Presto-Color: An LSST Cadence for Explosive Physics & Fast Transients

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Abstract

We propose a cadence for the LSST survey in which three visits are obtained per night: two different filters within a short time window (e.g., g & i or r & z within ~ 1 hour) and a repeat of one of those filters with a longer time window (e.g., ~ 4 hours). We colloquially refer to this as the *Presto-Color* strategy (quick-color). This observing strategy delivers both the color and light-curve evolution of transients on the same night. This will enable us to identify and characterize fast transients – or fast features of longer timescale transients – such as rapidly-declining supernovae (SNe), kilonovae (KNe), and the signatures of SN ejecta interacting with binary companion stars or circumstellar material. Such extragalactic transients are intrinsically rare, thus LSST could dramatically improve our understanding of their origin and properties. This cadence can be implemented as a Mini-Survey or as part of a Wide-Fast-Deep survey on selected portions of the extragalactic sky.

1 White Paper Information

1. **Science Category:** Exploring the Transient Sky, Dark Energy
2. **Survey Type Category:** We are proposing this cadence as a variation of the 'wide-fast-deep' (WFD) Main Survey, but it could also be considered for implementation as a Mini-Survey or a Deep Drilling Field, observing only a portion of the sky.
3. **Observing Strategy Category:** a specific observing strategy to enable specific time domain science, that is relatively agnostic to where the telescope is pointed.

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2 Scientific Motivation

The advent of wide-field time domain surveys has revolutionized the field of transient astrophysics. Coverage on *short timescales*, in particular, has faciliated rapid strides in our understanding of both supernova (SN) explosions and peculiar transients. Observations of "infant" SN—obtained hours to days after explosion—provide vital constraints on their explosion mechanisms and progenitor systems. The emission at these epochs contains natal information about the progenitor characteristics [1-4], potential non-spherical behavior [5-6], and shock collision with a binary companion [7]. In addition, rapidly-evolving transients ($\lesssim$10 days) may be associated with a variety of poorly-understood events, including accretion-induced white dwarf collapse [8], underluminous and fallback SN [9], ultra-stripped SN [10-12], compact-object mergers [13,14], orphan GRB afterglows [15], and common-envelope ejections [X].

Despite progress, the detection rate for both rapid transients and rapidly-evolving *phases/features* in SN explosions has remained low—due to a combination of survey efficiency and intrinsic event rates. The volume surveyed by LSST brings the promise of detecting many more intrinsically rare events. However, *using* these events to probe the science questions described herein requires adequate time- and filter-sampling of relatively short-lived events—sampling that will *not* be achieved through the WFD survey alone. Thus, we require a cadence that allows us to effectively *recognize* young and rapidly-evolving transients from within millions of LSST alerts in order to trigger additional follow-up. Such a cadence has two requirements: (1) observations in two filters obtained in quick succession so that color can be measured, and (2) a same-filter revisit within hours so the light-curve behaviour can be analyzed and distinguished from slower-evolving transients.

As we will show, the WFD baseline survey's inter-night revisit rate of once every three nights is too sparse, and the intra-night revisit rate of ~30 minutes is too rapid, to detect *and recognize* fast transients/features. The exact form of our proposed cadence is given in Section 3. In order to define our diagnostics we have selected four exemplar types of extragalactic fast transients/features. Color and rate-of-change information for each type of transient, and the main science goals for each, are discussed below.

I. The Nature of Rapidly-Evolving Luminous Transients: "Rapidly-evolving transients" are defined as extragalactic events that reach SN luminosities but have timescales an order of magnitude faster [X]. To date, only a small number have been identified, but recent studies [31] have shown that they represent a significant channel (~5–10% of the core-collapse rate) which we must understand to have a complete picture of stellar death. Known events have rise times spanning 1–3 days and blue colors at maximum [x]. Leading theoretical models range from black hole formation to the birth of binary neutron star systems and recent observations of AT2018cow show evidence for a central engine [X,X]. More observations are required to understand their true nature and diversity.

