Astro2020 APC White Paper
Next Generation LSST Science

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☑ Stars and Stellar Evolution ☑ Resolved Stellar Populations and their Environments
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Abstract: LSST can advance scientific frontiers beyond its groundbreaking 10-year survey. Here we explore opportunities for extended operations with proposal-based observing strategies, new filters, or transformed instrumentation. We recommend the development of a mid-decade community- and science-driven process to define next-generation LSST capabilities.

1 Key Science Goals & Objectives

The highest priority large-scale ground-based project from the Astro2010 decadal survey, the Large Synoptic Survey Telescope (LSST), is planned to undertake a 10-year survey beginning in 2022 (LSST Science Collaboration et al. 2009; Ivezić et al. 2019). LSST and its 3.2 gigapixel camera will image the southern sky in six optical filters with an unprecedented combination of area, depth, and cadence, enabling a huge range of science. While the details of the observing strategy for the 10-year survey and its components (including the wide-fast-deep main survey, deep-drilling fields, and other mini-surveys) are still being refined, now is the time to start planning what comes after the 10-year survey and considering the next generation of LSST science. This connects to *all* of the science thematic areas and numerous science-focused White Papers.

Here we consider a selection of science cases that would motivate three scenarios for next generation LSST operations:

1. No modifications to the telescope or camera, but complete flexibility to undertake new observing strategies, cadence, sky coverage, exposure time, etc., building on the discoveries and scientific progress made during LSST operations and driven by the global scientific landscape at the completion of the 10-year survey.
2. Modest modifications to the camera, e.g., new filters.
3. Replacement of the camera with another instrument (e.g., a wide-field multiplexed spectrograph or near-infrared camera) or other major modifications.

We describe these possibilities in more detail in the following sections.

1.1 LSST + LSSTCam: Continuing Operation of a Flagship Facility

LSST emerged as the highest-ranked large-scale ground-based project in the Astro2010 Decadal report (National Research Council 2010), as was reiterated in the Midterm Assessment (National Academies of Sciences, Engineering, and Medicine 2016), because of its "transformational" scientific impact. As such LSST will be a flagship ground-based observatory and there is every reason to expect the telescope and camera will continue to be scientifically valuable "as is" well beyond the envisioned 10-year survey.

Even with the same instrumentation, extended operation of LSST will open up a wide range of observing strategies with more flexibility than is planned for the 10-year survey. Even working within the 10-year survey constraints, the 2018 LSST call for observing strategy white papers (`https://www.lsst.org/call-whitepaper-2018`) yielded 46 submissions (`https://www.lsst.org/submitted-whitepaper-2018`). The papers included varying choices for cadence in the main 10-year "Wide-Fast-Deep" (WFD) survey, proposed deep-drilling fields (DDFs), and target-of-opportunity (TOO) observations. More than half of the submitted papers proposed "mini-surveys" with a wide variety of scientific aims and scope of observational resources required. The proposals easily oversubscribed the 10-year limit, by about a factor of two in total (Jones et al. 2019), and the oversubscription of the non-WFD observing time is much higher.

The LSST Project is undertaking a process to optimize and iterate the observing strategy to respond to these requests (LSST Science Advisory Committee 2019), but it is clear that not all of these ideas can be accommodated in the 10-year survey. Moreover, the white papers were submitted *assuming 10-year survey constraints*; the flexibility afforded by extended LSST observations will surely allow for more novel ideas varying depth (exposure time), sky area, filters, and cadence.

Opening extended LSST operations to a proposal-based observing strategy has several advantages, the foremost of which is that it allows the most compelling science to drive the observations, without needing to know years in advance what that highest-priority science will be. A proposal-based process can also accommodate concurrent scheduling of surveys with different timescales, ranging from a fraction of a night to multiple years of data.

"Static-sky" science that makes use only of the 10-year co-added LSST images over a large fraction of the sky (i.e., with metrics that scale as $\sqrt{t}$) may not benefit greatly from extended operations without a long time baseline. However, "dynamic sky" science, ranging from the Solar System to cosmology, would continue to provide opportunities which cannot be matched at other facilities.

