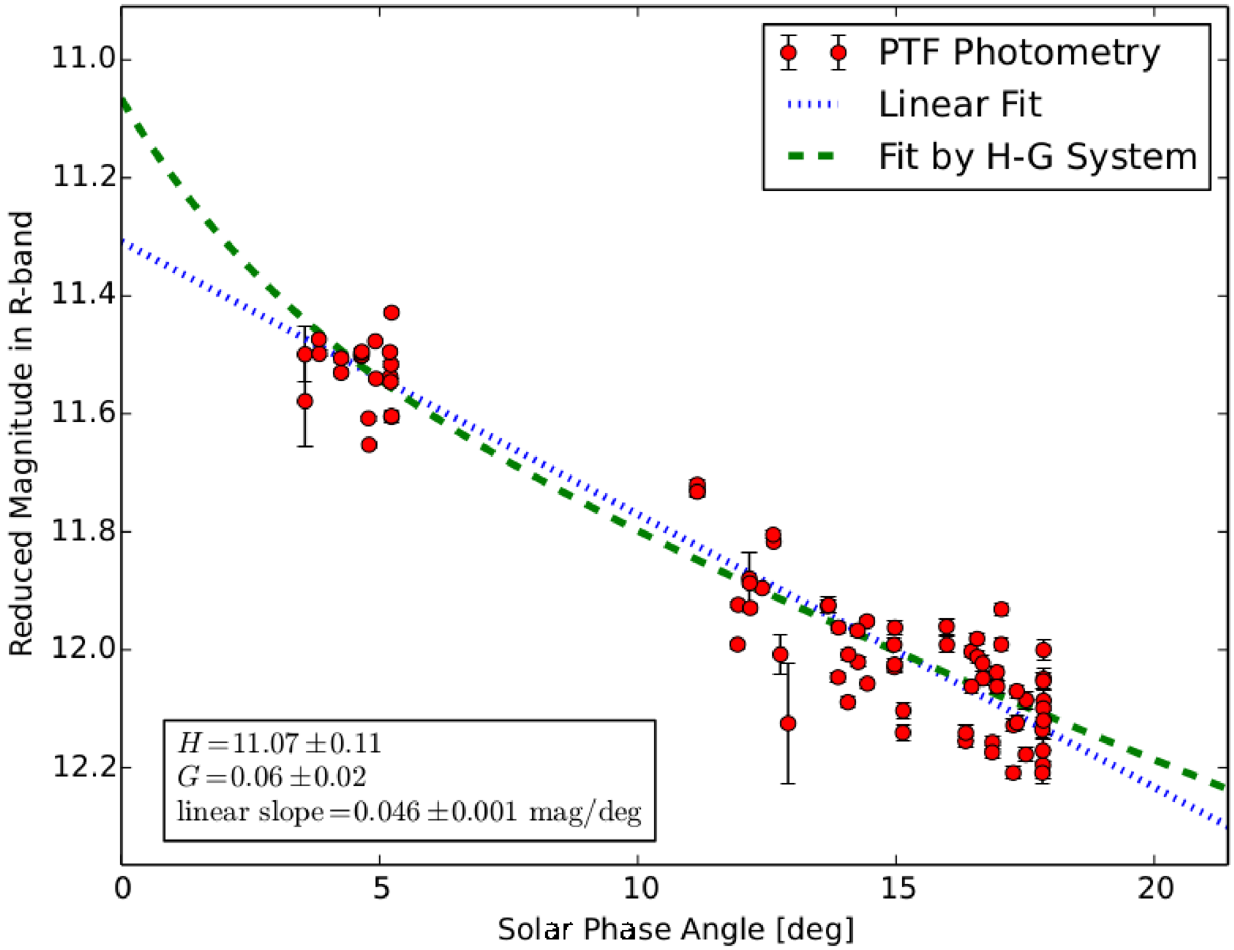


```
xterm
[System=NetBSD 7.0_BETA amd64]
[CWD=~/data/ptf_solsys]
daisuke@taian(31)> ./ptf_solsys.py -h
usage: ptf_solsys.py [-h] [-a ASTEROID_NAME] [-c CATALOG_DIR] [-d DATA_DIR]
                     [-l OBSLOG_DIR] [-m MPCORB_FILE] [-n] [-o OORB_FILE] [-v]

Solar System Object Search for Palomar Transient Factory Data

optional arguments:
  -h, --help            show this help message and exit
  -a ASTEROID_NAME, --asteroid-name ASTEROID_NAME
                        Asteroid name (e.g. "00001", "Ceres", "2014 AB123")
  -c CATALOG_DIR, --catalog-dir CATALOG_DIR
                        location of PTF source catalog directory (location of
                        ctlg files)
  -d DATA_DIR, --data-dir DATA_DIR
                        location of data products directory
  -l OBSLOG_DIR, --obslog-dir OBSLOG_DIR
                        location of PTF obs log directory (dump of database)
  -m MPCORB_FILE, --mpcorb-file MPCORB_FILE
                        MPCORB orbital element file
  -n, --no-mpcorb-download
                        No new MPCORB download
  -o OORB_FILE, --oorb-file OORB_FILE
                        OpenOrb orbital element file
  -v, --verbose         verbose flag
[16/Sep/2014 Tue 14:43:41]
[System=NetBSD 7.0_BETA amd64]
[CWD=~/data/ptf_solsys]
daisuke@taian(32)>
```

The usage of the phase curve generation program. The program is implemented as a Unix command, and thus is easily applied to deal with large number of asteroids.



The photometric phase curve of (6051) Junichi. The figure is generated by the the phase curve generation program using PTF data archive. The data are fitted by the linear slope and IAU's H-G magnitude system. The phase curve derived parameters are also shown in the figure.