II. Kilonovae and the Origin of Heavy Elements: Kilonova (KN) are produced by the radioactive decay of r-process nuclei synthesized in the ejecta of neutron star mergers [X].

Observations of the KN associated with GW170817 revealed thermal emission that rose in < 1 day and cooled from a temperature of >10,000K to 3,000K over 5 days, followed by a longer-lived IR transient [X]—consistent with the production of a signifcant quantity of of r-process elements of *multiple* compositions. Additional examples—with or without associated LIGO triggers—are required to ascertain the "typicalness" of GW170817, with the frequency of early blue emission providing critical constraints on the ratio of light and heavy elements formed, and therefore the total contribution of NS mergers to cosmic nucleosynthesis.

III. Progentiors and Pre-explosion Mass Loss of Core-Collapse SN: Early observations of core-collapse SN (CCSN) provide critical constraints on the progenitor radius and envelope structure through the detection of either shock breakout (∼1 day) or cooling envelope (∼1-4 day) emission. Indeed, in recent years, there has been growing evidence that many CCSN either explode in "non-standard" evolutionary states or undergo enhanced pre-SN mass-loss and outbursts in their terminal years [23,X,X]. Theoretical studies have pointed to a range of potential explanations to accommodate the observations, such as pulsation-driven superwinds [24], wave heating outbursts [25], and inflated progenitor envelope [26]. However, the nature of this mass loss and the types of SN experiencing it remain uncertain.

IV. Progenitors and Explosion Mechanisms of Thermonuclear SN: Type Ia SN result from the thermonuclear distruption of a CO white dwarf [18]. However, questions remain regarding the nature of their binary companions. Recently, observations of SN2017cbv obtained within ∼1 day of explosion revealed a rapidly-rising blue "bump", interpreted by some as a collision with a non-degenerate companion [19], while preliminary population studies reveal an as-yet-unexplained red/blue color dichotomy in the early (< 5 days) rising light curves of Type Ia SN [X], with implications for outwardly mixed radioactive material predicted by the double detonation explosion model [X]. Further observations are required to ascertain the nature of this early emission, with implications from stellar physics to cosmology.

V. Additional Science Cases: While we have focused on extragalactic fast transients here, a cadence that allows measurement of both color and rate-of-change on the timescale of ∼hours will have general applicability across many areas—from variable stars to microlensing.

Finally, though we describe here an adaptation to the general WFD cadence to facilitate the timely identification of rapid events, our cadence could alternatively be adopted as a mini-survey over a portion of the sky. If coupled with a shorter intra-night cadence (as part of a mini-survey or due to a rolling candence) LSST observations alone could provide sufficient light curve coverage to probe progenitors and explosion physics of fast transients/features.

MRD Note: I'm still working to clean this up and cut some text. A few things could move to later sections. Ah, we now have more room! I will expand a few things slightly and fix the references.