Figure 1 shows the unique position LSST will occupy in exploring the optical time-domain (Yasuda et al. 2019). LSST will play the starring role in the era of celestial cinematography, but the movie of the Universe does not end in 2032. We can be confident that time-domain optical astronomy will remain a compelling field through the 2030s and beyond; if LSST ceases to be the chronicler of the changing sky, another facility would need to take its place. Furthermore, new large multiwavelength/multimessenger facilities beginning operations in the 2030s require simultaneous or near-simultaneous LSST observations. For example, studies of fast extragalactic X-ray transients discovered by the large-grasp Athena X-ray Observatory (e.g., Yang et al. 2019) will benefit greatly from supporting LSST observations, as would studies of fast radio transients from the SKA, and gravitational wave events from LIGO Voyager, Cosmic Explorer, and LISA.

1.2 Upgrading LSSTCam: Building on an LSST Legacy

Alternatively, while keeping LSST focused on wide-field optical imaging, minor modifications to the camera could have a large scientific impact at modest cost. One of the simplest to consider is expanding the LSST filter set beyond the currently planned six filters (*ugrizy*). Additional filters would not preclude continued use of the original filters (though having only five slots in the filter exchanger may become more of an issue), and as such would complement the increased flexibility in observing strategy described above.

Yoachim et al. (2019) describe a science case for 15-20 nm FWHM narrow-band filters for LSST, with applications to deriving physical stellar parameters, mapping emission-line nebulae, improving galaxy photometric redshifts, and creating cosmologically-useful samples of extragalactic objects in narrow redshift shells. Surveys with narrow-band filters are not well suited for the majority

