Transient Observations with LSST

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Abstract

In the coming decade, LSST's combination of all-sky coverage, consistent long-term monitoring, and flexible criteria for event identification will revolutionize studies of a wide variety of astrophysical phenomena. The umbrella of time domain science with LSST encompasses objects both familiar and exotic, from classical variables within our Galaxy to explosive cosmological events. The instrument of choice for finding very rare and faint transients, LSST will make localization for gravity wave events possible, identify counterparts to GRBs and X-ray flashes, and discover new supernovae. Increased sample sizes of known-but-rare observational phenomena will quantify their distributions for the first time, thus challenging existing theory. Perhaps most excitingly, LSST will provide the opportunity to sample previously untouched regions of parameter space, where transient events are expected on theoretical grounds, but have not yet been observed. LSST will generate 'alerts' within 60 seconds of detecting a new transient, permitting the community to follow up unusual events in greater detail. Here, I highlight some of the scientific opportunities LSST will provide, as well as the challenges we face and opportunities for community involvement.

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1. The Basics of LSST

The Large Synoptic Survey Telescope (LSST) was recently rated the top priority large ground based project by the National Academy of Sciences Decadal Survey (REF). Heralded as a treasure trove of discovery, the NAS reports that "The [LSST] would employ the most ambitious optical sky survey approach yet and would revolutionize investigations of transient phenomena." Further they note that "the top rank of LSST is a result of its capacity to address so many of the identified scuence goals and its advanced state of technical readiness" (Astro2010).

The operational and technical specifications of the telescope and survey design are detailed elsewhere (e.g. Ivezic et al. 2008), but we provide a brief summary here for convenience. LSST unique advantage over current and past surveys is its *étendue*, the product of its wide field of view and sky coverage. The telescope consists of a 8.4m mirror (6.7m effective clear aperture), possessing a 9.6 deg^2 field of view. LSST will survey the entire visible sky ($\sim$20,000 deg^2) nightly over a period of 10 years, resulting in roughly 1000 visits per field. The 3.2 Gigapixel camera, which once completed will be the world's largest, will obtain observations in six filters: *ugriz* (comparable to those of the Sloan Digital Sky Survey) plus the addition of the near-IR y band filter, providing coverage from 320 - 1035 nm. In a single visit, the LSST will reach a depth of r $\sim$ 25, and image stacks resulting from multiple visits will reach to nearly r $\sim$ 28. This impressive depth, combined with photometric precision on the order of hundreths of magnitudes or better, will reveal the twinkling of the transient and variable universe on a scale never before possible.

The LSST mirrors have already been manufactured with the help of generous private donations, and preparation for construction of the telescope and base facility at its eventual home on the summit of Cerro Pachon in Chile has begun. The base facility will host a co-located Data Access Center, allowing users to develop and run open source code/tools on site (so as to avoid latency associated with transferring large amounts of data). Major construction is scheduled to begin in earnest around 2014, with first light expected in $\sim$2020. Once the primary survey begins, data will be immediately publicly available to the US and Chilean communities, with no proprietary period.The survey is expected to generate 30 Terabytes of data per night, resulting at the conclusion of the survey in a 30 petabyte database and approximately 100 petabytes of images. The data will be stored at the Archive Center, which will be located in Illinois.

LSST produces data products on both a nightly and annual basis. Examples of nightly data products might be single-visit images, differences images, source and object catalogues from difference images, and of course alerts for transient and moving objects. Annual data products are analogous to survey data releases, and comprise deeper stacked images, multiband images, source and object catalogues from calibrated images and optimally extracted properties, as well as alert statistics and summaries.

The astronomical community currently participates in LSST via the LSST science collaborations, 11 topical working groups that provide valuable scientific feedback to the project. Collectively the science collaborations wrote what has become known as the LSST Science Book (LSST Science Collaborations, et al. 2009), a 545 page document describing not only the technical aspects of the telescope and survey, but a vast assortment of cutting-edge research projects that will be enabled by the LSST. These myriad applications of the LSST survey are far too great in number to describe here, but this proceeding highlights a few interesting science cases, and describes some of the current activities of the Transients and Variable Stars Science Collaboration.