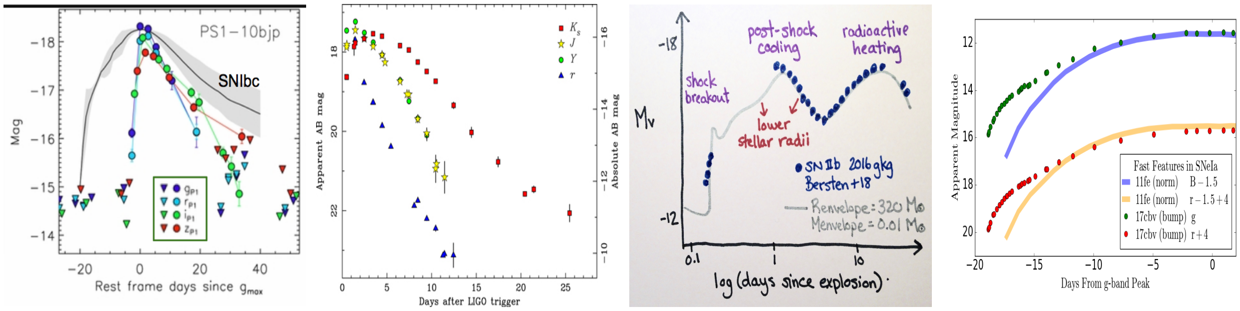

Figure 1: Light curves for our examples of fast transients and fast features. From left to right: fast transient PS1-10bjp (Drout et al., 2014); kilonova for GW170817 (Tanvir et al., 2017); a simple cartoon of the shock breakout model fits for SN 2016gkg's stellar radius (Bersten et al., 2018); SN Ia 2017cbv's blue bump compared to SN Ia 2011fe's "normal" light-curve (Hosseinzadeh et al., 2017).

3 Technical Description

3.1 High-level description

The prompt characterizaion of these transients, which enables the triggering of crucial follow up observations, requires determination of *both color and lightcurve shape*. This in turns requires observations in 2 different filters within a short interval of time $\Delta T_1$and to return to the same field with one of those filter at a later time ΔT_2. The constraints on these timeline are :

1. $\max(\Delta T_1)$
2. $\min(\Delta T_2)$
3. filter pair $f_1 - f_2$.

This can be implemented simply by alternating pairs of visits on a field, and single visits on *the previous field*. The single visits can alternate between the 2 filters reducing the number of filter changes.

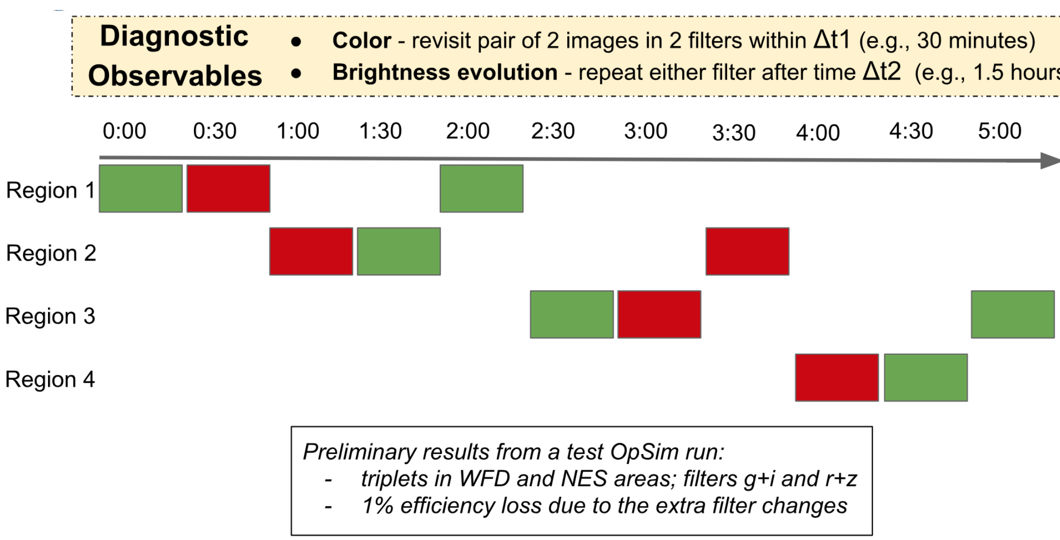

Figure 2: Cadence example: two alternating filters cover regions of sky to obtain 3 observations per region, in 2 filters, with apprioriate time gaps to measure lightcurve color and shape.

3.2 Footprint – pointings, regions and/or constraints

Describe the specific pointings or general region (RA/Dec, Galactic longitude/latitude or Ecliptic longitude/latitude) for the observations. Please describe any additional requirements, especially if there are no specific constraints on the pointings (e.g. stellar density, galactic dust extinction).

