ZTF Solar System Science Feedback

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1. Outline of the ZTF Solar System Projects

For clarification and the ease of further discussion, we present a summary of the cadence requirement/compatibility of each solar system project:

Project	**Cadence requirement/compatibility**
Small NEO Survey	Compatible with the MSIP/strawman survey
Monitering of Comets	Compatible with the MSIP/strawman survey
Twilight Survey	Targeted survey with specific cadence requirement
Super-fast Rotator Survey	Targeted survey with specific cadence requirement
Asteroid light/phase-curve	Compatible with the MSIP/strawman survey

For the projects that are compatible with the MSIP/strawman survey, the scheduling requirement is flexible, and the cadences provided in the White Paper are only presented as “preferred” sample cadences.

2. ZTF Solar System Projects under the Proposed Strawman Cadence

2.1 MSIP/Strawman-compatible projects

It must be noted that the choice of survey fields (namely, distance to the ecliptic belt) will have a significant impact on all solar system projects. Fields close to the ecliptic belt will positively impact all solar system projects and vice versa. Without this information, we assume that the survey fields will be chosen randomly. For the combo survey, we also assume that the ggg-band survey targets a subset of the field by the i-band survey at the same night.

As shown below, our consensus are (1) as MSIP/strawman-compatible solar system projects do not benefit from high cadence observation, wide survey is about twice as good as either fast or combo survey; (2) i-band observation is not particularly useful for solar system projects.

2.1.1 Small NEO Survey (streaking asteroids)

	Fast	Wide	Combo
Number of streaks detected	0.15	0.30	0.15

Note: the number does not account for the repeat detection occurs in the MSIP survey.

2.1.2 Monitoring of Comets

	Fast	Wide	Combo
Number of comets detected	1.6	3.2	1.6

2.1.3 Asteroid light/phase-curve

	Fast	Wide	Combo
Number of asteroids detected	1600	3200	1600

2.2 Twilight Survey (ZTF-TS)

Making the entire twilight time from mid Nov to mid Feb available will help ZTF-TS to reach its science goal. However, the estimate of survey performance depends on how much of the rest of 10% collaboration time is available. Since the time will be splitted by four projects -- ToO, calibrations, Twilight Survey, and M31 -- we assume that 25% time will be available to Twilight Survey from mid Feb to mid Nov. This will make the average time available to be 0.28 hours per night.

The efficiency of ZTF-TS is measured by the following Figure of Merit (FoM):

$$FoM = A\,\Omega\,10^{0.6\,m_{limit}}$$

where *A* is a normalization factor, Ω is the total area that can be surveyed in deg^2 per night, and m_{limit} is the limiting magnitude of the survey. We compare the *FoM* for ZTF-TS to CFHT Kreutz survey (Ye et al. 2014), the only reported twilight survey equivalent, by taking the *FoM* of CFHT Kreutz survey to be unity. It should be noted that CFHT Kreutz survey is a short term survey (only 4 hours in total) with a restricted science goal (only look for Kreutz comets) and therefore has a rather different scope than ZTF-TS.

For ZTF-TS, m_{limit} =18, Ω=563 deg^2 where the constant of 563 deg^2 is calculated taking that each field is visited 4 times and the maximal possible observation time (i.e. the requested time) per night is 0.67 h. Here is the calculated *FoM* for ZTF-TS compared to CFHT Kreutz survey:

Survey	Ω(deg^2)	*FoM*
CFHT Kreutz Survey (m_{limit} =21)	6	1
ZTF-TS, 100% time	563	1.5
ZTF-TS under the strawman strategy (42% time)	236	0.6

We conclude that ZTF-TS will only be 60% as efficient compared to the CFHT Kreutz Survey, and 40% as efficient to its full potential. However, it should also be noted that ZTF-TS will be running year-round for a 3-year survey (though most of the time are allotted in winter) while CFHT Kreutz Survey had only run for a limited time.

2.3 Super-fast Rotator (SFR) Survey

At Palomar, the opposition region of ecliptic belt is highest during winter nights. Making continuous winter nights available to the SFR Survey will help the science. A detailed justification of the proposed cadence is attached in the Appendix.

