OPTICAL POLARIMETRY WITH THE LSST

Introduction

The LSST will address several fundamental problems in Astronomy as well as provide an unparalleled legacy to Science. The purpose of this brief document is to propose that the LSST consider augmenting even further its legacy by observing the polarized sky.

Science Case

Below we summarize several areas where the LSST would make a fundamental, unprecedented contribution by measuring the polarization of the incoming photons. This was prepared from text by several enthusiastic astronomers, listed at the end of this document, specifically for this purpose.

1 Cosmology

- The much improved sampling of starlight polarization across the sky will allow for a much better knowledge and modeling of the Foreground Galactic polarization at the far-IR & sub-mm wavelengths. This correction is crucial for analyzing the observed **CMB polarization** from WMAP, PLANCK & CMBPol, as the Galactic polarized emission signal from dust dominates above 70 GHz.
- Knowledge of the polarization of chosen sources will help calibrate the position angle of the detectors on space missions such as Planck and CMBPol.
- The relation between quasar axes and surrounding large-scale structures may help constrain models of structure formation.

2 Extragalactic Astronomy

- **Active galactic nuclei** (AGN) are variable on time scales of minutes to years. Because the shorter wavelengths are produced closer to the energy source, they are better at measuring the changes in magnetic field structure near the central engine than radio waves.
- Temporal polarization observations of broad-line type 1 AGN, to date identified in only a few galaxies, should provide characteristic sizes of the dominant scattering regions, essential to understanding of the **structure of AGN**.
- Similar observations of radio-loud FR-I AGN, presumed to be the parent population of BL Lac objects, will allow for a determination as to whether the compact blue cores found in these objects are due to scattering, synchrotron radiation or a ‘naked’ thermal accretion disk.
- Many **blazars** will of course be discovered by this LSST survey. In addition, most of the unidentified (observable) COMPTON/EGRET sources will likely be identified.
- The **magnetic field structure** of interacting systems such as the **Magellanic Clouds**, and its relation with the gas dynamics, may be determined from starlight polarization. Other resolved systems may be mapped as well.

3 Galaxy, Interstellar Medium and Star Formation

- Grain alignment theory, crucial to interpret dust polarization as a tracer of magnetic fields, has had a recent, remarkable progress (Lazarian and collaborators), with radiative torques becoming the most promising mechanism. Testing the theory's predictions for the polarization by grains of different composition and in various environments will be provided by the LSST polarimetric survey, allowing quantitative modeling of polarization and the interpretation of the observational data.
- Observations of starlight polarization from LSST, in conjunction with stellar parallaxes determined by the LSST itself, will provide an unprecedented knowledge of the general **magnetic field structure of the Galaxy**, down to the Local Bubble.
- Further, this topology will be known from the general ISM down to across several ISM structures, such as clouds at several densities and velocities recognized from existing surveys (dark clouds & globules, COBE/DIRBE clouds, 21-cm, open clusters, etc.). This will tie the field from the less dense regions in the optical to that obtained from longer wavelength mapping from ground studies or from PLANCK.
- Mapping the magnetic field through **Giant Molecular Clouds**, from which most stars form, will provide understanding the connection of the field from the diffuse ISM, through the GMCs and down to the embedded dense cores from molecular line and dust emissions.
- It will be possible to study the **coupling of the ISM gas and the magnetic field**. The field intensity of dynamically separate regions may be more reliably estimated using the Chandrasekhar-Fermi method. Predictions of analytical and numerical theories in development will be checked, and the role of the field on dynamical processes such as **star formation, turbulence and dynamo** will be better understood.

4 Stellar Astrophysics (in the Galaxy and beyond)

- Statistics and time evolution of **explosive phenomena**: optical polarization of GRBs and associated Optical Transients will provide insight into the explosion mechanism, its asymmetry, how such asymmetry evolves with time and its relation to photometric signatures. This is another example of a scientific synergism between polarimetry and a core LSST program. This can be applied to SN as well.
- Polarimetry of **echos of transient events** (novae, SN or variable star) will allow us to characterize events that took place long ago (e.g., in the Magellanic Clouds) or from a different perspective; understanding the geometry of the event can reveal a geometric distance to a SN or Cepheid.
- LSST may allow a much better census of **magnetic white dwarfs** in both cataclysmic binaries and the field, helping clarify the current dichotomy where highly magnetic objects are significantly less frequent among the field white dwarfs, in addition to discovering extreme objects presently undetected.
- LSST polarimetry of the highly non-spherical **circumstellar environments** of both YSOs (HAeBe, T Tau, etc.) and evolved objects (RGB, AGB, post-AGB, PPN, PN, LBV, WR, B[e]) will provide a breakthrough in the study of angularly resolved and unresolved envelopes.

