Science White Paper for LSST Deep-Drilling Field Observations
High Cadence Observations of the Magellanic Clouds and Select Galactic Cluster Fields

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1 Science Goals

1.1 Concise List of Main Science Goals

The LMC and SMC are the nearest large galaxies to the Milky Way and represent excellent testbeds for investigations related to many stellar astrophysics topics. Unlike nearby star clusters, the Magellanic Clouds have been shaped by complex dynamical processes and have extended star formation histories that vary with position. Unlike fields probing our Galaxy, objects in the LMC and SMC are all at the same projected distance from us (to first order), and therefore their study eliminates one important degeneracy in testing stellar evolution models. We propose high cadence observations of the LMC and SMC in order to fully exploit the power of LSST to characterize these two galaxies in the time domain. The stacked images, since they would achieve unprecedented depth over a large field, would also allow us to use the LMC and SMC for population studies of non-variable objects as well. Our specific goals are to:

1. Fully characterize variable stars in the Magellanic Clouds via a much higher cadence of observations in g and r filters to determine the range of stellar variability between 15 sec and 3 days. Combined with the main survey, this will enable the variability of stars to be described over timescales of 15 sec to 10 years, something that has never been done before in any context. We would place special emphasis on the bluer variables that will not be obtained during the main survey.

2. Determine accurate periods for all regularly variable objects, whether periodicities are due to binary periods or pulsations, down to approximately M_v of 6.5 (assuming a limit for variability measurements of m_v of 25) in the LMC and SMC.

3. Obtain light curves for a statistically complete sample of eruptive and flaring objects permitting estimates of the frequency of various types of eruptive behavior, including cataclysmic variables and late type stars. These observations will be important for a variety of problems, including population synthesis calculations for binary objects, magnetic field strengths and rotation properties in active stars, and the distribution, energetics and characteristics of stellar flares.

4. Compare variability properties of objects in the Galactic halo, galactic clusters vs the LMC and SMC to determine how metallicity and age affect various populations of short period variables and test a variety of stellar evolution models.

5. Use the proposed cadence and colors to aid in classification efforts for a wide range of variables and provide a basis for the main survey to accomplish the distinction between transients and variables. This will be especially valuable if the Deep Drilling observations we propose are carried out in the commissioning or early operational phases of LSST.

6. Place unprecedented constraints on the star formation and chemical abundance history of the Magellanic Clouds and probe their dependencies with environment. The observations will establish complete surveys of the luminosity and mass functions of stars down to very low masses for accurate color-magnitude relations at different metallicities compared to the nearby Milky Way population.

1.2 Details of Main Science Goals

1.2.1 Detailed Census of the Complete Range of Variable Stars

With the emphasis of the general survey on red objects and the cadence structured to find asteroids, there will be many short period and blue variables that will be missed, or poorly characterized. This includes short period eclipsing binaries, pulsating white dwarfs, γ Dor variables, β Cephei stars, mass transferring binaries with flickering due to sporadic accretion, ultrashort period AM CVn systems, super soft sources flares in late type stars, accretion in T Tauri stars, etc. In order to construct an accurate picture of stellar evolution, the effects of binarity and wind loss must be known, as well as the numbers of stars that undergo these effects. Thus, a complete picture of variability is the first step toward understanding the causes and effects of variability on stellar evolution.

The main survey will do well in identifying variability that is periodic and for periods longer than a few days. But there are many other variables that are aperiodic or have random fluctuations, short periods or maximum changes occurring in the blue. While many of these objects will be seen to be variable in the main survey, it will be extremely difficult to characterize the nature of these objects with the main survey cadence. Furthermore, there will be many objects in the period range of a few days to a year, which may ultimately (in the entire 10 year LSST time frame) be characterized, but which if accomplished in the first 1-2 years of LSST, would advance our understanding of these objects to benefit later results. Early high cadence observations will also allow us to pick out changes in behavior of aperiodic variability in a timely manner for follow-up observations that will simply not be possible with the normal cadence of observations.

