THE LARGE SYNOPTIC SURVEY TELESCOPE

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Introduction

The four major themes in LRP2010 were identified as “Where did it all come from?”, “How did it all form?”, “How does it all work?” and “Are we alone?”. The recent decade in astrophysics was extremely rich in discoveries in all these area, and lot of the progress was made possible thanks to dedicated ground and space based surveys performed over a wide range of wavelengths. Future discoveries rely on our ability to not just generate more better data, but also more data being *different*. The future is not only about quantity, but also about the transformative nature of the data.

This white paper will describe the Large Synoptic Survey Telescope (LSST) and its anticipated transformative role in the coming decade that is relevant to the LRP2010 themes. LSST was not prioritized in LRP2010, however the international context is changing quickly and the financial situation of LSST is a lot more secure than before. The operations period for LSST will run over the next decade, starting in 2020, coinciding with the next Canadian LPR2020. It is therefore a good time to reconsider Canada’s priority regarding LSST within the constantly evolving canadian astrophysical landscape. In the US, LSST and WFIRST have been ranked as the top ground and spaced based projects in the 2010 US Decadal Study.

Presentation of LSST and survey design

The Large Synoptic Survey Telescope will be an 8.4m ground based telescope to be located in northern Chile in Ceron Pachon. With a field-of-view of 9.6 deg^2 and a 3.2 Gigapixel camera, LSST will become the premier optical wide field imager ever built. LSST is a survey telescope and the current baseline design is a 30,000 deg^2 survey with DEC < +34.5. The observing cadence is going to be 10,000 deg^2 every night using pairs of 15 seconds exposures in 6 bands ugrizy, therefore a new sky will be observed every three night. One LSST image is equivalent to 3000 HST images.

The first light is expected in 2020 and the start of the 10-years survey is in 2022. After 10 years of operations, the coadded depth will reach r~27.5 containing ~38 billion stars and galaxies. 90% of the survey time will be dedicated to a homogeneous 18,000 deg2 region, the remaining 10% are allocated to the Very Deep and Fast Time Domain projects. Data will be released on three timescales, to US astronomers and those international affiliates who have signed MOUs with LSSTC (LSST Corporation):
-All objects whose properties have changed on a given exposure relative to a fiducial exposure: released 60 seconds after the shutter is closed, together with the past history of the object in question.
-Rough processing of a night's observations: object catalogs released ~24 hours later.
-Full processing and coaddition of all data to date released yearly.

Scientific context

The LSST will revolutionize astrophysics in two distinct areas: 1- its ability to provide very deep high quality images over ~30,000 deg^2 that will work in synergy with other wavelengths surveys and 2- the access to the time domain.

<u>LSST imaging:</u>

To date, nearly all wavelengths, from radio to gamma ray, have been explored with various astrophysical surveys, from the ground or from space. The power of imaging lies clearly in the cross-correlation between the future surveys of different wavelengths[1]. This is probably the main reason why countries increasingly focus their efforts and resources on specific wavelengths and scientific collaborations are established through international MOUs. The synergy between these facilities/surveys is obvious to everyone. For the first time in history, there is a

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[1] J. Rhodes et al. “Exploiting Cross-correlations and joint analysis”, http://xxx.lanl.gov/abs/1309.5388

possibility that the whole sky will be nearly completely imaged in all wavelengths by the end of the next decade (2030). From gamma ray to radio the -non exhaustive- list of, existing, in construction or planned, wide-field facilities goes as:

FERMI-LAT/eROSITA/CASTOR/LSST (2020)/Euclid (2020)/WFIRST (2023)/Planck/SKA (2020)

The expected first light is indicated in parenthesis when applicable. From the list above, only LSST will provide complete optical imaging that matches other surveys depths. None of the current generation of optical surveys (the Kilo Degree Survey, the Dark Energy Survey, the Hyper-SuprimeCam) are anywhere close to the required optical depth and area to match Euclid and WFIRST, in fact none of the existing facilities are even capable of doing such survey in a competitive manner. In order to have a taste of how transformative LSST imaging is going to be, one should remember how transformative the Sloan Digital Sky Survey was: an impressive record of discoveries in stellar, galactic, extragalactic and cosmology areas that lead to thousands of publications. SDSS had a phenomenal synergistic power with all other surveys, all wavelength. In r band, SDSS is 5 magnitudes shallower than the nominal LSST imaging. Every three nights, LSST will generate images two magnitudes deeper than SDSS over the entire SDSS area. LSST will provide the critical optical imaging needed by future surveys at other wavelengths (e.g. WFIRST, Euclid, eROSITA, SKA). Optical imaging is absolutely essential because this is where most of the emitted light from galaxies is visible up to very large redshifts, and one of the lessons learned from SDSS is that the full scientific exploitation of non optical wavelengthts requires optical data. LSST will provide limitless target opportunities for TMT, JCMT and CCAT. We see today the power of SDSS increased tenfold with the addition of spectroscopy. If Canada and its international partners go forwards with MSE, the explorative power of LSST+MSE will reach an entirely new frontier. The study of the dark sector with LSST will characterize dark matter, dark energy and modified gravity models, especially when combined with the revolutionizing time domain aspect discussed in the next section. In fact, the LSST imaging could also have a crucial contribution where it is not necessarily expected; for instance, when searching for primordial gravitational waves through B-polarisation mode of the cosmic microwave background (CMB), LSST will provide a solid model for the distribution of foreground galaxies that would complement the CMB lensing measurements necessary to clean the B-mode from lensing. LSST will of course provide a census of galaxies that is going to be crucial for a complete analysis of the secondary anisotropies in CMB measurements. This is particularly relevant for future high resolution CMB temperature and polarisation surveys.