2. Transient Science with LSST

The Transients and Variable Stars collaboration is one of the most scientifically diverse working groups within LSST, concerned with transients of both local and extragalactic natures, as well as the behavior of classical variable stars, geometric variables (such as eclipsing binaries and microlensing), and the largely untapped theoretical discovery space for cosmic explosions both faint and fast. In Figure 1 (reprinted here from the LSST Science Book, modified from Rau et al. 2009), we show this discovery space with examples of well-studied transient events (filled boxes), rare transients (vertically striped boxes), not-yet-detected events (horizontally striped boxes), and theoretically predicted events (open boxes). The large question mark in this figure indicates a region of parameter space for fast, faint transients that is as yet untapped. This region will be made accessible via differences between LSST image pairs as well as by specialized cadences within the main survey.

Table 1 shows the expected yield of selected transients from the LSST survey. As is evident from the variety of astrophysical phenomena shown here, LSST will impact many areas of transient astronomy. For example, LSST will detect many off-axis GRB orphan afterglows, placing constraints on the true rate and beaming fraction of GRBs. The LSSTs high étendue will also allow it to capture contemporaneous optical counterparts to GRBs, as well as very early afterglows. However, the most exciting discoveries that LSST makes may not be represented in this table– its reach will allow it to rake in sizable numbers of not only very rare events, but of new kinds of transient phenomena not previously observed.

3. Current Activities within the Collaboration

The Transients and Variable Stars collaboration has several ongoing activities, whose intent is to provide feedback to the LSST project as a whole. One such activity is the collection of spectrotemporal surfaces for inclusion in the LSST survey simulations (Delgado et al. 2006). The LSST simulation team is working to create an end-to-end simulation of the entire survey, utilizing the best known distribution of sources, optical path properties, site atmospheric data, and of course source variability. The simulations will in turn allow us to determine the expected output of the survey, and how to make best use of those outputs. Clearly, these simulations are an important tool in evaluating how the current survey implementation affects the ability of our collaboration to tackle the many wonderful projects outlined in the LSST science book. If there are particular quantities that are necessary to include in the database, or contextual data that is required to better categorize an event and determine its worthiness for followup, these needs must be determined as soon as possible. To this end, our collaboration is collating templates that describe the multiband variability behavior of various transient and variable sources for inclusion in the survey simulations. When these templates are implemented in the simulations, we will be able to test the database output and evaluate figures of merit for how well we are currently meeting our scientific goals.

Our group is currently also in the process of evaluating the capability of the LSST to identify electromagnetic counterparts to gravitational wave events. The LSST footprint is uniquely well-matched to the localization radius of Advanced LIGO, and the two are expected to be online contemporaneously based on current schedules. It may be possible that LSST will observed an electromagnetic counterpart to a GW event as part of its main survey (as GW astronomy is sensitivity limited, the number of potential false positives can be greatly limited by looking for events colocated with galaxies within 200 Mpc; Kasliwal, in prep.). A more intentional way of pursuing such a potentially interesting scientific discovery would be to include a GW co-observing capability in LSST. One might imagine this capability would be similar to a Target-of-Opportunity program, triggered by gravitational wave facility alerts that meet certain criteria. Practically speaking, implementing this capability would incur an operational cost to the main survey, whose goals must necessarily be the highest overall priority in the operation of the telescope. However, this unique synergy between the GW and EM facilities is sufficiently tantalizing that we are investigating this possibiilty in greater detail by writing a whitepaper on the operational cost and potential scientific payoff of a

