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LSST and the Epoch of Reionization Experiments

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Abstract. The Large Synoptic Survey Telescope (LSST), a next generation astronomical survey, sited on Cerro Pachon in Chile, will provide an unprecedented amount of imaging data for studies of the faint optical sky. The LSST system includes an 8.4m (6.7m effective) primary mirror and a 3.2 Gigapixel camera with a 9.6 sq. deg. field of view. This system will enable about 10,000 sq. deg. of sky to be covered twice per night, every three to four nights on average, with typical 5-sigma depth for point sources of $r = 24.5$ (AB). With over 800 observations in the *ugrizy* bands over a 10-year period, these data will enable coadded images reaching $r = 27.5$ (about 5 magnitudes deeper than SDSS) as well as studies of faint time-domain astronomy. The measured properties of newly discovered and known astrometric and photometric transients will be publicly reported within 60 sec after closing the shutter. The resulting hundreds of petabytes of imaging data for about 40 billion objects will be used for scientific investigations ranging from the properties of near-Earth asteroids to characterizations of dark matter and dark energy. For example, simulations estimate that LSST will discover about 1,000 quasars at redshifts exceeding 7; this sample will place tight constraints on the cosmic environment at the end of the reionization epoch. In addition to a brief introduction to LSST, I review the value of LSST data in support of epoch of reionization experiments and discuss how international participants can join LSST.

Keywords. surveys, galaxies: active, quasars: general

1. Introduction

Optical imaging data provided by the LSST and other surveys will enhance the science delivered by the Epoch of Reionization (EoR) experiments. The connections between optical and radio regimes are strong and include:

• Science results: similar and often the same questions are being asked in both wavelength regimes (e.g., about stellar and galaxy formation and evolution, or dark energy),
• Tools and methods (e.g., massive databases, image processing),
• Complementary data (e.g., identification of radio sources using multi-wavelength data, constraints for astro-physical processes, HI measurements).

Within the context of the Epoch of Reionization (EoR) experiments (e.g., Morales & Wyithe 2010; Pritchard & Loeb 2012), faint optical survey data can enhance our understanding of the relevance of the first stars and galaxies for EoR and provide constraints for both Galactic foregrounds (e.g., inter-stellar medium) and extragalactic foregrounds (e.g., clusters of galaxies). The optical-radio synergies work in both directions: deep EoR observations will improve our understanding of very faint extragalactic sources and test theoretical models which predict a significant contribution of star-forming galaxies at sub-mJy flux densities. A combination of deep optical and radio imaging will reveal details about the formation and evolution of galaxies as a function of cosmic time and their environment (e.g., Smolčić *et al.* 2008).

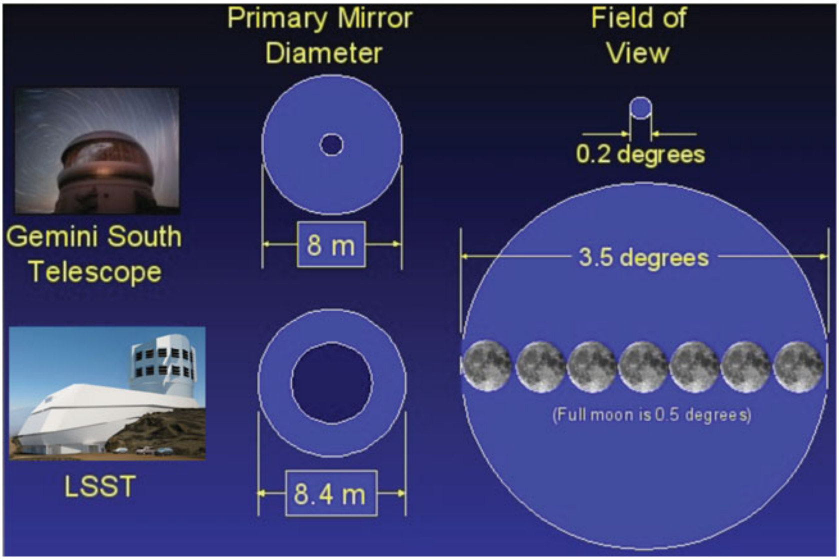

Figure 1. A comparison of the primary mirror size and the field-of-view for LSST and Gemini South telescopes. The product of the primary mirror size and the field-of-view, the so-called étendue (or grasp), a characteristic that determines the speed at which a system can survey a given sky area to a given flux limit, is much larger for LSST. Figure courtesy of Chuck Claver.