<u>LSST time domain:</u>

The two main categories of these divide into moving objects, or time variable signals from essentially stationary sources.

MOVING TARGETS

Galactic structure

In its large survey, LSST will probe the faint high proper motion objects: probing the end of stellar mass function and search for free-floating planet candidates. Also, due to its depth and the fact that it images large amounts of sky from Earth's vantage point 6 months apart, it will use trigonometric parallaxes to directly constrain the faint end of the stellar luminosity function. For example, LSST will deliver 10% or better distances for a sample of about 2,500 stars with $18<M_r<19$. There are only a handful of such stars known today (and Gaia will detect fewer than 100). As part of this study, LSST should also deliver a complete census of the solar neighborhood to a distance of 100 pc based on trigonometric parallax measurements for objects as faint as $M_r=17$.

Asteroids

With LSST, the main asteroid belt will be studied more completely than ever before. PanSTAARS will have probed to a completeness magnitude of roughly 21, and only patchy deeper asteroid surveys have been done. In contrast LSST should see moving targets down to magnitudes of roughly 24.5, and in about 2 years of operation should find every asteroid above this limit. Comparison of images taken a few hours or days apart will allow detection of these non-stationary targets, and linkages to the object over weeks and months of repeated observation will determine the the orbit while also supplying photometric in several different passbands (allowing the spectral type to be determined). This multi-colour view of the main asteroid belt will allow integrated compositional, collisional, and dynamical studies of the main asteroid belt with samples orders of magnitude better than those provided in the past by Sloan and PanSTAARS.

In contrast, the near-Earth asteroid population consists of objects on orbits whose geocentric distances change drastically with time. Objects from sizes of a few meters up to kilometer scale will be visible, but only at certain times. Due to the smaller interval of time available to detect the objects, the synoptic nature of LSST's view of the sky is critical and unprecedented for their detection.
A recent National Research Council report titled ``Review of Near-Earth Object Surveys and Hazard Mitigation Strategies'' found that LSST is the most cost effective way of surveying the most likely and potentially most damaging Earth threatening objects. Canada has a long history of study of meteoritics, impacts, and asteroid science, and is well situated to make important contributions to this field.

Outer Solar System

The Kuiper Belt

Due to the its large aperture and repetitive imaging, LSST will bring up the completeness limit on our Kuiper Belt to the depth it will achieve. Current large-scale surveys for Kuiper Belt objects are a few magnitudes shallower and only cover a few hundred square degrees. Because outer Solar System objects move along the ecliptic very slowly, LSST will sweep across essentially every Kuiper Belt object it will be capable of detecting. Within the first year of operations, for objects larger than roughly 50-300 km, somewhere between 10,000 and 30,000 detections are expected (with the current inventory being roughly 1,500.

The objects in the outer solar system are the most pristine material left from the proto-planetary cloud. One requires a sample of at least 10,000 objects in order to definitively sample both the spatial distribution and mass distribution. Telescope aperture and field-of-view cannot be traded for longer time on a smaller telescope because objects are faint and they move. In fact, most solar system objects discovered are lost because they are not monitored long enough to get a sufficiently precise orbit.

Investigating the extent and content our Kuiper Belt will in turn lead to an improved understanding of the link between our Solar System and those being discovered around other stars. There is direct evidence for extensive material at large distances from central stars other than the Sun - in some cases this material extends to 1,000 AU from the star. The study of the outer solar system will not only clarify the formation history of our solar system, but will point the way to how other solar systems may form and how star formation in general proceeds.

Again, Canada has world experts in this field who would be able to exploit the LSST data at very high levels due to their expertise (a) the background science of the Kuiper belt and associated studies in debris disks, and (b) high data-flow moving object detection science, using experience made form significant time investments involving CFHT's wide-field imagine capabilities in the time domain.