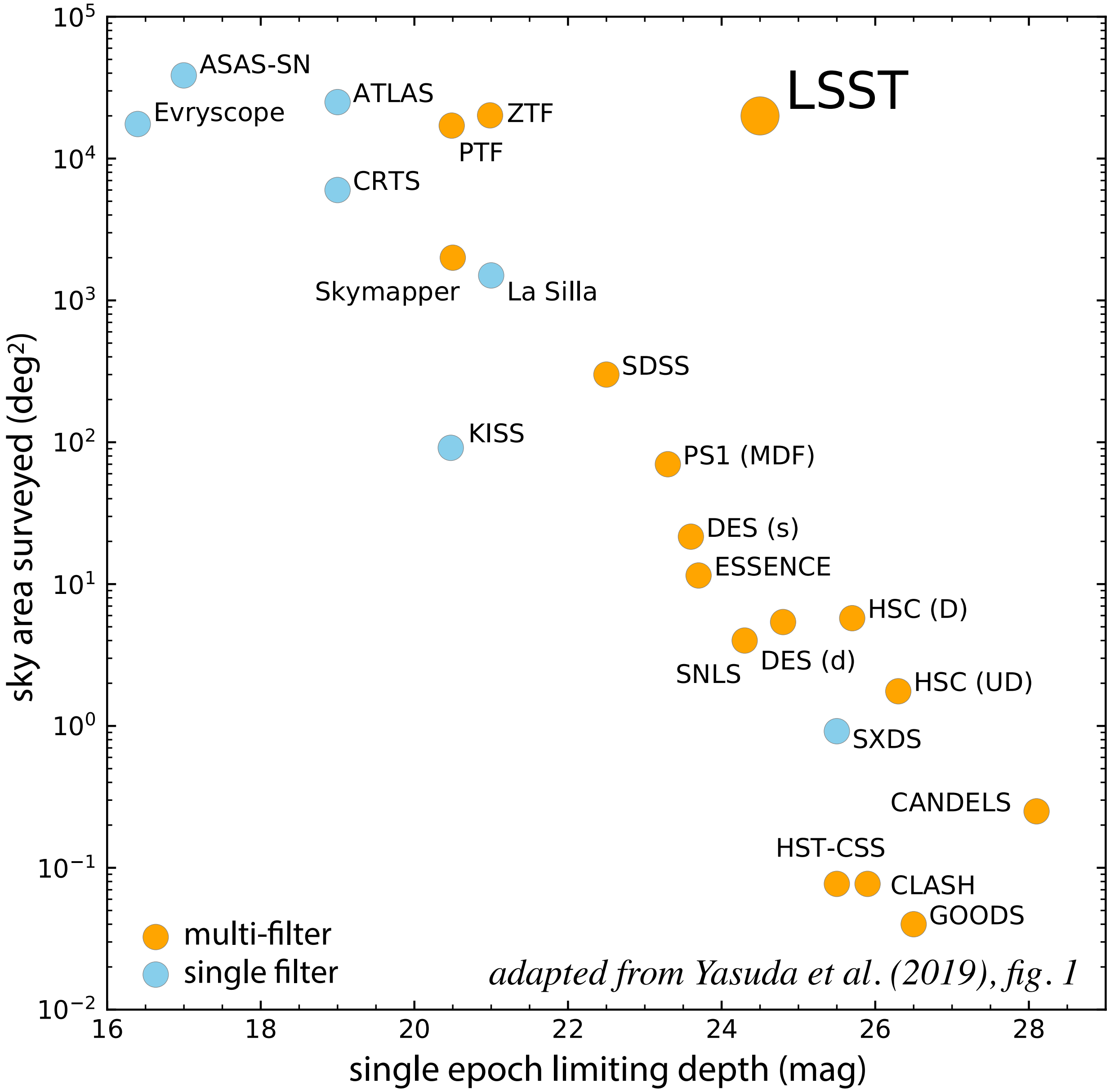

Figure 1: Sky area versus single-epoch depth for time-domain optical surveys. LSST is unique in its ability to characterize the changing sky, and it should remain as the premier facility in this application even after its 10-year survey. *This figure is adapted from Yasuda et al. (2019).*

of transients and variables, so extensive time-domain coverage or cadenced observations are not essential, and thus large sky area narrow-band images (to scientifically interesting depths) can be obtained economically, in just nights to weeks of survey time.

A set of narrow-band filters with widths of 15–20 nm (the smallest allowed by the $f/1.2$ beam), would build on the results of a variety of past projects which used ~30 nm FWHM medium-band filters with good results (e.g., Wolf et al. 2004; Ilbert et al. 2009; Cardamone et al. 2010). Implementing a carefully-designed narrow-to-medium-band filter set for LSST could enable greatly improved photometric redshifts over limited sky areas (in contrast photo-z uncertainties would only be modestly improved if the observations cover the full LSST sky footprint in the same survey time). A particular opportunity would be presented by surveys covering regions with grism observations from WFIRST, in which case effective low-resolution spectroscopy of hundreds of millions of objects covering a broad wavelength range in the optical and near-infrared would be available. Even considering LSST photometry alone, a 10-year survey over 2000 square degrees (instead of 20,000) with 30 optical bands would yield photo-z uncertainties at least a factor of 7 smaller than the original LSST survey[1](i.e., redshift uncertainties for $i \sim 25$ galaxies of $\sim 0.005(1 + z)$, with smaller uncertainties for brighter objects), which would have high impact across many science areas (particularly studies of galaxy evolution or WFIRST cosmological measurements).

A "shifted" broad-band filter set (i.e., with the same filter widths, but shifted central wavelengths, for example halfway between the current filter centers) would provide additional opportunities. Such filters would still have high throughput for single-visit discovery (transients, variables, moving objects, etc.) and could be optimized to improve estimates of galaxy properties including photometric redshifts and/or measurements of stellar parameters. A 10-year survey with shifted filters would reduce photometric redshift uncertainties across the full sky by $\sim \sqrt{2}$ and provide greater effective spectral resolution on all objects for astrophysical studies, while continuing to provide discoveries and light curves for transients at a comparable rate to the original LSST survey.

New filters could be developed where the bandpass varies over the focal plane. The variation might be continuous as a function of position on the detector, or else define discrete regions (e.g., like the SDSS imaging camera; Gunn et al. 1998). This could enable rapid tiling of the sky in multiple wavelengths, leveraging the fast slew time of LSST (seconds) compared to the slower filter change time (minutes). Cleverly patterned bandpasses (e.g., a checkerboard of square tiles) combined with an appropriate dither pattern could allow contiguous sky coverage in all of the bandpasses without any filter changes. Such an approach could also allow a larger complement of passbands to be available to LSST at all times, at the expense of the field of view for any given passband. Photometric calibration of these variable filters could be challenging, but variation of the response across the focal plane must already be calibrated for the "uniform" filters (Ivezić et al. 2019).

Polarizing filters for LSST should also be investigated. These could allow studies of interstellar magnetic field structure, asymmetries in explosive transients, jets of radio-loud active galaxies, and obscuration geometry in active galaxies.

[1] In the limit of constant number of effective spectral features, equal filter coverage, and fixed sky area, photometric redshift uncertainties should scale as $N_{\rm bands}^{-1/2}\, t_{\rm total}^{-1/2}$, where $N_{\rm bands}$ is the number of photometric passbands and $t_{\rm total}$ is the total observing time. If effective spectroscopic resolution increases significantly, new spectral features start to be accessible, making this a worst-case scaling.