An efficient way to study galaxy populations shortly after the reionization epoch is to use clusters of galaxies as gravitational telescopes. With a cluster-scale gravitational lens one can gain several magnitudes of magnification, enabling the study of intrinsically lower luminosity galaxies than would otherwise be unobservable with even the largest telescopes (Bacon *et al.* 2015). Using this method, LSST will identify and constrain the properties of first galaxies and address the question of whether these objects were responsible for reionizing the Universe. The LSST galaxy sample at $z \sim 5$ will provide an important calibration of stellar mass density and galaxy clustering, as a function of galaxy properties and environment, and thus complement interpretations of measurements of the brightness temperature fluctuations from the epoch of reionization (Bacon *et al.* 2015). Furthermore, the LSST census of about 1,000 $z \sim 7$ quasars (using the z-band drop-out technique) will place tight constraints on the cosmic environment at the end of the reionization epoch and on the SMBH accretion history in the Universe.

2. Brief overview of LSST

The last decade has seen fascinating observational progress in optical imaging surveys. The SDSS dataset is currently being greatly extended by the ongoing surveys such as Pan-STARRS (Kaiser *et al.* 2010) and the Dark Energy Survey (Flaugher 2008). The Large Synoptic Survey Telescope (LSST; for a brief overview see Ivezić *et al.* 2008) is the most ambitious survey currently being constructed or planned in the visible band. The LSST survey power is due to its large étendue (see Figure 1). LSST will extend the faint limit of the SDSS by about 5 magnitudes and will have unique survey capabilities for faint time domain science.

The LSST design is driven by four main science themes: probing dark energy and dark matter, taking an inventory of the Solar System, exploring the transient optical sky, and mapping the Milky Way (for a detailed discussion see the LSST Science Book, LSST

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Figure 2. The figure shows a photograph of the LSST summit at the time of this Symposium (September 2017). First light for LSST is expected in early 2020 with a 144 Mpix engineering camera, and with the full 3.2 Gpix camera in late 2020. The small dome on the left is an auxiliary telescope that will be used for photometric calibration. For more photographs, see https://www.lsst.org/gallery/image-gallery. Credit: LSST.

Science Collaboration 2009). LSST will be a large, wide-field ground-based system designed to obtain multiple images covering the sky that is visible from Cerro Pachón in Northern Chile. The system design, with an 8.4m (6.5m effective) primary mirror (Gressler *et al.* 2014), a 9.6 $\deg^2$ field of view, and a 3.2 Gigapixel camera (Kahn *et al.* 2010), will enable about 10,000 $\deg^2$ of sky to be covered using pairs of 15-second exposures in two photometric bands every three nights on average, with typical 5σ depth for point sources of $r \sim 24.5$. The system is designed to yield high image quality as well as superb astrometric and photometric accuracy.

2.1. *Anticipated LSST surveys*

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The survey area will include 30,000 $\deg^2$ with $\delta < +34.5°$, and will be imaged multiple times in six bands, *ugrizy*, covering the wavelength range 320–1050 nm. About 90% of the observing time will be devoted to a deep-wide-fast survey mode which will observe an 18,000 $\deg^2$ region over 800 times (summed over all six bands) during the anticipated 10 years of operations, and yield a coadded map to $r \sim 27.5$ ("the main survey"). These data will result in databases containing about 20 billion galaxies and a similar number of stars, and will serve the majority of science programs. The remaining 10% of the observing time will be allocated to special programs such as a Very Deep and Fast time-domain survey.

First light for LSST is expected in early 2020 with a small commissioning camera (144 Mpix), with the full 3.2 Gpix camera integrated by the end of 2020. The construction phase of LSST, funded by the U.S. National Science Foundation and Department of Energy, started in 2015 and is progressing according to the planned schedule (see Figure 2).

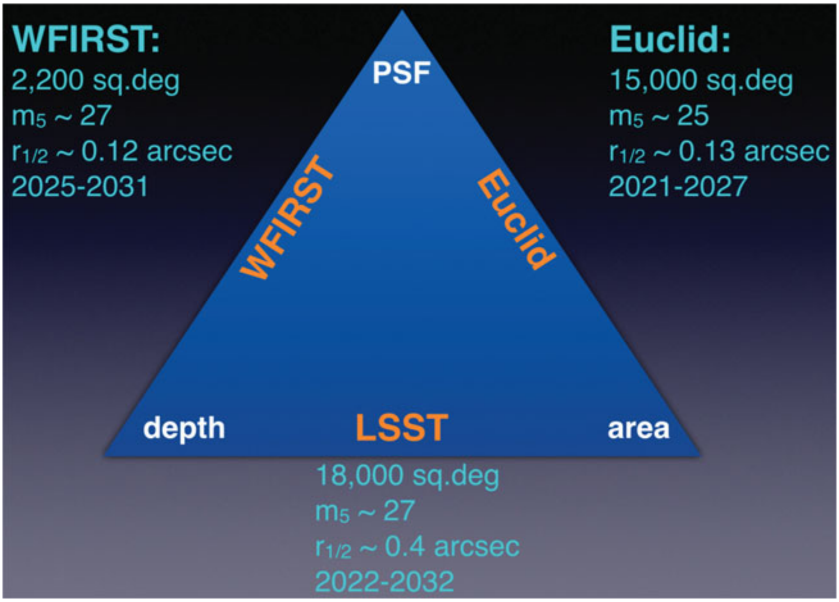

Figure 3. Complementarity between LSST, WFIRST and Euclid. The limiting 5-σ magnitude for point sources is listed as m_5, and the radius enclosing half light from point sources as $r_{1/2}$. The anticipated sky coverage and survey duration is also listed for each mission.

