NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: April 2, 2018 **Category:** Small Bodies & Moons

Lightcurves of Main Belt Asteroids

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
We propose to obtain dense, continuous time sampling of 10 main belt asteroids with LCO as follow up to sparse light curve sampling obtained with ZTF. The extremely well-characterized light curve segment from LCO will serve to validate Gaussian Process techniques we are developing to analyze sparse asteroid light curves from surveys like ZTF or LSST.

Sparse light curve data from asteroids can provide constraints on their rotation periods, shape, spin states, and (because they have to be accounted for when fitting the multi-band data) colors and phase curves. The distribution of these parameters provides information on the structural properties of asteroids and constrains models of the collisional history of the asteroid belt. Spin states provide valuable inputs for Yarkovsky and YORP models, and color information provides statistical constraints on the composition of asteroids.

These Monte Carlo Markov Chain + Gaussian Process techniques provide posterior probability distributions on asteroid rotation periods, as well as allowing us to account for non-sinusoidal period profiles, and (in future work) fit for colors, phase curves and shape models when using survey data from a multi-band, long-term survey such as ZTF or LSST. Obtaining LCO data to supplement the ZTF data while developing these algorithms will provide invaluable real-world tests of our methods.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	LCO-1m	Sinistro	101 hrs	dark	Jun - Nov	Jun - Nov
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to six lines).*

Investigators *List the name, status, and current affiliation for all investigators. The status code of "P" should be used for all investigators with a Ph.D. or equivalent degree. For graduate students, use "T" if this proposal is a significant part of their thesis project, otherwise use "G".*

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Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

With the start of all-sky synoptic surveys (PanSTARRS, ZTF, LSST), new opportunities are opening up for studying some of the smallest members of our Solar System: Near Earth and Main Belt Asteroids. These asteroids provide keys to understanding the formation and evolution of our Solar System, entangled in their distributions of sizes, shapes, spins and physical structure. We can learn about these properties from the details of the light curve information available in the survey data, but it requires processing tens of thousands to millions of sparsely sampled light curves to fit the asteroid rotation periods, the profiles and amplitudes of the asteroid light curves, phase curve variations and the asteroid colors.

With any individual asteroid, the amplitude and period of the light curve can be used to derive the rotation period and estimate the elongation. Together, these can be used to constrain its structural properties (rubble pile vs. monolithic rock) (Pravec et al. 2002). The light curve profile can be used to determine the asteroid's shape, particularly when data is obtained over a wide variety of viewing geometries and phase angles. Observations over a wide range of phase angles must also fit for the phase curve of the asteroid, constraining the surface properties (smooth vs rough, as well as variable light scattering properties which vary with composition). Asteroid colors (and any variations in color with phase angle or rotation) must also be accounted for when using the non-simultaneous multi-band observations typical of all-sky synoptic surveys. These colors correspond statistically with the taxonomic type of the asteroid, thus constraining its chemical composition. The population-wide distributions of colors, shapes, periods, and spin states can be used to help constrain models of asteroid formation, collision history and orbital evolution.

Current methods of fitting asteroid sparse light curves fall under the categories of fourier analysis of the light curve such as with Lomb-Scargle (Lomb 1976; Scargle 1982) or FALC (Harris et al. 1989); or non-parametric minimization algoriths such as Phase Dispersion Minimization (PDM) (Stellingwerf 1978) or SuperSmoother (Freidman 1984). For applications, see *e.g.* Waszczak et al 2015, Polishook et al 2012, Harris et al 2012, Warner & Harris 2011, Masiero et al 2009, Heinze & deLahunta 2009, Mann et al 2007. These methods have multiple drawbacks: (1) finding the correct period can be difficult when the data are sparse and the power in the periodogram is distributed equally among multiple peaks; (2) uncertainties in the magnitudes can only be taken into account via computationally expensive Monte Carlo simulations; (3) there is no natural way to calibrate the uncertainty in the period estimate; (4) it is difficult to propagate uncertainties into population studies, leading to potentially biased results.