- These observations will include the critical **time domain**, once again revealing the synergy between core LSST projects and polarimetry. This will allow the study of development of asymmetries as a function of evolutionary state and, from the ensuing time scales, the distance of the asymmetry from the central object.
- The LSST polarimetric survey offers the potential to revolutionize our understanding of the basic properties of **protoplanetary disk systems** in metal poor (SMC/LMC) environments.

5 Solar System

- Polarimetric observations of **asteroids** are the best available technique to derive the albedos, and hence the sizes, inventory and size distribution, of these objects.
- A multi-year polarization survey of the full sky will result in a dramatic increase in the number of measured asteroid polarization-phase curves allowing us to further clarify the population divisions among the **Main Belt**, **NEOs**, etc.
- By solving the albedo-polarization calibration problem, the LSST survey will also open new fields to investigate all categories of **minor bodies** in the SS.

6 Additional considerations

- If feasible, a circular polarization capability, although applicable most readily to magnetic cataclysmic variables and dust environments such as protoplanetary disks, might considerably increase the chances of unexpected discoveries.
- In addition to the serendipitous discovery of many highly polarized objects (e.g., reflection nebulae, edge-on disks, blazars, etc.), many of these will have unresolved fine structures that might be excellent candidates to the future, AO-equipped 30m-class telescopes and to ALMA.
- **Calibration of space-based polarimeters** has been increasingly important, especially with ACS and NICMOS aboard HST, and the proposed EXCEDE mission. The current limitation of the existing standards (e.g., sparse, too bright, etc.) could potentially be eased by sky polarimetric surveys. This expanded calibration could also potentially benefit the legacy polarimetry from FOC, FOS & WFPC2.

Technical aspects

- The details of implementing a polarimetric capability to LSST will of course have to be discussed closely with LSST's team. Tony Tyson has already mentioned to one of us (AMM) the difficulties with installing a rotating linear polarizer. Indeed, at the time consideration was also given to the fact that, alternatively, the camera itself instead might be positioned at distinct angles. For instance, images at 0, 90 deg would provide the Stokes parameter Q and those at 45, 135 deg would provide Stokes U across the field. Subsequent visits to the same field at different overall orientation of the camera should help to minimize systematics.
- As pointed out by Dean Hines and Chuck Claver by email, the LSST itself should provide nearby, unpolarized stars to further help eliminate the systematics of a single beam measurement (a double beam, birefringent polarizer is not an option due to size).

Selected (i.e., non-emission line, non-variable, non-binary, main sequence) Hipparcos stars as unpolarized stars have indeed been used earlier (AMM). Nearby objects found by LSST would hence provide a measurement of the instrumental polarization.

- Another aspect is that of spectral coverage (i.e, how many filters). A dedicated filter with an appropriate polarizer, mounted together, could provide a single band solution. For a multi-band approach, an option might be, if feasible, to optionally mount a (fixed) polarizer ahead of each of two selected filters (r and g, for instance).
- Finally, the observing strategy would have to be discussed, e.g., at what cadence to cover the sky (the nominal one would probably be a good initial choice), whether to use a different cadence for targeted campaigns, how to best proceed with targets of opportunity (e.g.., GRBs), etc.

Hardware Implementation

Linear polarization is usually measured by obtaining the Stokes parameters, Q and U, usually expressed in fractional or percent form. Q expresses the difference in flux between light polarized at position angles 0^o and 90^o, while U refers to that difference between position angles 45^o and 135^o. Images through the polarizer oriented at 0^o and 90^o will provide Q and those at 45^o and 135^o will provide U.

The polarization percentage P is related to Q & U by $P = \sqrt{}(Q^2 + U^2)$, while the position angle of the polarization is $\theta = 0.5$ arctg (U/Q). If the polarimetric S/N, σ_P/P, is larger than about 4-5, Q and U are statistically normally distributed. If they are measured with the same accuracy, that will be the accuracy of P as well.

In order to avoid or minimize the influence of atmospheric transparency fluctuations, it would be best to measure Q and then U (or vice-versa), as opposed to obtain the images through increasing position angles. Various additional schemes to obtain each parameter could be used in less than ideal weather, such as splitting the observing time in a 0-90-90-0 sequence for obtaining Q, etc.