3. Complementarity between LSST, WFIRST and Euclid

In addition to LSST, several other optical and near-IR surveys will also provide excellent datasets for complementing the EoR experiments. The two most significant upcoming surveys in this context will be space-based Euclid (Rhodes *et al.* 2017, and references therein) and WFIRST (Jain *et al.* 2015, and references therein). As space-based surveys, both Euclid and WFIRST will have angular resolution superior to that of LSST (see Figure 3). Euclid will cover about seven times larger sky area than WFIRST, while WFIRST imaging will be about 2.5 magnitudes deeper than Euclid. The advantages of LSST are the survey area in comparison to WFIRST, and imaging depth in case of Euclid. The combination of these surveys will be powerful: about 2,200 sq.deg. will be covered by all three surveys (with 0.12 arcsec resolution in the visual and YJH bands, and photometry in $ugrizyYJH$), and the Euclid-LSST overlap will include at least about 7,000 sq.deg. (with 0.13 arcsec resolution in the visual and YJH bands, and photometry in $ugrizyYJH$). The expected limiting magnitudes for the three surveys are shown in Figure 4.

4. Opportunities for International Participation in LSST

LSST was designed to be a public project, with full access to all data and data products† open to the entire U.S. and Chileans scientific communities and the public at large. Unlimited immediate access to LSST Data Releases will also be granted to international partners who signed Memoranda of Understanding or Memoranda of Agreement with LSST. For other users of LSST data, there will be a 2-year delay‡. LSST is currently seeking additional international partners and we encourage the interested colleagues to

† LSST Data Products are defined in a living document available as http://ls.st/dpdd
‡ The transient stream, based on image difference analysis, will be available to everyone in the world within 60 seconds from closing the shutter.

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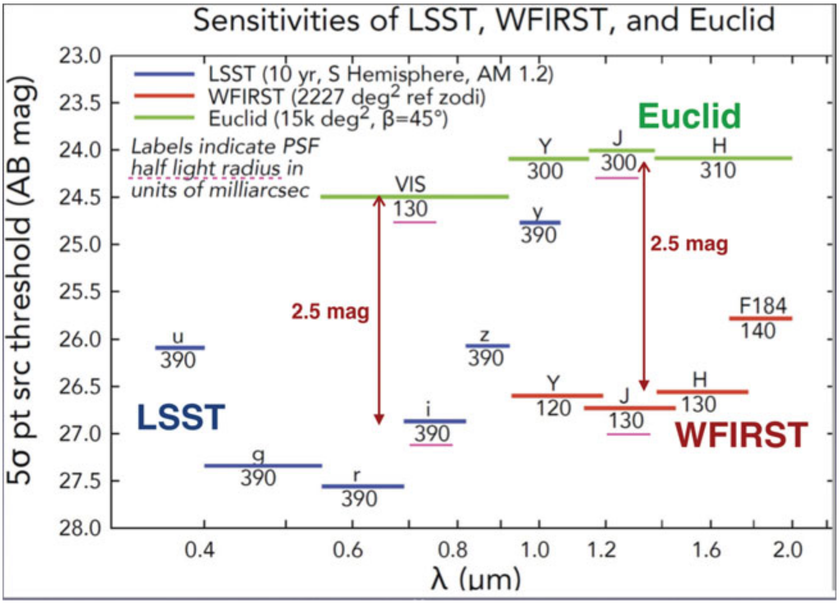

Figure 4. The expected limiting magnitudes for LSST, WFIRST and Euclid surveys (adapted from Jain *et al.* 2015 and modified).

contact the LSST Corporation. For details about application process for International Affiliates, please see Section 3 in Ivezić, Kahn & Eliason (2014).

5. Conclusions

Datasets collected by the Epoch of Reionization (EoR) experiments on the one hand, and surveys such as LSST, Euclid and WFIRST on the other hand, will be highly complementary and synergistic. For example, simulations estimate that LSST will discover about 1,000 quasars at redshifts exceeding 7; this sample will place tight constraints on the cosmic environment at the end of the reionization epoch. Within the EoR context, faint optical and near-infrared survey data will enhance our understanding of the relevance of the first stars and galaxies for EoR and provide constraints for both Galactic and extragalactic foregrounds. At the same time, deep EoR observations will improve our understanding of very faint extragalactic sources and test theoretical models which predict a significant contribution of star-forming galaxies at sub-mJy flux densities. A combination of deep optical and radio imaging will reveal details about the formation and evolution of galaxies as a function of cosmic time and their environment.

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