We are developing techniques to model sparse light curves using Gaussian Processes (GPs). Unlike traditional methods, GPs provide a generative model of the time series and include effects such as the non-sinusoidal nature of many asteroid light curves. Via Markov Chain Monte Carlo, they yield a posterior probability distribution for the period that is directly interpretable. They allow easy quantification of uncertainties in period estimate, and posterior probability distributions can be fairly straightforwardly combined for population studies. Further advantages include the capability of including fits for the phase function, potential tumbling, and multi-color observations. These techniques will be necessary to fully exploit the large amounts of sparse light curve data coming from surveys like PanSTARRS, ZTF and LSST. We will develop and test our process with simulated light curves and against archive data. However, simulated data may not sample the full range of true light curve profiles and archive data will generally not be obtained during the same apparition as the sparsely sampled data obtained with ZTF, thus may not present the same light curve profile. Obtaining real, densely sampled light curve data will provide an invaluable resource to fully test our methods.

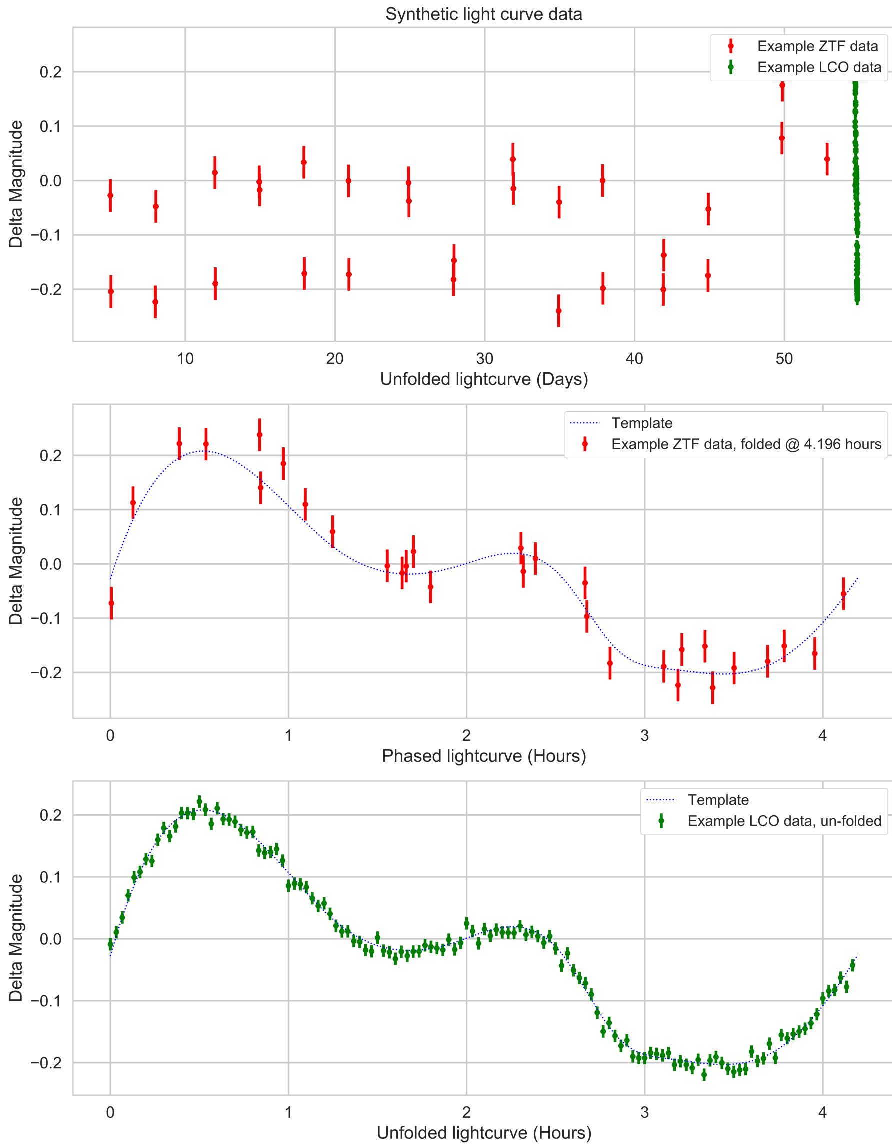

Figure 1: A set of synthetic light curve data, simulated using a template similar to Psyche's light curve profile. The true period of the light curve is 4.196 hours. Light curve data points, as they might be acquired by ZTF (on average, two data points per night separated by 3-4 nights) and by LCO (a continuous rotation period), are plotted over time in the top panel. In the second panel, the ZTF data have been phased by the true period. In the bottom panel, the LCO data are shown without need for phasing.