3. Response to Referee's Comments

3.1 Small NEO Survey

> Cadence requirements for small NEOS are 2 observations a night (small NEOs will streak 20 arcsecs in 30 second exposure) over 10,000 sq degrees with observations separated by an hour. Repeated observations are to improve the trajectory calculations to enable followup within 24 hrs. A number of simulated data sets exist and it would be good for the proposers to demonstrate that they a) can recover the trajectory with 2 exposures b) that one exposure per night is not sufficient for fast movers (even given the fact that the direction of motion would not be known). There is a high impact on other surveys if a 2 per night cadence is adopted but this might be offset if the observations were in different bands.

Most asteroids are found well beyond several lunar distances (LDs). Asteroids at 10 LD, for example, moves at an apparent motion of 15 deg/day (Veres et al. 2012) or 0.6 deg per hour. That is well within ZTF's field of view. As long as the same field will be revisited (this will be done, as astrophysical projects need to eliminate asteroids as well), a typical fast moving asteroids will be imaged multiple times. Revisit in different band is acceptable though it will reduce the detection limit by a few 0.1 mags compared to *R*-band only observations.

One exposure per night is not sufficient as the direction of the motion would not be known, and uneconomical to trigger a ToO for all possible NEO events.

3.2 Monitoring of Comets

> Re comets activity - as far as I know the duration of comets outbursts is longer than 1 day (is this true?) they don't mention the typical time scale and why 1 night cadence is required + in any given moment there are a few tens of visible comets (and we know where are they) - easier to monitor them with a small dedicated telescope. Using ZTF is an overkill.
> Finally, this strategy will have negative impact on some other ZTF proposals. For example, 1 day cadence means that any survey that requires early transient detection (e.g., SN, GRBs) will become in practical.

We do not request dedicated comet pointings. We request that the entire sky is observed as often as possible, and will extract photometry of all known comets in that survey. There is no dedicated facility that monitors all known comets, and existing surveys focus on a small number bright comets. This introduces a strong bias towards nearby comets that have their perihelion close to the Sun.

At this moment, we know of two outburst regimes: very large (5 mag) that are mostly discovered by amateurs first, and mini outbursts (<0.1 mag total brightness), that can only be discovered and observed from spacecraft missions to comets (i.e. 9P and 67P). Large outbursts can last for weeks; small outbursts live for 10s of minutes at most. Our survey addresses the spectrum in between, i.e. 0.3 - 3 magnitudes. We do not know how long they last, but a higher sky survey cadence allows us to better characterize the outburst (better constraint on how long it lasts and on how much material is released) and is necessary for rapid follow up of outbursts we discover. Rapid follow up is needed to investigate volatiles and ices ejected by the outburst; these will disappear over time.

The fact that the duration of comet outbursts is longer than 1 day is caused by sampling bias -- there is no high cadence survey like the ZTF that monitor the outburst of comets and this is exactly why we propose to do this project.

The project is compatible with MSIP/strawman survey and does not impact on other proposals that also seek wide coverage.

The comet survey benefits most from first r' (dust, easiest to interpret), second g' (gas). the i filter is not particularly useful for comets, which are fainter at those wavelengths.

The fast cadence of 1 day will improve the outburst monitoring, especially when it's near the ecliptic plane (where the Jupiter Family comets are). This will allow us to evaluate the bias of the 3-day monitoring, i.e. how much did we miss?

The best option is not listed - that would be the wide survey, 1-day cadence, with g and r.

3.3 Twilight Survey

> Re: twilight survey: 5min cadence justification is missing (i.e., some NEOs at this line of sight maybe very slow moving objects); the justification for R-band seems wrong. G-band should be darker.

The 5 min cadence is largely limited by the narrow observation window (20 min per evening/morning session) and the requirement to conduct 4 visits.

NEOs that are moving along the line of sight might indeed move slowly, but they rarely move slower (when they do, they will not stay in that movement for long) than main-belt objects which move at a rate of ~0.5-1"/min. At a pixel size of 1", an observational time span of 20 min will reveal even objects moving at this rate.

It is true that sky under *g*-band should be darker. However, fainter NEOs tends to be slightly redder due to their more weathered surface. Therefore we gain a small advantage by observing in *R*.

> Proposes a twilight survey which seems good use of observing time but it is not clear from the text what the optimal choice of filter is (given the color of the sources, amount of twilight time and sky brightness).

See the response above.