Thus, we need to cover the time and color domain that will not be obtained in the main survey in order to encompass a complete study of variability. A few examples of the science derived from these different classes of variables are given below.

LMC/SMC EBs Prsa, Pepper, & Stassun (2011) have assessed the science yield of the main LSST survey that will take place for eclipsing binaries (EBs). They find that the main survey will have good sensitivity to EBs with r < 20 and with periods ranging from 0.1 days to 200 days, especially for periods less than 10 days. This sensitivity arises from the long duration of the main survey, which permits a sufficient number of data points in eclipse to be obtained over the course of the survey lifetime. The vast majority of the detected EBs will be in the field, not associated with clusters or stellar associations. Indeed, at present, the number of benchmark-grade EBs that are members of clusters or associations numbers fewer than 20. Such EBs are particularly important because not only are the fundamental parameters of the EB determined (masses, radii, temperatures, luminosities) but, in addition, an independent age constraint can be determined from the main sequence turnoff and/or from the white dwarf cooling sequence. DDF will permit clusters to be specifically targeted, and importantly will allow the EBs in these clusters to be identified early in the LSST survey.

CVs and AM CVn stars The primary science gain for this group of objects is the number density of the population. The SDSS covered 10,000 deg^2 to a magnitude of 21 out of the galactic plane and found about 300 cataclysmic variables (Szkody et al. 2009) and 12 AM CVn double degenerates (Anderson et al. 2008; Solheim 2010). This translates into about $5{\times}10^{-5}$/pc^3 for CVs and an order of magnitude less for AM CVns, but these numbers are highly uncertain. The SDSS was not complete as the identification was primarily made from the objects that were selected by color for spectroscopic fibers, and the numbers should increase toward the galactic plane which was not covered. Followup data to obtain the orbital periods from the SDSS objects (Gänsicke et al. 2009) revealed a different population of CV objects, one that better matched the population models computed from stellar evolution (Howell et al. 2001) than previous surveys due to the capability of SDSS to go fainter than previous surveys. These population models also predict an even fainter (22-24 mag) large group (70% of CVs) should exist past the period bounce, where the periods increase due to the degeneracy of the low mass companion. This group remains to be discovered with larger telescope surveys such as LSST. Because the orbital periods are very short ($<$ 80 min) and the colors are blue (due to the white dwarf and the accretion disk) and the variability is largest in the blue (due to the accretion activity), the discovery and hence the correct numbers of these systems are dependent on a bluer color and a faster cadence than the general survey will accomplish. Recent work by Heinke (2011) has shown that NGC6397 shows a fainter population of X-ray selected CVs that could be this missing population. The identification in globular vs open clusters will bear on the question of the numbers of CVs that form by interactions in clusters. While the LMC and SMC are too distant to detect the quiescent CVs (M_v=11-13), for the first time, many dwarf novae in outburst should be found. A CV space density of $5\times10^{-5}/\mathrm{pc}^3$ and a local mass density of 0.044 $M_\odot/\mathrm{pc}^3$, yields about 10^{-3} of the local mass in CVs, so for the mass of the LMC (10^{10} $M_\odot$), there should be about 10^4 CVs, of which only a few have been observed so far.