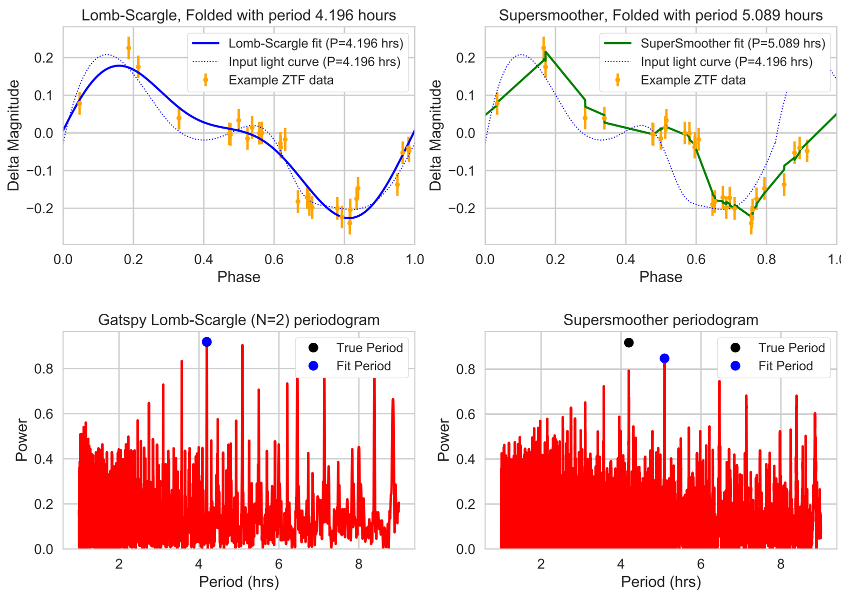

Figure 2: The simulated ZTF sparse light curve data from the previous figure were fit using Lomb-Scargle (with 2 harmonics) and SuperSmoother (similar in approach to PDM) methods available in gatsby (VanderPlas & Ivezic, ApJ 2015). The top panels show the ZTF data phased according to the period fit by each method; L-S recovered the true period, but to the eye, the fit looks better with the Supersmoother template (fit period = 5.089 hrs). Uncovering the uncertainties in the periods fit by either approach from their periodograms is difficult. There are multiple peaks and the total power in the periodogram is unknown, as can be seen in the bottom panels.

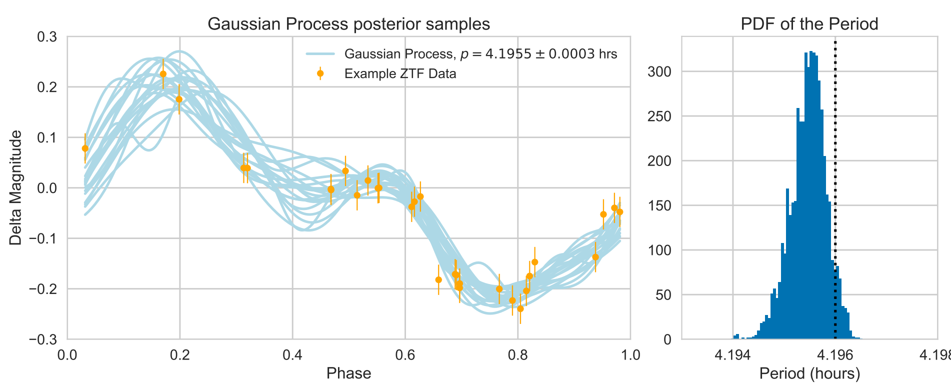

Figure 3: The same simulated ZTF sparse light curve data were run through our Gaussian Process technique. On the left, we show the phased ZTF data (orange) and draws from the posterior probability distribution for the Gaussian Process (blue). On the right, we show the marginalized posterior probability distribution for the period. Unlike traditional methods, the Gaussian Process converges on a well defined probability distribution including the true value, and thus allows for much more precise estimation of the period and its uncertainty than is possible with traditional methods

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

The observations we are proposing to obtain with LCO are intended to densely sample the light curve, following up on the sparse sampling obtained with ZTF.

We will use our Gaussian Process methods on the sparsely sampled data obtained with ZTF, but need densely sampled light curves over a full rotation period to verify the results, especially non-sinusoidal features in the light curve profile.

We expect ZTF to observe more than a thousand main belt asteroids brighter than $r = 20$ in the region with RA between 22 and 2 degrees and Declination between +10 and -30 degrees, consistent with the footprint of the ZTF survey, avoiding the galaxy, and suitable for LCO observations with the 1-m network between June and Dec 2018. This provides plenty of potential targets, with a range of expected light curve periods, profiles and amplitudes. We will choose a sample of approximately 10 objects which provide the best challenge to the Gaussian Process method development, with a range of periods between 2 and 10 hours.