3.4 SFR Survey

> Re: fast rotators - cadence is overkill. Fast rotators are very rare. In order to find candidates, best to use ~1-2 hours cadence (with quasi-random sampling). This will allow to scan much larger sky area and find more candidates. Followup/confirmation can be done elsewhere.

The appendix provides an in-depth discussion why hourly cadence observation would not be useful in finding SFRs.

> It is not stated whether the high cadence observations need to be done for the length of the survey or as a targeted campaign.

The SFR Survey is a targeted campaign, therefore high cadence observations need to be done throughout the campaign.

3.5 Asteroid light/phase-curve

> Re: asteroid light curve - the 1 night cadence is not justified. This project can be done with the regular ZTF cadences (e.g., MSIP, or high cadence).

The 1 day cadence was listed as an example. This project is compatible with the MSIP/strawman cadence.

Appendix: Strategy of Super-fast Rotator Survey

We have 40% observation time per night, which is ~2-3 hours. Assuming one data point taken with 1 hour cadence + another data point taken with random cadence, we therefore have two data points within two hours per night. The simulations were carried out for super-fast rotator of ~20 mag, 1.3 hr rotation period, and 0.6 amplitude with time-span from 1 to 30 nights (i.e., consecutive good weather nights). We are not able to recover the rotation period until to a time-span of 18 nights. However, we have multiple solutions and none of them are significant enough (see Fig. 1). Even up to a time-span of 30 nights, we are just barely to detect the synthetic rotation period and not able to determine whether it is a reliable determination (see Fig. 2).

A1. 1-day cadence justification

To derive rotation period from “archive” dataset, we propose 1-day cadence. This will help us to detect rotation periods of asteroids with diameter down to 1 km, whose rotation periods were mostly missed to be detected in the PTF archive data (see Waszczak et al. 2015). The reason is explained below:

Assuming a limiting magnitude ~20.5 mag,

1. An asteroid of ~1 km at 2.2 au would be observable only around its opposition (i.e., ~20 mag at opposition). Therefore, 1-day cadence would allow us to collect ~30 data points of that asteroid, and we are not able to derive its rotation period from that light curve (see Fig. 3). Never to say 2-day or 3-day cadence, it would result in a light curve with even fewer data points. This has also been seen in Waszczak et al. (2015), rotation periods derived from the PTF archive data, where we see that the lower diameter limit of asteroids that can have reliable rotation period determinations is around 3 km.
2. An asteroid of ~2 km at 2.2 au would be observable for ~1.5 months before/after its opposition (i.e., ~19 mag at opposition). With 1-day cadence, we are able to detect its rotation period (see Fig. 4). If the cadence is loosen to 2-day, we are still able to detect the rotation period (see Fig. 5). However, we would miss to detect the rotation period with 3-day cadence (see Fig. 6)

