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The Large Synoptic Survey Telescope (LSST) and its Impact on Variable Star Research

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Abstract. The Large Synoptic Survey Telescope (LSST) is conceived as an 8.4-m telescope with CCD or CMOS focal plane covering most of a field 0.6 m in diameter, the latter exceeding the size of the largest photographic plates ever used in astronomy. The telescope design is driven by the desire to cover much of the accessible sky to faint magnitudes on a timescale of $\sim$ one night, with major science drivers the search for near Earth-orbit asteroids down to a diameter of 300 m, discovering supernovae to z $\sim$ 2, and mass tomography of the Universe via gravitational weak lensing. Here the suitability of this facility for more "traditional" variable star research is investigated.

Key words. Stars: variables – Telescopes

1. Introduction

The origin of the LSST concept evolved from discussions on quantifying the dark matter content of the Universe by mapping the gravitational lensing signal from faint galaxies over very wide areas of the sky. At this stage, the telescope concept was refereed to as the Dark Matter Telescope (DMT). It was soon realized that two other science projects of high interest required much the same kind of facility, these projects are the search for Near Earth Orbiting asteroids (NEO's) down to a diameter of a few hundred meters, and derivation of the equation of state of the Universe, so-called mapping the dark energy of the Universe, accomplished using type Ia supernovae as standard candles, over a wide range of red-shift. These projects serve to define a telescope concept, a tentative experiment design, and allow estimates of the data rates and information database requirements. As is the case for the Sloan Digital Sky Survey (SDSS), telescope construction and operation, the instrument, and data handling are tasks of similar complexity and cost. All these aspects of the project will be refined over the next two years under the guidance of the LSST Science Working Group, chaired by Michael Strauss (Princeton), with a view to having a detailed proposal ready for the funding agencies by 2004. This early part of the project is being funded by the National Optical Astronomy Observatory (NOAO). A top-level rationale for LSST can be found

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in the influential report "Astronomy and Astrophysics in the New Millennium", see URL http://www.nap.edu/books/, while much information, and links to conference papers and technical reports, can be found at URL's http://www.noao.edu/lsst/ and http://www.lsst.org/. Many of the numbers, and the operations concepts for the LSST that are described below, originate from these sources.

2. The Concept

The LSST telescope optical concept is based on the Paul (1935) design, which uses three mirrors to produce a large, well-corrected field. An important development was that of Willstrop (1984), who describes a three-mirror telescope with perforated primary, which allows a very compact configuration. He actually built such an instrument, which can be viewed in the grounds of the Institute of Astronomy, University of Cambridge (U.K). The LSST optical design is described by Angel et al. (2000), with important modifications by Seppala (2002), this has excellent image quality over a field of diameter three degrees; thin refractive elements remove residual aberrations, and the most recent design has a flat field, which simplifies construction of the detector mosaic. The LSST primary mirror is 8.4 m diameter, this being the largest size borosilicate mirror that can be produced by the University of Arizona Mirror Laboratory.

To cover the large focal plane and provide well-sampled images requires of order 48Kx48K 15 micron pixels, this could for example be achieved with a mosaic of 568 2K CCDs. A quick calculation suggests that this number may not be too different than the total number of CCDs in service at professional observatories worldwide! Such a large mosaic, along with the desire for a read-out time of a few seconds, implies a massively parallel readout structure, and use of ASIC's, pioneered by Rockwell Scientific Co. for IR arrays, looks to be an elegant prospect for this purpose. More conventional highly parallel controllers, such as the MONSOON controller under development by NOAO, are also a possibility.

To reach the science goal of being able to image a large fraction of the accessible sky to faint magnitudes in one night requires short exposures, even with such a large field, and $20-25$ second exposure times are contemplated. Assuming a five second read time, with telescope moving to its next target within this period, allows the data volume and rate to be calculated: each read is 5 GB, so in one night 6 TB could be generated, and 1-2 PB per year. Processing the data in real time requires the pipeline throughput to exceed 200 MB/s. Although by observational astronomy standards these numbers are high, they are comparable with those handled by theoreticians modeling with large three-dimensional grids on super-computers. The high pipeline speed and near-real time availability requirements demands a system of high integrity and redundancy, and although the extrapolated increase of computer power, data storage and network speeds will provide the requisite raw performance, providing usable data reliably is likely the greatest challenge the LSST project faces.

