TDEs with LSST

Katja Bricman [*1] and Andreja Gomboc[†1]

[1]Center for Astrophysics and Cosmology, University of Nova Gorica, Vipavska 11c, SI-5270 Ajdovščina, Slovenia

November 30, 2018

Abstract

We investigate the prospects of observing Tidal Disruption Events (TDEs) with different LSST cadences proposed with the White paper call. We study their detection rates, the quality of their light curves and discuss which cadences sample TDEs better before or during the peak of the light curve. We suggest some constraints on the observing cadences that we believe will increase the number of reliable classifications of TDEs, in particular a WFD survey with 2 visits in different filters every night or at least every second night, observing the extra-galactic sky.

1 White Paper Information

1. **Science Category:** Transeints and variable stars

2. **Survey Type Category:** Wide-fast-deep survey

3. **Observing Strategy Category:** a specific observing strategy to enable specific time domain science, that is relatively agnostic to where the telescope is pointed (e.g., a science case enabled by relatively deep precise time-resolved multi-color photometry).

---

[*]katja.bricman@ung.si

[†]andreja.gomboc@ung.si

2 Scientific Motivation

When a star in a nucleus of a galaxy gets scattered into the vicinity of the supermassive black hole (SMBH) in the core of the galaxy, the star can be torn apart by black hole's strong tidal forces (Rees, 1988; Phinney, 1989; Evans & Kochanek, 1989). The process, known as a Tidal Disruption Event (TDE), can emit a bright flare of light, which slowly decays with time on time scales from months to years.

TDEs are very promising probes for studies of quiescent black holes, which form the large majority of SMBHs found in nuclei of most galaxies in the universe. Observed light curves of TDEs hold information on the SMBH mass involved, as well as on other parameters, such as the mass and the radius of the disrupted star, the distance from the black hole at which the star is disrupted, and others (Kochanek, 1994; Gomboc & Cadez, 2005; Lodato et al., 2009; Strubbe & Quataert, 2009; Lodato & Rossi, 2011; Guillochon & Ramirez-Ruiz, 2013; Mockler et al., 2018)

TDEs are rare transients, with only a few tens of candidates discovered so far (e.g. van Velzen et al., 2011; Gezari et al., 2012; Arcavi et al., 2014; Chornock et al., 2014; Holoien et al., 2014, 2016a,b; Leloudas et al., 2016; Wyrzykowski et al., 2017; Blagorodnova et al., 2017). A typical light curve is shown in Figure 2. The rate of TDEs was estimated to be between 10^{-4} and 10^{-5} per galaxy per year (Magorrian & Tremaine, 1999; Wang & Merritt, 2004). Due to the small rate, large surveys which are constantly observing billions of galaxies, such as the LSST, are more likely to catch these events and will substantially enlarge the observed TDE sample.
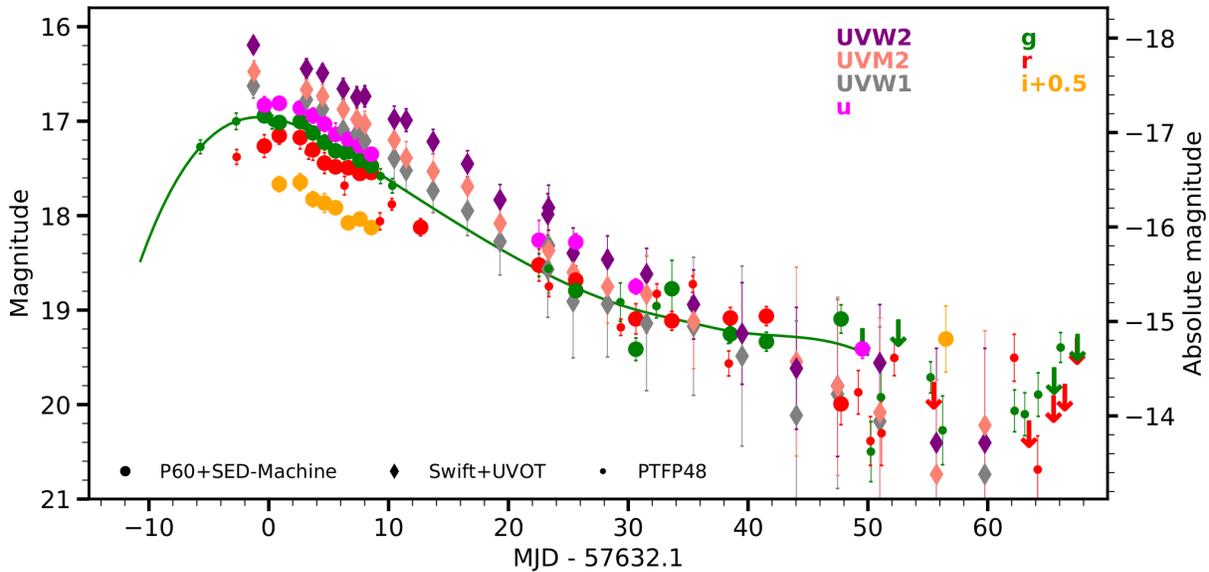