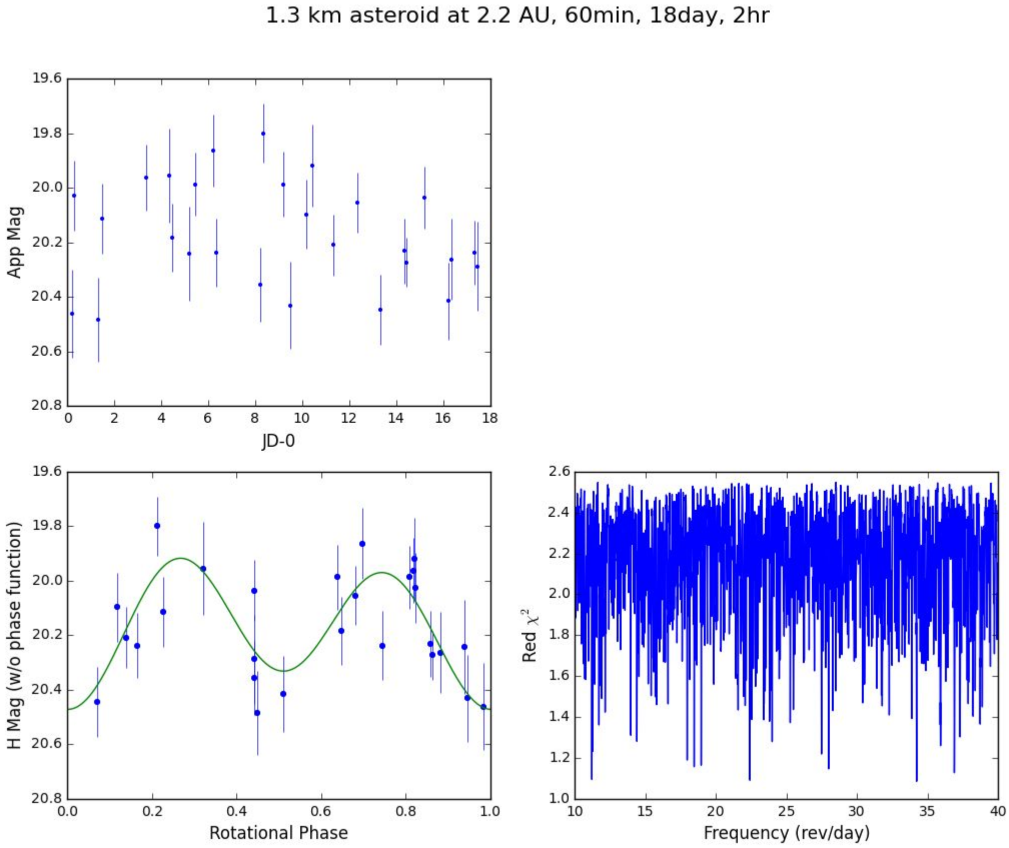

Figure 1. Top-left: light curve (apparent mag vs jd). Low-left: folded light curve (rotational phase vs relative reduce mag). Low-right: periodogram (Frequency vs Reduced Chi^2). The rotation period is derived from a observation of **a time-span of 18 nights**. Although we recover the synthetic rotation period, we cannot rule out other solutions that have almost equally good fitting.

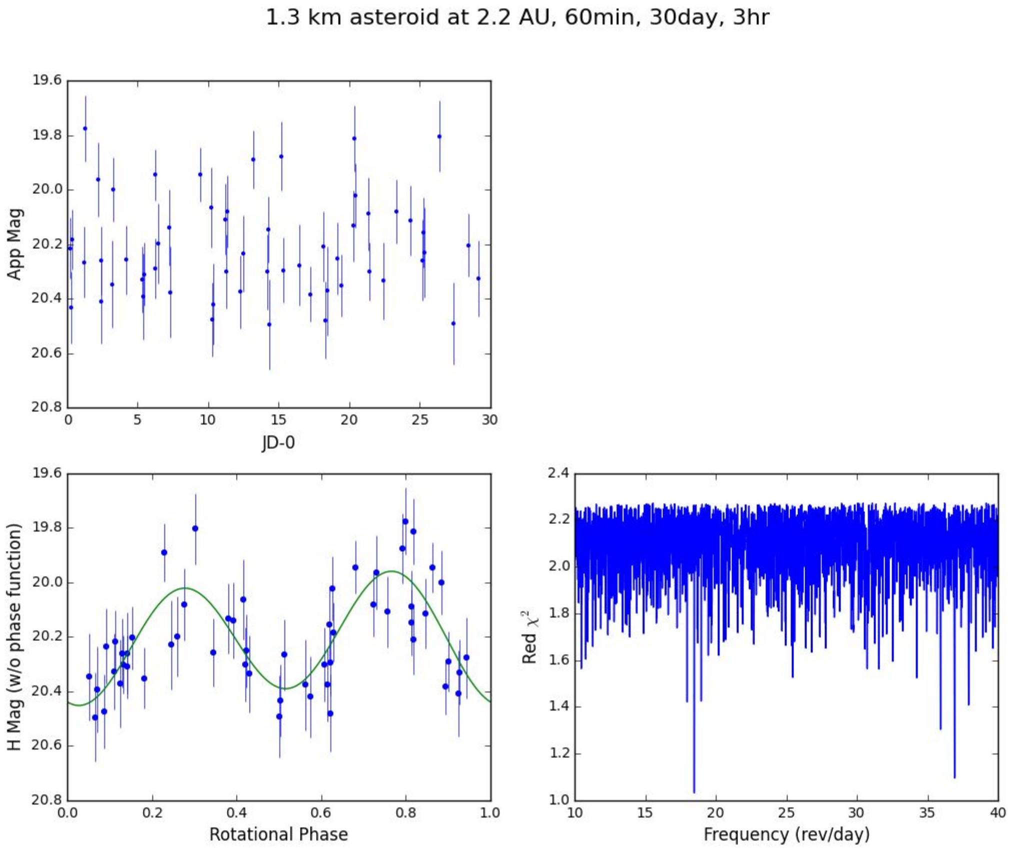

Figure 2. We barely to recover the synthetic rotation periods from an observation of a time-span of 30 nights. However, we cannot decide whether it is a reliable determination or not.