Super Soft Sources Supersoft x-ray sources (SSSs) vary on all timescales on which they have been observed. There are about a dozen known supersoft sources in the Magellanic Clouds (Greiner 2000). Because only a few SSSs have been discovered in the Galaxy, the Magellanic Cloud population is a unique resource. Twenty years of optical monitoring of these fields already exist, because of efforts by the MACHO, OGLE, EROS, SuperMACHO teams to find evidence of microlensing events. These teams have found optical variations of SSSs on all timescales. It has also been discovered that a subset of these sources exhibit anticorrelated x-ray/optical variations. They are off at x-ray wavelengths when in an optical "high" state, and bright ($\sim 10^{37}$ erg s^{-1}) in x-rays when dimmer by about 1 magnitude at optical wavelengths (Southwell et al. 1996). While the x-ray transitions have been observed during individual x-ray observations of SSSs in an external galaxy (Schwarz et al. 2001) , the optical transitions have not been observed. They seem to take place over an interval of minutes or hours. It is possible, but not assured that the Deep Drilling observations will take place during a transition. Whether or not we are fortunate enough to trace a transition, the Deep Drilling observations will study the optical variability of SSSs with a sensitivity and on a timescales that have not yet been explored. This is important, because the variability holds clues to the nature of the sources, which are presently believed to include hot white dwarfs and accreting black holes. In addition, despite evidence that indicates there may be a few dozen additional SSSs in the Magellanic Clouds, no new such bright sources have been discovered during the era of Chandra and XMM-Newton. The optical variability might by itself be used to identify members of this class. Greiner has demonstrated the feasibility of this approach in the Galaxy. Should we observe optical variability that could be due to SSS transitions during the Deep Drilling campaign, we can use Swift to check the variability at x-ray wavelengths.

Flare Stars Stellar flares are highly energetic and impulsive events, with energies of $E > 10^{30}$ ergs are routinely released. In some cases, superflares that rival the bolometric luminosities of the stars have been observed (see, e.g., Osten et al. 2010; $\Delta m_{\rm V}\sim3$). But while such enormous events are intrinsically interesting, it is the weaker counterparts that are critical towards a deeper understanding of the energetics of the phenomena. On the Sun, flares are are distributed as a power-law (Lin et al. 1984),

$$\frac{dN}{dE}\propto E^{-\alpha}$$

over many orders of magnitude in E, with $\alpha\approx1.8$ (see Aschwanden et al. 2000). The value of

$\alpha = 2$ marks a threshold beyond which it is possible to attribute all of the coronal heating budget to increasingly numerous but weaker flares. Photometric studies of low-mass active stars (see Robinson et al. 1995, Robinson et al. 2001) show that α ranges across the critical value of 2, with a number of cases, sometimes at specific wavelengths, having $\alpha > 2$. Studies of X-ray flares have also reinforced this (Audard et al. 2000, Kashyap et al. 2002, Güdel 2004) characteristic of low-mass active stars. The reason for the difference between solar and stellar flares are not known, and a concerted study covering a range of values in spectral type and activity is necessary to advance our understanding. Furthermore, there is evidence that the flare distribution turns over at both the low end (see Wargelin et al. 2008) and at the high end (fewer superflares are detected than are expected).

The LSST Deep Drilling observations provide a remarkable opportunity to monitor a large number of stars and determine their flaring characteristics. Flares of peak luminosity as low as $5{\times}10^{29}$ ergs s^{-1} would be directly *detectable* on M dwarfs in 90s observations. Weaker flares can be modeled (Kashyap et al. 2002, Wargelin et al. 2008) to determine their behavior indirectly at low energies.

Pulsating WDs All pulsating WDs show non-radial g-mode pulsations which probe up to the inner 99% of the mass, thus providing a unique insight into the stellar interior from a model fit to the observed periods between 1-20 min. SDSS discovered more than 100 WD pulsators. LSST should increase the known population to over a thousand brighter than 20th mag. Followup observations of known pulsators leads to knowledge of the nuclear reaction rates in red giant cores (Metcalfe et al. 2001), cooling rates (Winget et al. 2004) and the importance of convection (Montgomery 2005), crystallization (Metcalfe et al. 2004) and helium cores in stellar evolution. Ivezic et al. (2007) used the available repeat data from SDSS to identify the cooling curves of H and He WDs. Using the increased variability and blue color (g-r) from the DDFs will allow these sequences to be identified in the clusters and hence a comparison of the IMF across a range of metallicities. In the LMC and SMC, DOV pulsators (70,000-140,000K; M_v=0.5) can be identified, while the cooler DBV (25,000K; M_v=6) pulsators will be found in 47 Tuc and the coolest DAV pulsators (11,000-12,000K; M_v=11) in IC4651 (assuming a limit of g=21 for sufficient S/N to detect pulsations).