Figure 1: Light curve of a TDE discovered with iPTF in 2016 (Blagorodnova et al., 2017).

TDEs have been observed in optical wavelengths and in X-rays. It was recently suggested,

that the observed emission depends on the inclination of the star-black hole orbit as viewed from Earth (Dai et al., 2018). For the LSST only TDEs observed in optical wavelengths will be relevant, however multi-wavelength follow-up and spectroscopic observations will be needed for a firm classification and for a better understanding of the physical processes involved.

The main sources of contamination are type Ia Supernovae, which can exhibit a similar behavior in the light curve, especially near the peak. A few features which can help us distinguish TDEs from SNe are their colors (they should be quite blue, with g-$r \approx$ -1), their temperature evolution, the distance from the galactic center, and spectra.

LSST should substantially enlarge the sample of observed TDEs. Estimations have been done in the past, that the LSST should discover 40000 new TDEs in 10 years (van Velzen et al., 2011). In Abell et al. (2009) this number was estimated to be 60000, based on the universal TDE rates from Rau et al. (2009). The observations of TDEs are important for studies of SMBHs and stellar dynamics in central regions of galaxies, for determining more accurately their rates and observational signatures, for exploring the mass distribution of black holes (in particular on their low-mass end), accretion physics, and jet formation.

3 Technical Description

3.1 High-level description

Ideally, we would only have the WFD survey, with two visits per night or two visits every second night, where in each subsequent visit during the same night the filters would be changed. This would help us to more accurately determine the color of TDEs and their temperature evolution (main characteristics, which can distinguish them from SNe Ia).

3.2 Footprint – pointings, regions and/or constraints

TDEs are extra-galactic sources, therefore, due to the Galactic dust absorption, we do not expect to detect them in the optical in the direction of Galactic plane. Hence, the region between galactic latitudes $-15° < b < +15°$ should be avoided.

3.3 Image quality

No constraints.

3.4   Individual image depth and/or sky brightness

No constraints.

3.5   Co-added image depth and/or total number of visits

No constraints.

3.6   Number of visits within a night

Ideally 2 visits in different filters per night or 2 visits in different filters every second night.

3.7   Distribution of visits over time

There are no special constraints on the timing of visits within a night, between nights, between seasons or between years. 2 visits per night would be ideal. 2 visits every second night could also work. Although, concerning only the rates of discovered events, as shown later on, there are no large discrepancies between the single visit per night cadence (`Colossus_2667`) and other cadences.

3.8   Filter choice

Change of filters between subsequent visits in a night.

3.9   Exposure constraints

The 15 second exposure should work, it does not seem that there are any significant changes in the detection rate if the exposure is 20 seconds long.

3.10   Other constraints

No other constraints.

3.11   Estimated time requirement

TDEs are expected to be discovered within the WFD survey.

3.12   Technical trades

1. *What is the effect of a trade-off between your requested survey footprint (area) and requested co-added depth or number of visits?*
   The survey area and co-added depths remain unchanged.

Properties	Importance
Image quality	2
Sky brightness	3
Individual image depth	3
Co-added image depth	3
Number of exposures in a visit	1
Number of visits (in a night)	1
Total number of visits	1
Time between visits (in a night)	1
Time between visits (between nights)	1
Long-term gaps between visits	1
Other (please add other constraints as needed)	change filters between subsequent visits

Table 1: **Constraint Rankings:** Summary of the relative importance of various survey strategy constraints. The importance of each of these considerations is ranked as 1=very important, 2=somewhat important, 3=not important.

2. *If not requesting a specific timing of visits, what is the effect of a trade-off between the uniformity of observations and the frequency of observations in time? e.g. a 'rolling cadence' increases the frequency of visits during a short time period at the cost of fewer visits the rest of the time, making the overall sampling less uniform.*
Rolling cadence is disfavored, since it yields less events. However, in case of a rolling cadence, the light curves are sampled more frequently, and the number of TDEs discovered in the pre-peak phase is larger, but both improve only by a factor of at most 2 with respect to other (non-rolling) cadences.