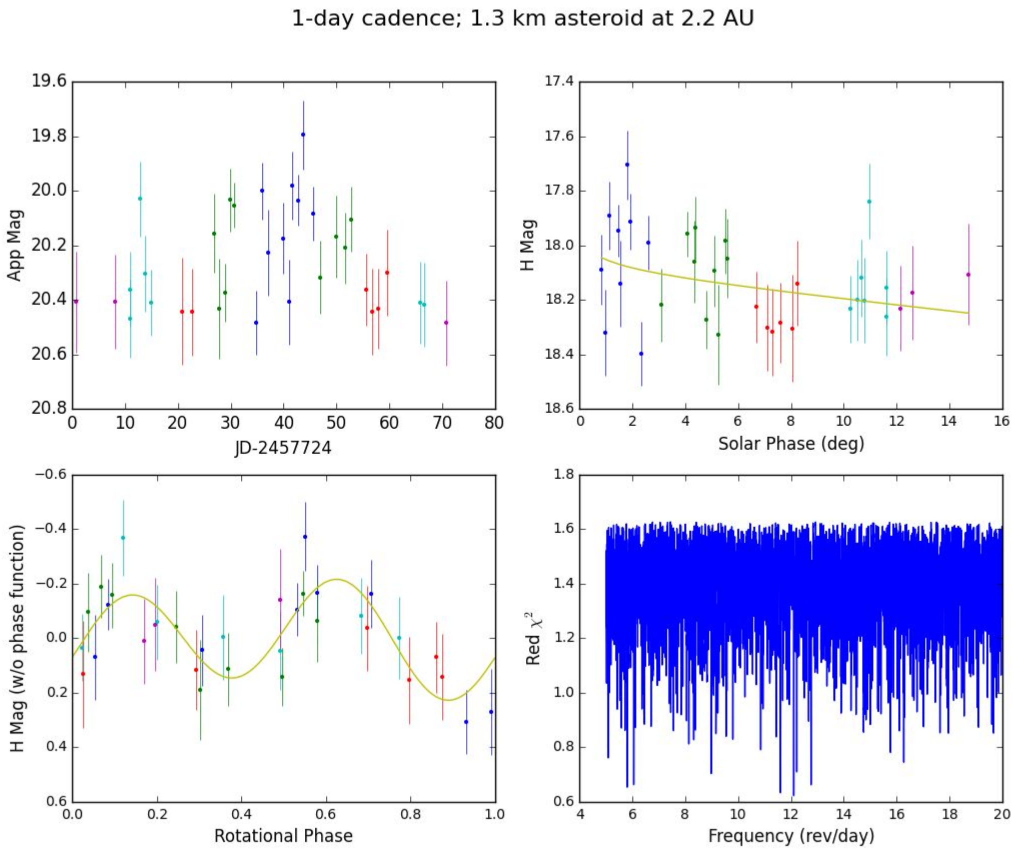

Figure 3. Top-left: light curve (apparent mag vs jd). Top-right: phase curve (solar phase angle vs reduced mag). Low-left: folded light curve (rotational phase vs relative reduce mag). Low-right: periodogram (Frequency vs Reduced Chi^2). **The best-fit frequency is not the same with the synthetic frequency (i.e., 9.23 rev/day).**