To gather data to fully sample the light curve over the entire rotation period, and to maintain sensitivity to non-sinusoidal elements in the light curve, we need to continually observe the targets for at least two light curve periods. By sampling two light curve periods, we can remove ambiguities due to the possibility of either the light-curve originating from a rotation period (a 'double-peaked' light curve) or albedo variations (a 'single-peaked' light curve). By continually observing the object, we are sensitive to non-sinusoidal variations in the light curve profile. LCO is unique in its capabilities to continually observe a target for longer than a few hours, due to its global distribution of telescopes, and is thus an ideal resource for this project. Although we can recover from missed observations due to local weather conditions, the ideal situation would be to observe each target continually throughout a 4-20 hour time period (depending on the rotation period of each asteroid).

A SNR of about 20 is required in order to obtain photometry with uncertainties small enough to accurately determine the light curve. At r=20, with Sinistro used on the 1-m telescopes, this is possible to achieve with exposure times of about 176 seconds during 'half' bright time (estimated using the LCO Exposure Time Calculator) or 124 seconds during dark time, which provides a reasonable sampling rate (218 seconds, including readout) for these multi-hour light curves.

Depending on the light curve profile and possible ambiguities between light curve period and rotation period, we may request alternating observations in g and r band. For targets with no ambiguity between double- and single- peaked light curves, but with complexity in their light curve profile, we will observe in just r band.

Proprietary Period: 12 months

Use of Other Facilities or Resources *(1) Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program. (2) Do you currently have a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?"*

We are proposing to obtain dense light curve coverage with LCO to complement sparse, LSST-style coverage obtained with the Zwicky Transient Factory, ZTF. The ZTF observations are expected to be obtained approximately every three or four days, with two observations in each night separated by approximately 30 minutes, continually over several months. The University of Washington is a ZTF partner, thus we can access both the public data (sampled at the rate described) and the partnership data, which has the possibility of providing a long-term light-curve sampled at a slightly higher rate (6 times per night instead of 2). This will help us understand the level of "sparse-ness" which works best when combining dense and sparse measurements.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

Observing Run Details for Run 1: LCO-1m/Sinistro

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for queue and Gemini runs).*

We have requested dark or moon-down gray time for this proposal, as our targets will be in the ecliptic and thus near the moon.

For each of our targets, we request observations covering a full rotation period (twice the light curve period). We will determine periods and light curve profiles for potential targets using Gaussian Process methods on the sparse ZTF data. We will select a set of approximately 10 targets with periods between 2 and 10 hours which provide challenges to the Gaussian Process technique for observation with LCO. Choosing 10 targets gives the opportunity to select a reasonable range of test cases. The chosen targets will be $r \leq 20$, with an average light curve period of 5 hours.

A SNR of 20 will allow us to resolve non-sinusoidal small amplitude features in the light curve profile, and can be reached in a single exposure on the LCO 1-m with Sinistro in 176 seconds during 'half' bright time or 124 seconds during dark time (estimated from the LCO ETC). Including a readout + overhead time of 42 seconds per exposure, we can sample the asteroid lightcurve on a timescale of 166 to 218 seconds, which provides a reasonable rate for these multi-hour light curve periods.

For each asteroid, we would observe in a sequence of $\approx$ 200s exposures, in either just r band or in alternating r and g, depending on the details of the sparse light curve data obtained from ZTF. Ideally the sequence would continue continuously throughout two light curve periods (as fit from the ZTF data) to unambiguously sample a full rotation period, but non-continuous coverage planned out over the entire rotation can be used if necessary. If filter changes are required, the overhead for the filter change will be absorbed in the sampling rate, without changing the total amount of time required to cover the light curve. Observing a target for 10 continuous hours (corresponding to a light curve period of 5 hours) with an airmass < 1.5 would require observations acquired from about three or four locations, adding approximately 6 minutes of slew settle and acquisition time per target.

Across all 10 targets, with an average light curve period of 5 hours (requiring observations spanning 10 hours) and an addition 6 minutes of overhead, we are asking for 101 hours of time.

Instrument Configuration

Filters: r, g	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 20 to 2

Dec. range of principal targets (degrees): 10 to -30

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v3.0.