3. *What is the effect of a trade-off on the exposure time and number of visits (e.g. increasing the individual image depth but decreasing the overall number of visits)?*
It seems there are no benefits if the exposure time is longer.

4. *What is the effect of a trade-off between uniformity in number of visits and co-added depth? Is there any benefit to real-time exposure time optimization to obtain nearly constant single-visit limiting depth?*
No benefit from a constant single-visit depth.

5. *Are there any other potential trade-offs to consider when attempting to balance this proposal with others which may have similar but slightly different requests?*
Other proposals that are similar in science case or strategy definition:

- Bianco et al. with Explosive Physics & Fast Transients LSST Cadence proposed a *Presto-Colore* strategy which is in some aspects similar to ours - they suggest 3 visits per night, 2 in different filters with a short time interval between them (~ 1 hour), and another visit in one of those filters repeated after a longer time

(~ 4 hours). There are no conflicts between their strategy and ours, although we would not require such frequent sampling, since TDEs are evolving much slower than fast transients.

- Gezari et al. with An Extreme Rolling Cadence Wide-Fast Deep Survey suggest an extreme case of rolling cadence intended especially for TDE search, in which the whole survey footprint would be observed only int the first and in the last year of the survey, while in the rest of the time they would divide the sky into 8 strips of 2500 deg^2 each, observing one strip per year with preference to observations in u, g and r bands. While this would surely yield very well sampled TDE light curves in the pre-peak and peak phase (around 200 per year), the light curves observed in the first and the last year (around 1600 TDEs) will not have a better temporal sampling than in case of any other non-rolling cadence. Due to such monitoring of the sky we also estimate that roughly 2/3 of the events will be lost.

4   Performance Evaluation

To evaluate the performance of a given survey strategy, we simulated observed light curves of TDEs with LSST simulation framework. The details of our simulations can be found in Bricman&Gomboc (in prep.). Using different cadences released with the White Paper call, we estimated the total number of discovered TDEs in 10 years of LSST observations and the properties of simulated observed light curves for each cadence.

Our simulations were done only on a small patch of the sky of 20.25 deg^2, which is covered in `GalaxyObj` base catalog model in `CatSim`, containing around 17 million galaxies. After simulating light curves of TDEs based on their rates and other parameters, which define the light curve of a certain event, we estimated the number of discovered TDEs on the whole sky observed by the LSST, but avoiding the Galactic plane. We do not expect TDEs from the Galactic plane, since the dust absorbs the light from extra-galactic transients. Subtracting the area of the Milky Way from the total area of the sky observed by the LSST (~ 18000 deg^2) results in 13300 deg^2 of the sky from which we expect TDEs.

As good positive detections we choose all TDEs with 10 or more observations above the (limiting - 2) magnitude of the telescope in any band. Setting the constraint to (limiting - 2) magnitude excludes all the light curves, in which observing points fall rather quickly in the area close to the limiting magnitude. There the magnitude error-bars are large, which would make the classification of TDEs more difficult. The estimated numbers of detected TDEs are shown in the first, top panel of Figure 2. The numbers do not vary much from one cadence to another, although in the case of rolling cadences, the number of discovered TDEs tend to be smaller by a factor of ~ 1.5.