This proposed cadence does not make any additional constraints on the imaging area compared to WFD. The science goals might be reachable if the proposed cadence was implemented over a sub-region of the WFD survey area.

3.3 Image quality

Constraints on the image quality (seeing).

This proposed cadence does not make any additional constraints on the image quality compared to WFD.

3.4 Individual image depth and/or sky brightness

Constraints on the sky brightness in each image and/or individual image depth for point sources. Please differentiate between motivation for a desired sky brightness or individual image depth (as calculated for point sources). Please provide sky brightness or image depth constraints per filter.

This proposed cadence does not make any additional constraints on the individual image depth or sky brightness compared to WFD.

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

Constraints on the total co-added depth and/or total number of visits. Please differentiate between motivations for a given co-added depth and total number of visits. Please provide desired co-added depth and/or total number of visits per filter, if relevant.

This proposed cadence does not make any additional constraints on the co-added image depth or total number of visits compared to WFD.

3.6 Number of visits within a night

Constraints on the number of exposures (or visits) in a night, especially if considering sequences of visits.

The proposed candence requires at least 3 visits per night.

3.7 Distribution of visits over time

Constraints on the timing of visits — within a night, between nights, between seasons or between years (which could be relevant for rolling cadence choices in the WideFastDeep. Please describe optimum visit timing as well as acceptable limits on visit timing, and options in case of missed visits (due to weather, etc.). If this timing should include particular sequences of filters, please describe.

Three observations in 2 filters, 2 in different filters separated by $\lesssim 45$ minutes, returning to the field in the same night with either one of the filters in $\gtrsim 90$ minutes.

We furthermore note that the science goals motivating this cadence – namely, well-characterized light curves for rapid events – have overlap with the science motivations of a rolling cadence. Our proposed cadence would benefit from being implemented in regions where rolling cadence is applied (i.e., an intranight gap < 3 days).

3.8 Filter choice

Please describe any filter constraints not included above.

Filters should be pair with a gap in the sequence: g-i or r-z.

3.9 Exposure constraints

Describe any constraints on the minimum or maximum exposure time per visit required (or alternatively, saturation limits). Please comment on any constraints on the number of exposures in a visit.

This proposed cadence uses the baseline exposure times of 2×15 seconds or 1×30 seconds.

3.10 Other constraints

Any other constraints.

We propose that this cadence be implemented on extragalactic fields, but note that it may also be useful in some Galactic Plane fields to detect and characterize microlensing events on short timescales, binary stars, and black holes, for example. Trade-offs and synergies with other proposals are discussed further in Section 3.12, Item 5.

3.11 Estimated time requirement

Approximate total time requested for these observations, using the guidelines available at `https://github.com/lsst-pst/survey_strategy_wp`.

Since our proposed cadence is a modification of the WFD strategy – a shuffling of the visits, not adding visits – we are not requesting that any additional time be added to the WFD component.

3.12 Technical trades

To aid in attempts to combine this proposed survey modification with others, please address the following questions:

1. *What is the effect of a trade-off between your requested survey footprint (area) and requested co-added depth or number of visits?*
   As with a rolling cadence, the area in which this *Presto-Colore* strategy is applied will lower the visit cadence in other areas.

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.*

Properties	Importance
Image quality	3
Sky brightness	3
Individual image depth	3
Co-added image depth	3
Number of exposures in a visit	3
Number of visits (in a night)	1
Total number of visits	3
Time between visits (in a night)	1
Time between visits (between nights)	2
Long-term gaps between visits	3
Other *filter pairs within night*	1

Table 1: **Constraint Rankings:** Summary of the relative importance of various survey strategy constraints. Please rank the importance of each of these considerations, from 1=very important, 2=somewhat important, 3=not important. If a given constraint depends on other parameters in the table, but these other parameters are not important in themselves, please only mark the final constraint as important. For example, individual image depth depends on image quality, sky brightness, and number of exposures in a visit; if your science depends on the individual image depth but not directly on the other parameters, individual image depth would be '1' and the other parameters could be marked as '3', giving us the most flexibility when determining the composition of a visit, for example.