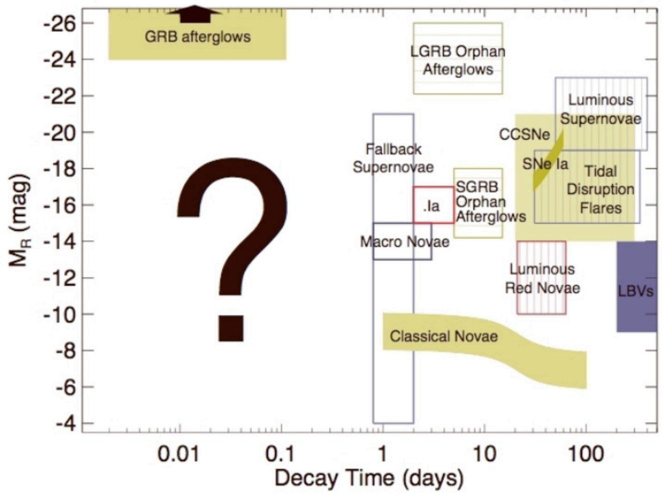

Fig. 1. Discovery space for cosmic transients. Peak absolute r-band magnitude is plotted vs. decay timescale (typically the time to fade from peak by $\sim$ 2 mag) for luminous optical transients and variables. The brightest transients (on-axis afterglows of GRBs) extend to MR $\sim$ -37.0. The color of each box corresponds to the mean g $-$ r color at peak (blue, g $-$ r < 0 mag; green, $0 <$ g $-$ r < 1 mag; red, g $-$ r > 1 mag). Unexplored parameter space of faint, fast transients is indicated with the large question mark. Figure reprinted from the LSST Science Book, adapted from the original in Rau et al. (2009).

Table 1. Properties and Rates for a Selection of Optical Transients[a]

Class	M_v [mag]	τ[b] [days]	Universal Rate (UR)[c] [yr^{-1}]	LSST Rate [yr^{-1}]
Luminous SNe	-19...-23	50 - 400	10^{-7} Mpc^{-3} yr^{-1}	20000
Orphan Afterglows SHB	-14...-18	5 - 15	3 $\times$10$-$7... $-$ 9 Mpc^{-3} yr^{-1}	$\sim$10 - 100
Orphan Afterglows LSB	-22...-26	2 - 15	3 $\times$ $10^{-10...-11}$ Mpc^{-3} yr^{-1}	1000
On-axis GRB afterglows	...-37	1 - 15	10^{-11} Mpc^{-3} yr^{-1}	$\sim$50
Tidal Disruption Flares	-15...-19	30 - 350	10^{-6} Mpc^{-3} yr^{-1}	6000
Luminous Red Novae	-9...-13	20 - 60	10^{-13} yr^{-1} L_{sun}^{-1}	80 - 3400
Fallback SNe	-4...-21	0.5 - 2	$<5 \times 10^{-6}$ Mpc^{-3} yr^{-1}	$<$ 800
SNe Ia	-17...-19.5	30 - 70	3×10^{-5} Mpc^{-3} yr^{-1}	200000[d]
SNe II	-15...-20	20 - 300	(3..8) $\times$ 10^{-5} Mpc^{-3} yr^{-1}	100000[d]

[a]Table adapted from Rau (2009); see references therein. [b]Time to decay by 2 magnitudes from peak. [c]Universal rate at $z < 0.12$. [d]From M. Wood-Vasey, pers. comm.

GW/EM ToO program.

Another major area of work for our collaboration will be the development of classification engines that can filter the LSST data stream to determine which of the many nightly alerts bear the use of precious followup resources. While the LSST project itself will not provide classifications with the alerts for transient objects, alerts will be accompanied by information about the source and its astrophysical context. One might imagine a classifier to act upon both nightly products as well as larger annual or multi-annual data products. Nightly products can be used for real-time categorization based on the behavior of the transient source as well as contextual information with that position (e.g. whether the source is co-located with a galaxy from another catalogue). A classifier acting on a larger dataset can, of course, do a more effective job at attaining a real astrophysical classification for a particular object, and the product of such an effort can in turn inform efforts to filter actionable items out of the 30 Tb of data produced on a nightly basis. The LSST project will have computing resources available within the Data Access Center for the development and implementation of such code, and we hope to additionally have write-back capability within the database such that classifications done by these independent engines can be included within the database itself. Once the variability templates have been completely folded into the LSST data simulations, one might imagine applying a plug-in classifier such as those currently existing or in development (e.g. Mahabal et al.

2011, Starr et al. 2009, Bloom & Richards 2011) to understand how they can best be applied to the vast LSST data stream, far in advance of first light.

Finally, our collaboration is also working to develop a plan for early science verification during the two years of telescope commissioning planned prior to the commencement of the main survey. Our goal is to identify observations that can both test the system performance and perhaps produce either interesting early science or data products that might help the survey be more effective (one such example would be early observations that can later provide astrophysical context for transient alerts).

4. Summary

With its ability to observe the sky wider, faster and deeper than any survey to date, LSST will uncover a treasure trove of new transient events. Some of these may be known classes, thus allowing us to further understand their behavior, and many will be rare events only predicted to exist, or perhaps more excitingly, not predicted at all. The vast data stream of the LSST will not enrich observational astronomy, it will challenge our theoretical understanding of a wide variety of transient phenomena.

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