However, the number of detected TDEs is not the only criteria used to evaluate the performance of different cadences. The first panel of Figure 2 also shows the number of TDEs discovered in the pre-peak phase. In all cases of cadences, between 50% and 60% of detected TDEs will be discovered in pre-peak phase, with only one rolling cadence (`pontus_2579`)
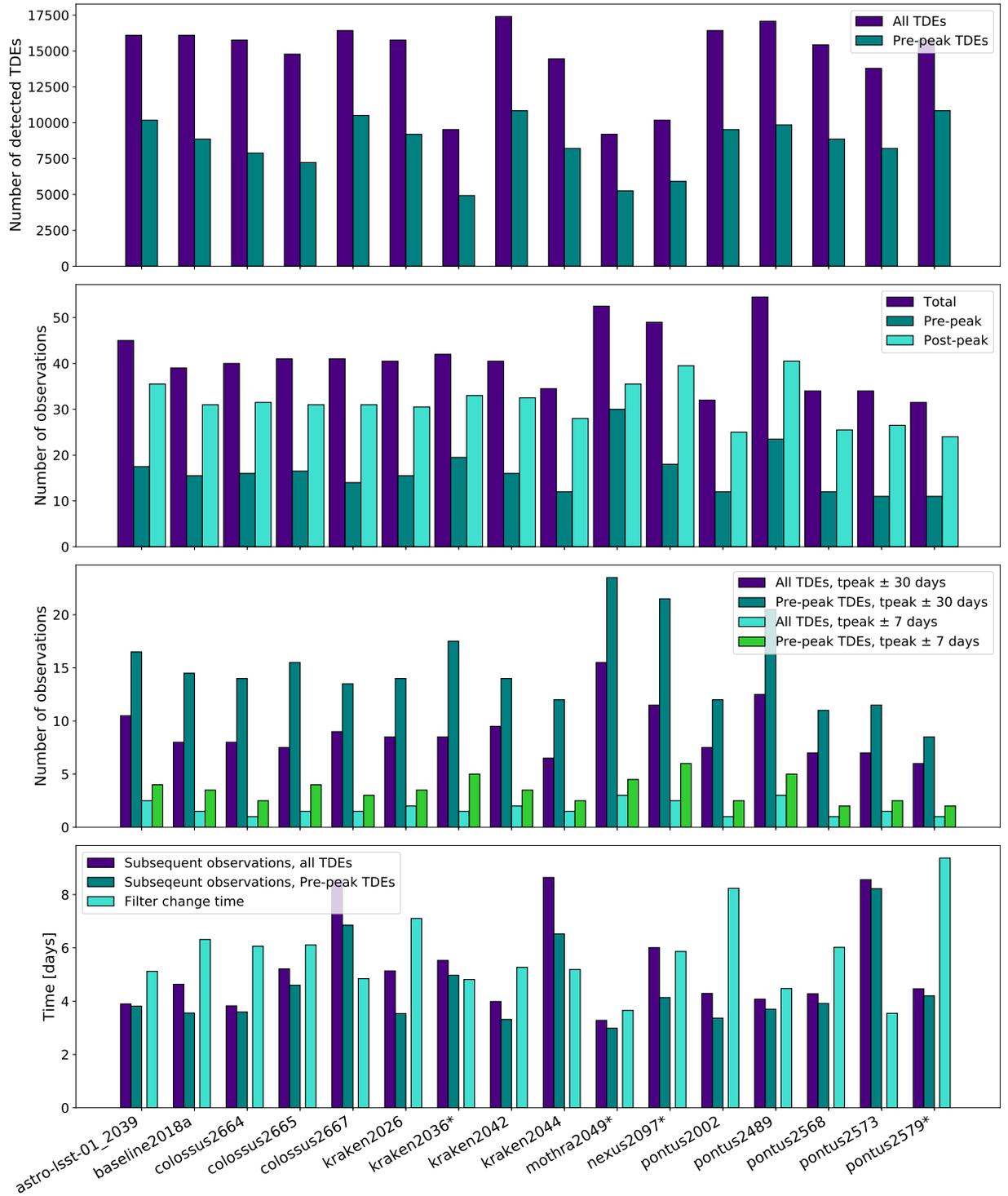
Figure 2: **Properties of detected TDEs**: in the upper panel the expected number of discovered TDEs with LSST in 10 years of observations on 13300 deg^2 is shown for all TDEs and TDEs discovered in pre-peak phase. The second panel shows average total number of observations, number of observations in pre-peak time, and number of observations in post-peak time. Third panel shows the number of observations in peak time $\pm$ 7 days, number of observations in peak time $\pm$ 30 days, both for all TDEs, and TDEs discovered in pre-peak phase. The fourth panel shows the time interval between subsequent observations for all and pre-peak TDEs, and the time interval in which filters are changed. Note that values are averaged over all detected TDEs and may largely vary between individual cases. Rolling cadences are denoted with *.

7

having as much as 68% of TDEs observed in pre-peak phase.

In the second panel of Figure 2 the average number of observations of a detected TDE in total, in pre-peak and post-peak phases are shown. The total average number of observations is of the same order of magnitude for all cadences, while the average number of pre-peak observations shows an increase in case of rolling cadences and in case of `pontus_2489` cadence, which has more visits, but two 15 s exposures in a visit are replaced by one 20 s exposure. It is not surprising that rolling cadences sample the light curves better, also in the post-peak phase.