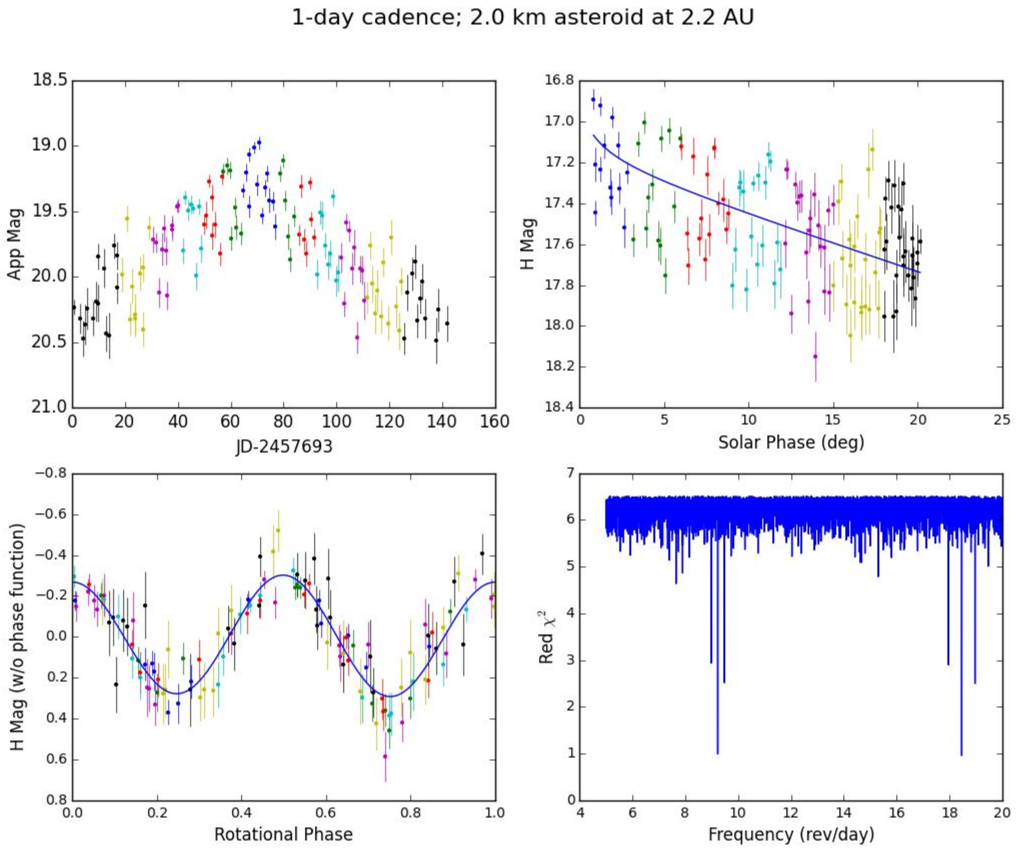

Figure 4. The best-fit frequency is the same with the synthetic frequency (i.e., 9.23 rev/day).