Unlike imaging through dual-beam polarizers (not an option here), which allow accuracies down to the photon noise limit, imaging through polarizers will include some systematic effects, such as those from the atmospheric effects. As pointed out in the previous section, observing nearby, unpolarized objects eventually as a small part of the program, should provide a good estimate of the systematics, which can then be applied to the program observations.

In any case, we should remember that the very symmetrical configuration of the LSST optics will ensure a negligeable instrumental polarization. Also, the single-beam polarizers proposed here will also allow for observations of extended sources (SNRs, light echoes, nebulae, galaxies, etc.), contrary to the double-beam counterparts. Finally, subsequent visits to the same field, with different camera orientations against the sky, will also help minimize systematic effects.

There are two main alternatives for the hardware, neither of which should interfere with any operational or scientific aspect of LSST. One of them, and probably the most efficient one, is to have a filter which combines a band filter (eg., r) with a polarizing film contacted to its surface. The other is to coat an optical glass with a polarizing film and have the option to use it together with (i.e., ahead of) one of the LSST band filters.

Option a. Band pass filter coated with polarizing film

This could basically consist of a copy of a 'normal' LSST filter, eg., an 'r' filter, built with the needed curvature and coated with polarizing film. There are films available which are 250μm thick to within ± 50μm, i.e., ~ λ/10 or better for wavelengths larger than those at r.

Ideally such filter could have its own rotating mechanism (eg., a pair of opposite motors and magnetic encoders mounted on the edge of the filter metal rim), so as to be an independent, integrated unit, within the filter space envelope currently envisaged, and mounted as a normal filter in the camera. It would have to be powered by LSST, whose control software would command the motors and read the encoders. Hence, essentially no redesign effort would be needed.

An alternative to a rotating polarizer/filter has been pointed out by Chuck Claver, which is to use three filters instead, each mounted with a fixed orientation (three positions, eg. 0, 60 and 120 deg, is the minimum required to obtain Q & U). Of course, polarimetry would require these three filters at the same time in the camera.

Yet another alternative using a fixed polarizer/filter combo would be to rotate the camera. In the first visit to a field, it could be observed through positions 0^o and 90^o (then at 90^o and 0^o for the next field and so on). On the second visit of the night, the camera would be positioned at the remaining angles, 45^o and 135^o.

Finally, mounting the polarizing film in pieces already properly oriented on the band filter might also be an alternative to rotating the whole filter. For instance, each 1/4 of the filter surface would have a polarization orientation. Obtaining Q & U for each 1/4 of the field would amount to shifting the telescope on the sky through each polarizer section. One disadvantage of this approach would be that the boundaries of each 1/4 (in this example) sector would be 'fuzzy' on the detector, since the polarizer will be at some distance from the detector, but this could be quantified.

Option b. Polarizing filter optionally mounted ahead of a chosen LSST filter

In this case, the polarizer would sit, unmounted, inside the stowed location of the filter. Prior to bringing the filter into the beam, the polarizer would be lowered and latched on the filter rim. After the observation, with the assembly back to the stowed position, the polarizer would be unlatched from the filter. The latter could then proceed to its normal photometric use.

Disadvantages of this approach include having to (even if relatively slightly) modify the basic design of the filter cells, as well as rotate the camera through the required angles for the polarimetric observation, as in the fixed filter in Option a. above.

Expected Accuracies

Using the LSST's Exposure Time Calculator (ETC), we have estimated the accuracies achievable for linear polarimetry. Within the ETC we assumed point sources with a range of AB magnitudes, r filter, 0.7" seeing and a 7-day Moon. We have also taken into account that the amount of light from the object is halved due to the polarizer (reasonable assumption for small polarizations) and that the polarizer itself has in addition a transmission of 80%, in step with realistic polarizers in the market.

The Stokes parameters Q and U are each obtained from quantities like $(N_0 - N_{90})/(N_0 + N_{90})$, where the N's are counts at each polarizer position. For polarization values of a few percent they are all ≈ N. The S/N of this measurement (Table 1, last column) is the one provided by the ETC and its accuracy is $\sigma = (S/N)^{-1}$.

Each Stokes parameter will hence have an accuracy of $\sigma_P = \sqrt{2}/2 \cdot \sigma$. For four exposures of 15 sec each, through the four polarizer orientations, we can build the following values displayed in the second column of Table 1.