From the third panel in Figure 2 it is obvious, that none of the proposed cadences sample the light curves of TDEs in peak time $\pm$ 7 days very well. The same goes for observations in peak time $\pm$ 30 days. TDEs detected in pre-peak phase are more frequently sampled in peak time $\pm$ 7 days and in peak time $\pm$ 30 days.

The average time interval between two subsequent observations is shown in the last panel of Figure 2 for all TDEs and TDEs discovered in pre-peak phase, together with the time interval between two subsequent filter changes. For all TDEs two observing points are on average between 4 and 8 days apart, while for TDEs discovered in pre-peak phase, this time is only slightly shorter. The filters are changed on average every 2-6 days.

We cannot claim that any of the proposed cadences would be ideal for our science case. The concern with the rolling cadences is that even though they seem to sample TDEs more frequently, especially in the pre-peak phase, they do tend to lose approximately half of the events that other cadences detect. On the other hand, for the case of non-rolling cadences the intervals between two subsequent observations and the time intervals between filter changes seem to long for a successful classification of TDEs.

We propose a cadence with 2 visits in different filters per night every night or every second night, which would sample TDE light curves frequently enough. Due to the low number of discovered TDEs to date, we cannot be certain whether 10 observing points we are assuming here as the minimum will be enough for a positive TDE classification. That is why the filters should be changed between subsequent visits, in order to calculate colors and color evolution, which are the basic parameters for the rapid TDE classification among other transients.

5 Special Data Processing

No special data processing beyond the standard LSST Data Management pipelines required.

6   Acknowledgements

7   References

Abell, P. A., et al. 2009. https://arxiv.org/abs/0912.0201

Arcavi, I., et al. 2014, ApJ, 793, 16, doi: 10.1088/0004-637X/1/38

Blagorodnova, N., et al. 2017, ApJ, 844, 46, doi: 10.3847/1538-4357/aa7579

Chornock, R., et al. 2014, ApJ, 780, 44, doi: 10.1088/0004-637X/780/1/44

Dai, L., McKinney, J. C., Roth, N., Ramirez-Ruiz, E., & Miller, M. C. 2018, ApJ, 859, L20, doi: 10.3847/2041-8213/aab429

Evans, C. R., & Kochanek, C. S. 1989, ApJ, 346, L13, doi: 10.1086/185567

Gezari, S., et al. 2012, Nature, 485, 217, doi: 10.1038/nature10990

Gomboc, A., & Cadez, A. 2005, Astrophys. J., 625, 278, doi: 10.1086/429263

Guillochon, J., & Ramirez-Ruiz, E. 2013, ApJ, 767, 25, doi: 10.1088/0004-637X/798/1/64,10.1088/0004-637X/767/1/25

Holoien, T. W. S., et al. 2014, MNRAS, 445, 3263, doi: 10.1093/mnras/stu1922

—. 2016a, MNRAS, 455, 2918, doi: 10.1093/mnras/stv2486

—. 2016b, MNRAS, 463, 3813, doi: 10.1093/mnras/stw2272

Kochanek, C. S. 1994, ApJ, 422, 508, doi: 10.1086/173745

Leloudas, G., et al. 2016, Nature Astronomy, 1, 0002, doi: 10.1038/s41550-016-0002

Lodato, G., King, A. R., & Pringle, J. E. 2009, MNRAS, 392, 332, doi: 10.1111/j.1365-2966.2008.14049.x

Lodato, G., & Rossi, E. 2011, MNRAS, 410, 359, doi: 10.1111/j.1365-2966.2010.17448.x

Magorrian, J., & Tremaine, S. 1999, MNRAS, 309, 447, doi: 10.1046/j.1365-8711.1999.02853.x

Mockler, B., Guillochon, J., & Ramirez-Ruiz, E. 2018. https://arxiv.org/abs/1801.08221

Phinney, E. S. 1989, IAU Symposium, 136, 345

Rau, A., et al. 2009, Publ. Astron. Soc. Pac., 121, 1334, doi: `10.1086/605911`

Rees, M. J. 1988, Nature, 333, 523, doi: `10.1038/333523a0`

Strubbe, L. E., & Quataert, E. 2009, MNRAS, 400, 2070, doi: `10.1111/j.1365-2966.2009.15599.x`

van Velzen, S., et al. 2011, ApJ, 741, 73, doi: `10.1088/0004-637X/741/2/73`

Wang, J.-X., & Merritt, D. 2004, ApJ, 600, 149, doi: `10.1086/379767`

Wyrzykowski, L., et al. 2017, MNRAS, 465, L114, doi: `10.1093/mnrasl/slw213`