δ Scuti/γ Dor These A-F main-sequence stars were originally thought to be 2 separate populations with the δ Scuti stars showing periods of about 2 hrs (due to the HeII ionization zone) and the γ Dor stars showing periods of 0.3-3 days from a convective zone. However, Kepler data (Grigahcene et al. 2010) have recently shown that the hundreds of objects identified pulsate with amplitudes of about 0.1 mag in both regimes (hybrids). Correct identification of the population numbers for each mode provides check points for the unstable regions in stellar evolution of 1.3-2.5 solar mass stars.

New phenomena Previous small-scale surveys of variability (Howell 2008) have shown that up to 40% of objects are variable at the 0.003 precision level. As fainter objects are observed with greater precision, new types of variability are found. Sampling the short end of the the time-domain will establish the norms of variability within this regime and should produce some surprises as well. The results will be of importance for comparison, for example, with Kepler.

1.2.2 A Complete Stellar Census

Whereas the main survey will sample all regions of the LMC and SMC to a depth of $g' = 27$, stacking a large number of deep drilling field exposures will offer sensitive imaging down to $g' > 29$ (each hour of DDF is equivalent to a year of the main survey). This increase in depth offers huge leverage on the shape of the stellar luminosity function since the bulk of the population is tied up in low mass stars. The deep drilling fields will be sensitive to stars with masses of just $0.2\ M_{\odot}$, and therefore establish new color-magnitude relations over a large range in mass for millions of stars. For spatial regions that have not yet dynamically relaxed, these color-magnitude relations will be translated to initial mass functions of stars, which themselves relate to the physics governing the stellar internal and atmospheric structure. In addition to new constraints on stellar models, the measured slope of the mass function, especially at the low mass end, will impact general derivations of the mass budget and gravitational potential of distant galaxies through a variety of techniques.

Over the large LSST field of view, physical relations such as that between color and luminosity can be uniquely connected to regions that show variations in star formation and chemical abundance history. This therefore provides a sensitive probe of the variation of the stellar mass function with environment, one of the most important inputs to generating reliable population synthesis models aimed at interpreting integrated light from extragalactic objects. Given the diverse star formation and dynamical history of the Clouds, these comparisons can be made for regions that are uniquely affected by dynamical interactions (e.g., tidal features or other disturbances), star formation processes (e.g., near young OB associations or clusters), and over metal-rich and metal-poor regimes in smooth, old components of the galaxies. Finally, an important aspect of the deep, wide field imaging enabled by these drilling fields will be to serve as the standard calibration to the general main survey of the Clouds (e.g., informing the incompleteness of that survey).

1.2.3 Classification of Transients/Variables

The main survey has a nominal cadence of about 3-4 days. Millions of objects will be seen to be variable; most of these objects will be stars, or one sort or another. Many thousands of transients will appear as eruptive objects at the position where nothing was seen previously. A crucial problem for LSST is selecting out the small percentage of interesting objects for follow-up given the limited amount of information provided as a result of the main survey. Until the full range of variability of all types of stars is known, it will be difficult to impossible to classify any apparent change in brightness of an object as a known variable type or a new transient. The most efficient way to accomplish this is with high cadence Deep Drilling of nearby extended objects, such as the Magellanic Clouds, and/or of relatively low galactic latitude fields, with a high surface density of stars. Data obtained in the first few years will aid in the correct classification of objects throughout the survey, thus guiding correct follow-up work on other telescopes.