Table 1. Accuracies of Polarimetry with LSST

	single measurement	all-sky survey	600 sq deg survey		LMC-SMC-Inter Cloud region		SMC, 2h/night		S/N
AB mag	4x15sec	per 10 sq deg	per year	10 yr mission	per year	per mission	per year	per mission	15 sec
15	0.071	0.050	0.035	0.011	0.020	0.006	0.006	0.002	1000.2
16	0.114	0.080	0.057	0.018	0.033	0.010	0.010	0.003	623.0
17	0.186	0.131	0.093	0.029	0.054	0.017	0.017	0.005	381.1
18	0.316	0.223	0.158	0.050	0.091	0.029	0.029	0.009	224.1
19	0.577	0.408	0.288	0.091	0.166	0.053	0.053	0.017	122.6
20	1.165	0.824	0.582	0.184	0.336	0.106	0.106	0.034	60.7
21	2.587	1.829	1.294	0.409	0.747	0.236	0.236	0.075	27.3
22	6.127	4.333	3.064	0.969	1.769	0.559	0.559	0.177	11.5
23	15.013	10.616	7.506	2.374	4.334	1.370	1.370	0.433	4.7

We can build upon this basic polarimetric exposure and explore a few possible scenarios within the current plans of LSST for its mini-surveys as examples. We have kept the LSST philosophy in them, in the sense that a given mini-survey should ensure a number of scientific problems to be tackled. We assumed that mini-surveys would include 2 nights/yr (or 20 h/yr), for a total of 20 nights during a 10-yr mission.

All-sky survey

We can realistically assume (Ivezic et al 2008, 2008arXiv0805.2366I) a number of 50 15sec exposures per hour per filter. This would translate in about 12 basic polarimetric observations, each with the accuracy in Table 1's 2nd column, covering then about 120 deg^2 per hour. One would then have ~600 deg^2 per night covered, with one revisit to every field, providing the accuracies in the 3rd colum of Table 1. Two nights a year would provide 1200 deg^2. A 10-yr mission would provide about 12,000 deg^2, covering hence a sizable fraction of the available sky.

A 600 deg^2 mini-survey

We have chosen this example as an area of interest that, if at high Galactic latitudes, could include the Magellanic Clouds, Extragalactic Astronomy (eg., identifying Gamma-ray source optical counterparts), Cosmology (eg., determining the Galactic foreground polarization), the NGP and high Galactic latitude ISM. Alternatively, this area might include several extended Dark Clouds and Bok Globules, as well as Giant Molecular Clouds, for mapping the magnetic field in several environments of interest for Star Formation between about 10 and 30 deg away from the Galactic Plane.

One such survey area would be covered in a single night, including a revisit to every field. Two nights a year would provide the accuracies in columns 4 and 5.

At this point it should be pointed out that, in certain circumstances, the accuracies quoted in Table 1 may be either further improved or would be quite acceptable depending on the desired science goals. Eg., for ISM studies one could use the fact that a number of stars may be averaged (there'll be ~100 MS stars per detector with $17 < r < 20$; Isvezic et al. 2008) over a small field for improving the knowledge on the ISM polarization towards a given direction. In the case of AGN, several classes of them present polarization values well above 1%, in which case 3-sigma detections might take place to magnitudes as deep as 22. Of course, more specific AGN programs might choose as goals a smaller area and a higher polarimetric S/N.

A mini-survey of the SMC-LMC-Inter Cloud region

This would be another example of a program which would impact several areas, such as mass-loss across stellar populations, the ISM within and between the Clouds, the NE/Wing sections of the SMC which is being disrupted by the LMC, the MC Giant HII regions, and so on. We should note that, for the Magellanic Clouds, the magnitude range where the polarimetric accuracies are about 1% or better (15 through 22 mag) encompass from AGB stars through RGB and Horizontal branch stars and down to the Main Sequence around solar values.

The size of this region is 200 deg^2. This area would be covered with 6 visits per night or 12 visits per year, with the ensuing accuracies shown in columns 6 and 7 of Table 1.

An SMC survey/monitoring program

Our final example shows the amazing capabilities of LSST in a program that requests only 2 hours per night for a synoptic study of the SMC (20 deg^2), during 10 nights distributed along the observation semester, totaling the usual mini-survey length of time per year. This program would provide, for instance, unprecedented stellar variability studies of the galaxy, where mass loss takes place in a low metalicity environment. A simultaneous detailed study of the ISM polarization of the galaxy would provide insight, e.g., into the magnetic field across ISM structures such as those detected by Spitzer.

This program would provide 12 visits per night on the galaxy, or 120 visits per year. Columns 8 and 9 show the accuracies per year and in a 10-yr mission. The attainable accuracies per night would be similar to those in column 6 (LMC-SMC survey, per year). These columns show that, on the bright ($V \lesssim 20$ mag) end, the accuracies will probably be limited by removal of systematics only.

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