TRANSIENTS EVENTS with STATIONARY SOURCES

LSST will open a new window on the variable sky. Recent surveys have shown the power of variability for studying gravitational lensing, searching for supernovae, determining the physical properties of gamma-ray burst sources, etc. LSST, with its repeated, wide-area coverage to deep limiting magnitudes will enable the discovery and analysis of rare and exotic objects such as neutron star and black hole binaries; gamma-ray bursts and X-ray flashes, at least some of which apparently mark the deaths of massive stars; AGNs and blazars. It will almost certainly discover entirely new classes of transients, such as binary mergers and stellar disruptions by black holes. It is likely that LSST will detect numerous microlensing events in the local group and perhaps beyond. LSST would provide alerts for concerted monitoring of these events, and open the possibility of discovering planets and obtaining spectra of lensed stars in distant galaxies as well as our own. LSST will provide multi-wavelength monitoring over time of objects discovered by the Gamma-Ray Large Area Space Telescope (GLAST) and the Energetic X-ray Imaging Survey Telescope (EXIST).
With its large aperture, the LSST is well suited to conducting a Deep Supernova Search in selected areas. Every night, LSST will detect a few hundred supernovaes, at the end of the 10 years operations, a total of 1.5 million supernovae will be detected. LSST will also provide a powerful new capability for monitoring periodic variables,

such as RR Lyrae stars, which can be used to map the Galactic halo and intergalactic space to distances exceeding 400 kpc.

In the fields of optical transient, especially supernovae, Canada has vast expertise honed using the very successful Supernovae Legacy survey performed using synoptic studies made possible by CFHT's synoptic use of Megacam. The kind of fast transit reporting to the community that was required (in order to facilitate follow-up observations) will also be necessary for LSST.

Budget considerations

The US (mostly through NSF and DOE) will be contributing close to $1 Billion for construction and operations. These agencies require that LSST has to raise the last $100M via partnerships with international affiliates to support operations for their access to the data releases. LSSTC calculated that the average cost per PI per year is 20,000 $US, that is 200,000 $US for the 10 years of operations, full survey access (this access is granted to the PI and his/her postdocs and students at any time). Two years ago, LSST sent a worldwide request for Letters of Intend to join LSST in order to raise this money. In Canada the Universities that submitted a letter are UBC, Waterloo and Victoria (representing ~ 20 PIs). Worldwide, 17 countries signed the LoI representing 68 institutions (with one or more PI per institution). From these 17 countries, 2 have finalized a MOU for full national access to the data (Denmark and China), similar negotiations with the UK are almost done. There are ongoing discussions for national access with Australia, France, India, Japan and Brazil.

If the potential Canadian PIs (those who sent a LoI) were to join LSST, the total cost would be 4,000,000 US$. It is important to note the existence of a maximum cost cap when an entire country in joining. The UK is currently undergoing such negotiation. Overall, the leverage that Canada gets by joining is many, many-fold given the cost of construction and operation and the scientific return.

Considerations for the MTR committee:

There is no need to emphasize again the very strong Canadian expertise in optical wide field imaging. LSST will provide optical images and give access to the time domain that will probably not be matched for decades to come. There is currently no wide field imaging survey that Canada will join for sure, and this is cutting us from a mode of observing that is absolutely fundamental to the Canadian community. If this situation was to last, it would probably take us a very long time to recover, if that is ever possible. Although Canada is contemplating joining WFIRST, MSE and/or building CASTOR, the question of joining LSST remains a fundamental strategic decision to discuss. The following options, either individually or mixed, should provide some guide to the MTR, ideas to pursue with the community interested in LSST:

1- **In-kind**: LSST is currently pursuing direct funding for the operations phase. The reason is that construction costs are already fully provided by NSF+DOE. The last $100M are needed for operations only which means activities on site and data processing. Although in-kind contribution in the form of construction or hardware does not seem to fit LSST’s immediate objectives to fund operations. However, an interesting alternative would be to offer LSST one canadian FTE per year for 10 years in support. This would be of the order of ~200,000 CAD per year.

2- **Strategic contribution**: if CASTOR or MSE were to be built, then one could imagine some agreement between LSST and Canada to explore the mutual integration of the facilities and surveys. But those facilities do not yet exist, and since LSSTC's immediate focus is on securing funds for operations, an alternative mechanism would likely be needed to allow some Canadian access in the immediate future.

3- **Universities**: if a department is successful with its CFREF competition, one could imagine a national fund raising campaign that would capitalized on the successful group to form a consortium of astronomers that would set the canadian LSST effort in motion. The cost of joining LSST for a few faculty is negligible compared to the funding available through CFREF. Universities, individually, could cover some of the PI contribution, but some sort of Canadian coordination could make this plan more convincing.