1.3 New Instrumentation for a Next Generation Observatory

Major upgrades to the telescope and its instrumentation could transform LSST into a truly "next generation" observatory. Approaches along these lines need to consider both what would complement the LSST data set after the 10-year survey as well as the landscape of other facilities in the 2030s and beyond.

Some types of advanced instrumentation would keep LSST capable of wide-field optical imaging, but with enhanced capabilities. This might minimally include maintenance and repair of LSSTCam or, more substantially, replacement with another optical camera. Beyond this, upgrades might improve the image quality through active optics and/or shifting charge on the detector. Similarly, utilizing energy-sensitive detectors like MKIDs (Mazin et al. 2018) could enable both higher overall throughput and observing efficiency *and* higher spectral resolution than broad-band filters. All of these more speculative ideas would require significant technological development and should be explored.

Alternately, LSST could radically shift from wide-field optical imaging to other modes, most notably wide-field near-infrared imaging or wide-field multiplexed spectroscopy in the optical and/or infrared. The science cases for large surveys in both of these modes are well developed (e.g., Kasliwal et al. 2019; Cuby et al. 2019; Eifler et al. 2019; Robertson et al. 2019; de Jong et al. 2014; Flaugher & Bebek 2014; Hill et al. 2018; Mandelbaum et al. 2019). The main question would be to identify an important niche that could best be filled by a transformed LSST. Competition for wide-field near-infrared imaging may come from space-based facilities with better spatial resolution (e.g., Euclid and WFIRST). Spectroscopic surveys that stare at limited fields with long exposure times would not take advantage of the fast-slewing capability of LSST.

The need for very wide-field spectroscopy with LSST-like telescope aperture to exploit the rich LSST imaging dataset has been repeatedly identified (e.g., in Najita et al. 2016); if no route to such spectroscopy is secured by the end of the 2020s, it may be necessary to explore how LSST can be used in this role after its 10-year survey is completed. As mentioned above, the opportunity cost of eliminating a leading wide-field optical imager for time-domain science should also be considered, and some science cases (particularly in the time domain) require spectroscopic observations contemporaneous with LSST optical imaging (see also, e.g., Hložek et al. 2019).

2 Technical Overview

Technical considerations associated with extended operation of LSST in these three scenarios will be presented in a separate white paper by the LSST Project. Stubbs & Heitmann (2019) reports on the LSST Next Generation Instrumentation workshop held in April 2019, and notes the scientific benefits and technical challenges associated with new LSST filters, new detector technology, wide-field multiplexed spectroscopy, and wide-field near-infrared imaging.

3 Technology Drivers

The more radical changes to LSST instrumentation discussed here would require significant technology development. Improvements to the image quality in the optics or detector, energy-sensitive detectors, and concepts for wide-field multiplexed spectroscopy or near-infrared imaging all need exploration.

4 Organization, Partnerships, & Current Status

The LSST 10-year survey is jointly supported by the US NSF and DOE, and the science community comprises the United States, Chile, and other select foreign partners. A funding model for extended operations would need to be developed.

5 Schedule

Decisions about the future of LSST after the 10-year survey should be community and science driven. We recommend that the Astro2020 Decadal Survey help develop a timeline for this process, taking into account the context of other facilities that should come online in the 2020s (ELTs, JWST, wide-field ground- and space-based imaging and spectroscopic capabilities, etc.) as well as likely future scientific priorities. The 2025 Midterm Assessment may provide an opportune time to make concrete recommendations for the future of LSST. We advocate a review after the first LSST full-year data release (c. 2024) to evaluate what the most productive uses for LSST may be in the 2030s, taking into consideration the real-world performance of LSST, the optical/infrared astronomical landscape, and the evolving landscape of the most compelling scientific directions.

6 Cost Estimates

A major upgrade to LSST instrumentation (§ 1.3) would almost certainly be in the Large ground-based cost category (>\$70M). Even minor (§ 1.2) or no (§ 1.1) instrumentation changes would still require significant annual operations costs for the observatory, but would provide excellent added value to the investment in telescope and camera construction and the first ten years of operations, building on the developed hardware, computing, and science infrastructure. Additional costs would be associated with a proposal process for observing strategies. Specialized data reduction or analysis pipelines may be needed for some proposed observations and would need to be supported. Depending on the timescale for extended operations (e.g., several years), this again could reach the Large ground-based cost category. More details regarding the cost of LSST extended operations will be provided by the LSST Project Team white paper.

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