As with a rolling cadence, during the time when a field is not within the area being covered by the *Presto-Colore* strategy, it will receive fewer visits.

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)?*
Discovering and characterizing fast transients and fast features does not benefit from an increase in exposure time at the expense of the number of visits.

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?*
The science goals that motivate the *Presto-Colore* strategy do not benefit from increased co-added depth or maintaining a constant single-visit limiting 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?*
There are a few other proposals similar to the *Presto-Colore* strategy proposed in this white paper.
(1) Street et al. "The Diverse Science Return from a Wide-Area Survey of the Galactic

Plane", which proposes the "paired-i" strategy: fields in the Galactic plane are imaged every 2-3 days, first in i-band and then 1-4 hours later a revisit in g, r, or z. The basic motivation is the same – to identify rapidly varying transients and characterize them via colors – just for Galactic variables like Young Stellar Objects and Cataclysmic Variables. However, since we propose the *Presto-Colore* strategy for the extragalactic WFD there is no tension between these two white papers.
(2) Bricman et al. "TDEs with LSST", proposes to get same-night color information. The version that we read requested to change the filter between the two 15-second exposures of a visit, which isn't possible, but we surmised that what they actually want is for two visits in a night in two different filters. If so, then this *Presto-Colore* proposal would also suite their needs.
(3) Gezari et al. "An Extreme Rolling Cadence Wide-Fast-Deep Survey", proposes to do the full WFD area in only years 1 and 10, and rotate through 8 equal strips of area in years 2 through 9. While this would often result in 2-3 visits per night, probably in multiple filters, no specific filter pairings or revisit timescales are requested. The trade-off between these proposals is that such an extreme rolling cadence would remove the opportunity for longer-term monitoring of transients with fast features, such as Type IIn SNe, which can last for years.

4 Performance Evaluation

Please describe how to evaluate the performance of a given survey in achieving your desired science goals, ideally as a heuristic tied directly to the observing strategy (e.g. number of visits obtained within a window of time with a specified set of filters) with a clear link to the resulting effect on science. More complex metrics which more directly evaluate science output (e.g. number of eclipsing binaries successfully identified as a result of a given survey) are also encouraged, preferably as a secondary metric. If possible, provide threshold values for these metrics at which point your proposed science would be unsuccessful and where it reaches an ideal goal, or explain why this is not possible to quantify. While not necessary, if you have already transformed this into a MAF metric, please add a link to the code (or a PR to sims_maf_contrib) in addition to the text description. (Limit: 2 pages).

4.1 Diagnostic Metric

Based on our evaluation of the light curves of fast transients, and the fast features of longer duration transients, we create a *diagnostic* metric that checks for the frequency with which the LSST observing simulation executes our desired filter-revisit cadence.

4.2 The Other Kind of Metric

The metric is the fraction of events for which the color and risetime is constrained (within some accuracy). Different science cases may have different input lightcurves and different gap constraints

4.3 Create OpSim

`OpSim` runs are being created that perform f_1 observations on a field, 30 min later repeat the pointing pattern in f_2, and 60 min later repeat the pointing pattern in f_1 or f_2, where f_1 and f_2 are g and i, or r and z. Non-adjacent filters are used to get a better leverage on the Spectral Energy Distribution (SED) color.

5 Special Data Processing

Describe any data processing requirements beyond the standard LSST Data Management pipelines and how these will be achieved.

The science goals that motivate the proposed cadence in this white paper will not require any data processing outside of the planned Prompt and Data Release pipelines and their data products.

Bibliography

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Tanvir, N. R., Levan, A. J., González-Fernández, C., et al. 2017, Astrophysical Journal, Letters, 848, L27, doi: 10.3847/2041-8213/aa90b6