3. Comparison with existing Wide Field Imagers on large telescopes

Most of the present generation of 6-10 m class telescopes do not offer a wide-field imaging capability, Subaru is an exception with the 10Kx8K Suprime-Cam operating at prime focus. Magellan IMACS, an imaging spectrograph now being commissioned, will also provide a relatively wide-field, while the Large Binocular Telescope (LBT) will offer two prime-focus cameras, one optimized for the red and the other for the blue wavelength range. In all cases the imagers cover approximately 0.25 sq. deg., and since they compete for telescope time with other instruments, they are best suited for low duty-cycle programs.

As the 6-10 m class telescopes, each with several state-of-the-art instruments, take the place of the previous generation of 3-5 m telescopes, the tendency is for the smaller telescopes to become more specialized, generally also consistent with the not uncommon desire to lower operating costs for these older facilities. Their operational mode ranges from classically or service scheduled with many runs of a few nights each, to a combination of large multi-year projects and smaller "principal investigator" projects. Examples of the former are the SuperMACHO and the W Projects being scheduled over five years at the CTIO Blanco 4-m telescope, additional examples are most of the other Survey projects that are scheduled on NOAO telescopes, see http://www.noao.edu/gateway/surveys/.

The present generation of CCD imagers have typically 8Kx8K pixels (8Kx12K on CFHT) but with 16x16K imagers either being built or planned for some of the facilities.

In a parallel development, only mentioned briefly here, infrared arrays have grown to 2K x 2K and have already appeared in wide-field instruments (e.g. U. Florida Flamingos, CTIO ISPI, Cornell WIRC) and are being scheduled to undertake a similar mixture of large and small science projects in much the same way as are the big CCD imagers. Still larger instruments (eg NOAO's NEWFIRM 4Kx4K, VISTA Project 8Kx8K) are underway, building up large mosaics using 2Kx2K building-blocks.

Facilities designed for "survey science", of which LSST will be one, are really experiments rather than general user facilities; data-mining of the archived results will be the main mode of use, in addition to the principal experiments. The concept of a large and expensive facility as an experiment is one that is still somewhat alien to ground-based astronomical thinking, but very familar to the space community, and to particle physicists. 2MASS and SDSS are present-day LSST precursors in terms of their scope and aims. OGLE, designed originally as a gravitational lensing experiment, and now as OGLE-III using a dedicated 1.3-m telescope with 8Kx8K CCD imager sited at Las Campanas, is the benchmark by which the use of "survey science" facilities for variable star research should be rated: 268,000 candidate variable stars in the Galactic Bulge and the Magellanic Clouds (MC), see e.g. Wozniak et al. (2002). As pointed out by Djorgovski (2002), surveys, by dint of their exploration of new parameter space sometime uncover the unexpected; rare variables such as the apparently normal main sequence F stars that flare by several magnitudes is one example he gives.

With this brief summary of existing and soon-to-be-built facilities, and neglecting some experiments in planning that may scientifically compete (PanStars, SNAP), we now turn to address the question: How will the LSST impact variable star research?

4. LSST and variable stars

Variable stars have been traditionally broadly divided Kukarkin (1985) between eruptive variables, periodic variables, and eclipsing variables, and are useful for (inter alia) (i) the determination of fundamental characteristics such as masses, radii, temperatures; (ii) the comparison and calibration of evolutionary models; (iii) determining the internal structure of stars; (iv) characterizing stellar populations; (v) distance indicators. For eruptive variables, such as the SN science that is one of the main purposes of the telescope, LSST will of course efficiently discover them, with follow-up mostly or totally accomplished by other facilities, and one can easily imagine a greatly increased demand for follow-up facilities, especially those with a spectroscopic capability. With the advent on the (Inter-)National Virtual Observatory (NVO) the process of finding all known information about a particular object will become far more efficient than at present. Clearly, near real-time availability of both the LSST "trigger" and the archive information will be essential to allow efficient follow-up. For study of non-eruptive variables, the utility of LSST is not so clear, and it is first necessary to summarize the envisaged mode of operation.