1.3 Identifying Non-standard Behavior

LSST will create a huge database of variable objects. Many of these objects, especially regularly variable stars like RR Lyrae stars and Cepheids will be fully characterized with the cadence of the main survey. However, the vast majority will not be so "simple", and for these objects, departures from their normal behavior, the type of departure that would merit follow-up, will be very hard to identify in the main survey. With the Deep Fields we propose, we would establish an early baseline for a sample of stars that would allow us to identify non-standard behavior at least in these fields both during the course of the Deep Drilling, but equally importantly throughout the main survey as these fields are reobserved. The baseline established by Deep Drilling would allow one to recognize when objects have changed their behavior early enough to trigger observations of interesting objects when the character of the variability begins to change. This baseline is also important to form training sets for the complete survey, where the cadence is more limited.

1.4 Supplementary Science

There are 2 additional science opportunities that will be afforded by our proposed DDF project:

1) Along directions where lensing observations have been done before, LSST will make improvements of two types. The superb photometry will mean that events are discovered at earlier times in their evolution, allowing us to monitor them for up to 2 times longer. The photometry also allows us to more precisely determine the magnification at the times of LSST observations, which makes up

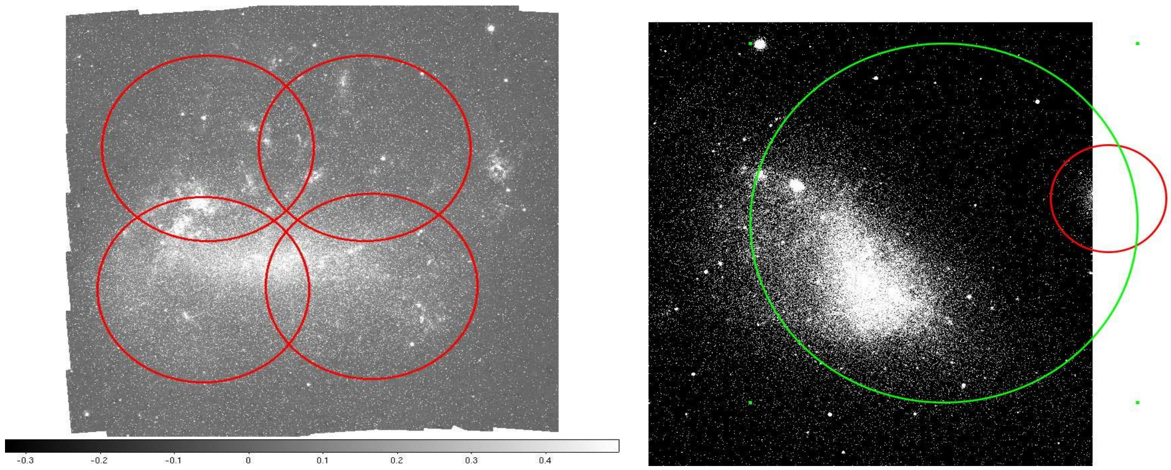

Figure 1: **(a)** Possible field coverage for LMC assuming a mosaic of 4 pointings. The circular regions indicated have a radius of 1.67 degrees. **(b)** Possible field coverage assuming a single pointing center for the SMC and 47 Tuc. The position of 47 Tuc is indicated by the red circle.

for the relatively low cadence of observations during the main LSST survey. Deep Drilling will allow for more efficient and reliable identification of events during the main survey, by characterizing the variability of stars in the field. It is interesting to note that, whenever the Deep Drilling observations take place, there will almost certainly be an event in progress. It may be in very early or late stages, but the opportunity for almost continuous monitoring during parts of the survey, and the ability to come back in about a month, will provide a combination of depth and cadence not achieved before.

2) The fast cadence in g would increase sensitivity to shock breakout of SN in galaxies behind the LMC/SMC and other transient behavior such as binary neutron star coelescence (Metzger et al. 2009) on hour timescales or objects such as GRB070610 (Kasliwal et al. 2008) on minute timescales.