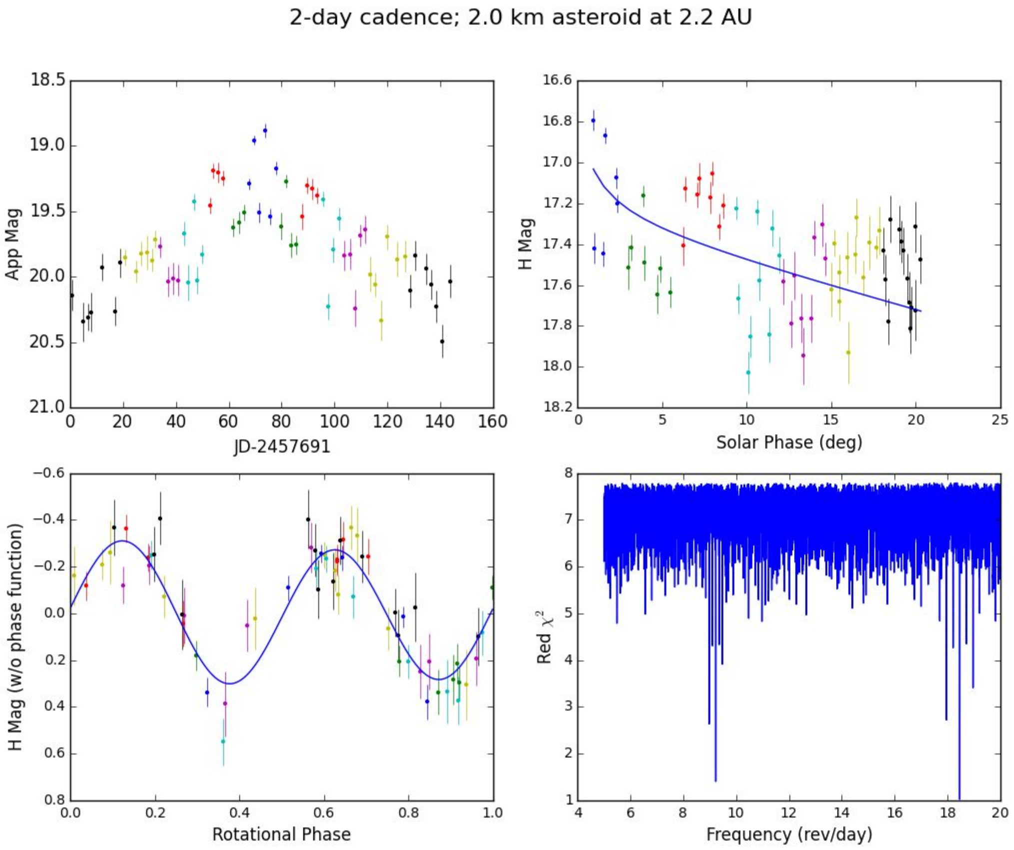

Figure 5. The best-fit frequency is the same with the synthetic frequency (i.e., 9.23 rev/day).

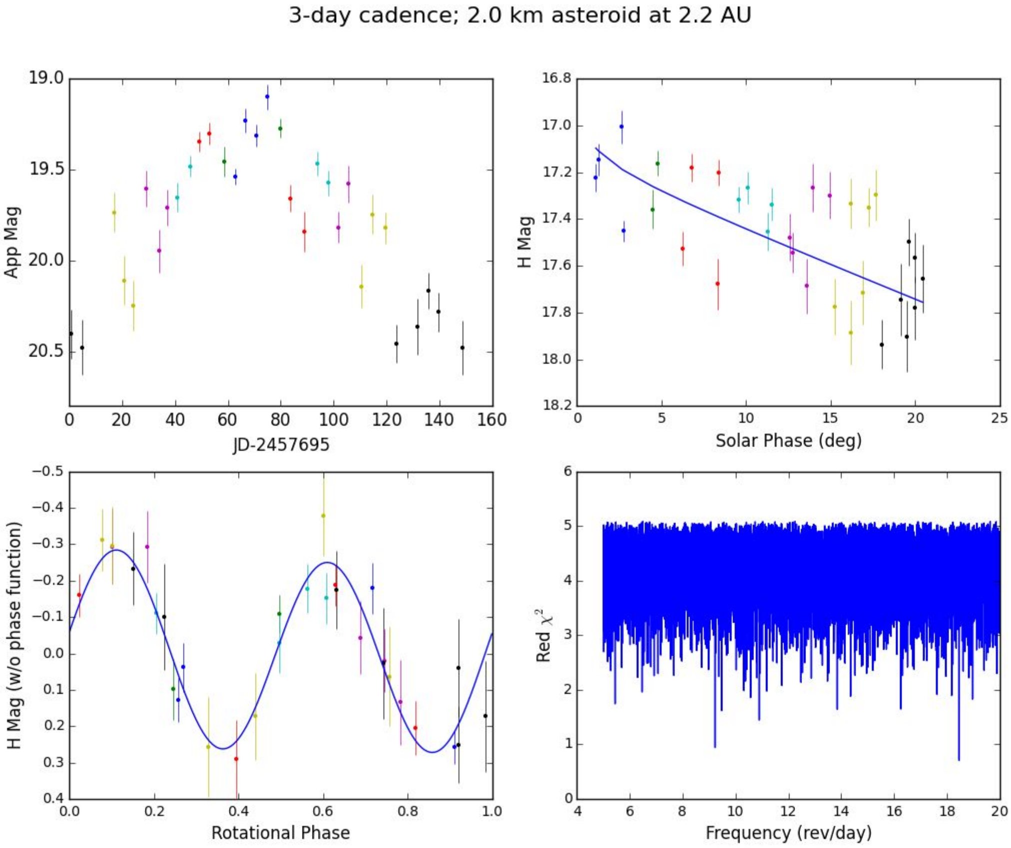

Figure 6. Although the best-fit frequency is the same with the synthetic frequency (i.e., 9.23 rev/day), the folded light curve is pretty sparse that might need confirmation.