The strawman LSST operations plan is to operate in two survey modes: (i) An Ultra-Deep multi-band probe mode, covering 1000 square degrees to 29th magnitude, with 10 hours exposures. This would determine weak lens tomographic mass versus cosmic time, and also discover 3000 high-z supernovae per year, and identify faint transients; and (ii) an All-Sky Synoptic Survey Mode, reaching 24th magnitude at 10-sigma with 20 second exposures, this survey would identify NEO's with diameter greater than 300 m, 200,000 local supernovae, and also identify faint transients. Preceding the start of the two surveys, a full year would be spent covering 14,000 square degrees to 26th magnitude in g,r,i,z, to provide a reference. In subsequent years 25 percent of the time will be spent on the Ultra-Deep survey, and 75 percent of the time on the All-Sky survey, the latter using only the r-filter. It is instructive to calculate the efficiency of the All-Sky survey. Using figures representative for Cerro Tololo and Cerro Pachon, we assume operation for 200 dark-grey hours per month, 75 percent photometric or usable, and of these nights 85 percent have usable seeing, and of this the telescope uptime is 95 percent. Thus with 75 percent for the All-Sky survey, this gives 91 hours/month, and with 30 seconds between exposures (exposure time plus all overheads) the sky coverage is 63,300 square degrees/lunation. If the whole available sky (14,800 square degrees nominally) is to be covered this corresponds to only four visits, so there is an immediate trade to be made between area coverage and re-visit rate. Although the desirability of putting the telescope on a highly photometric site cannot be disputed, there are many open questions remaining to be answered concerning techniques and strategy. For instance, it is not envisaged to use the telescope for these surveys near full Moon. Disregarding possible difficulties in baffling the telescope against stray light, the difference in S/N between new Moon and full Moon through an r filter of a 24-th magnitude star in a 20 second exposure, assuming 0.9 arc sec seeing, is only a reduction from S/N 10 to 7; the critical factor with a brighter sky is the seeing. So although this restriction may be replaced by a more complicated one involving a combination of sky brightness and seeing, we will return below to utilization of this possible niche. Clearly the diverse main science projects make optimization a difficult task, without even considering any constraints that might be desirable in order to allow other science projects.

We are now in a position to make a general evaluation of the usefulness of the LSST for periodic variable star studies. For objects on the sky less than a few square degrees in area (i.e. up to the MC in size) targeted surveys such as OGLE and Super-MACHO will be more efficient at the largest size, with a whole range of facilities able to better study smaller objects such as Local Group dwarf galaxies, see 3. above. Where the LSST will be supreme is in its ability to rapidly survey huge volumes of our galaxy, for instance it will allow study of the galactic halo structure via RR Lyraes, and even with the short exposures envisaged will have the sensitivity to discover these stars out to $\sim$ 500 Kpc. Any halo structure that is old and thus containing RR Lyraes will be able to be measured and mapped. It will efficiently survey the galactic disk, although how far it pushes to low galactic latitudes has not been decided. It will be able to discover, and follow quite efficiently, long-period variables such as Miras. It will find myriads of cataclysmic variables (CV's), and should be able to overcome the biases inherent in surveys for these objects to date, allowing an objective comparison with CV formation theory, at present very discordant with the observations. As has been stressed above, having facilities available for follow-up, both photometric and spectroscopic will be essential, together with

the availability of multi-wavelength cross-identifications to filter out non-interesting objects. Much of what is said above is also generally applicable to eclipsing binaries, presently of much interest after the discovery of sub-stellar companions by Henry et al. (2000) via this technique.
It should be stressed that the usefulness of the LSST for traditional variable star studies is restricted by the operations model, not the telescope design itself. For instance, the LSST can cover 28 sq. deg., i.e. most of the LMC, in 4 exposures, and with 0.9 arcsec seeing, S/N $\sim$ 25 is achieved in B and R at magnitude 23 in 60 seconds, even at full Moon; the LMC could be surveyed in two filters to this magnitude in under 10 minutes! Thus the operational niche that should be explored is that where the sky is bright and perhaps the seeing in the worst quartile. This parameter space will not be without competition, as I and z band photometry will be even less dependent on lunar phase than shorter wavelength bandpasses.

5. Conclusions

The $2-8$ m class telescopes plus $8-16$K imagers will continue to do the "few square degree" science, operating in both conventional few hour - few night runs, and in longer "survey" modes. Pure survey-mode facilities also do some of this science, but as they tackle projects requiring more and more area, the repeat rate per field drops rapidly towards one. The LSST will open new parameter-space - deep and wide and fast, and it is likely to discover new classes of variables, where follow-up by other facilities will be essential. Its periodic-variable targets are those in the Galaxy, since even for structures several degrees across, such as the MC, other facilities performing targeted studies will do better, by trading field for time.
The LSST Project is in definition phase, and now is the time for scientific input, via the LSST Science Working Group, which will define the science cases which will flowdown into the technical requirements. Questions as to the optimum number of filters, the required calibration accuracy, the photometric depth needed - all are awaiting detailed treatment. While the thrust for the main scientific projects of the LSST should not be diluted, some parameters of the design may be able to be tweaked to enable other science. In particular, use of the time around full Moon, and poorer seeing conditions, are a parameter space that could be exploited for variable star programs of many types.

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