2 Description of Proposed LSST Observations

2.1 List of Proposed Fields

1. LMC, 05 23 35, -69 45 22 We request 4 pointings in this region to cover much of the LMC. See Figure 1 for positions.

2. SMC and 47 Tuc, 00 38, -72 28 These coords are about halfway between the two - see Figure 1 (FOV is 3.5 deg and separation of 47 Tuc-SMC is about 2 deg)

3. IC 4651 17 24 49, -49 56

2.2 Motivation for Proposed Fields

We want to sample well-known and studied clusters and galaxies so that the parameters of distance, metallicity, and age are well determined. The LMC and SMC provide a large selection of different populations of stars. We want to compare both the types of short period variables in each case as well as building deep color-magnitude diagrams to compare with stellar evolution models. The observations of the Clouds will sample the brighter end of the H-R diagram (stars down to M$\tilde{+}$11), while the globular cluster 47 Tuc will reach to M_v of 15.5 and the open cluster IC 4651 to +19.5. To reach variability levels of 0.1 to 0.005 mag will require co-adds depending on the timescale of the particular variables but in general the main-sequence variables will be well-sampled in the Clouds while 47 Tuc and especially IC 4651 will reach all the way to the white dwarf pulsators. Due to the extent of the LMC (10.75x9.17deg), it will take 4 pointings to cover most of the galaxy. With the proximity of 47 Tuc to the SMC, one pointing should suffice to capture both. The open cluster IC 4651 needs only one pointing. This cluster was chosen as it has a well-observed main sequence, a close distance, small reddening (0.116 mag), a good placement in the southern sky and an estimated age of 1.1 Gyr. This is the optimum age to test the comparison of the white dwarf cooling sequences with and without convection and compare the age from white dwarf cooling to that from main-sequence evolution models (Meibom et al. 2002).

2.3 Observing Plan, Cadence, Filters, and Expected Depth

Our plan is to optimize the missed observing timescales of the general survey between 30 sec to 3 days and provide bluer colors than provided by the survey. To minimize time spent changing filters, the first hour would be spent in continuous integrations in g with the next observation a continuous observation in r. To fill in the time sequence correctly from 1 hr to 3 days, we will need to have the observation times scattered but concentrated within a week and then repeated several months later to eliminate the one day aliases. At a minimum, we would need to cover this time span twice to determine if variability is periodic rather than random.

The 15 sec images would be stacked to reach fainter magnitudes than the main survey. With 18 sec per integration (15 sec + 1 sec shutter + 2 sec readout), there would be 200 integrations per hour. Using the exposure time calculator with a B5-7 star with g mag of 25, 200 integrations would provide a S/N of 44 (0.02 mag). In the entire time for accumulation of data (16 hrs), the stacked images would reach 29th mag in g for a 10000K white dwarf (BB in the calculator) with S/N of 5. To sample variability, brighter stars with increased accuracy must be used (depending on the timescale and amplitude of the variability). For a g=21 mag white dwarf, 30 sec would give 0.01 mag accuracy and 90 sec would reach an accuracy of 0.005 mag.

2.4 Observation-Time Cost

We estimate it will take about 8 hrs to adequately sample a 3 day interval for each field, assuming a 10% sampling as a minimum for the longest periods (i.e. 72 hrs/10). We need 1 hr of continuous sampling to cover the shortest interval of minutes. That leaves 7 hours that would be spread over time. Subsequent to the continuous hour, the sampling would be in roughly 228 sec timescales (5 sec slew, 2x18 sec exp+shutter+read, 2 min filter change, 2x18 sec int) to cover g and r in each field. To cover the 4 LMC fields will take about 15 min. The 8 hrs would then entail about 200 phase points spread over 3-4 intervals with about 50 pointings/week in each interval.

With 8 hrs/field, 6 fields will require 48 hrs. To do this in 2 filters (g and r) will need 96 hrs and to repeat twice to validate periods will then take 192 hrs. If 2% of the LSST observing time per year (we estimate that would be about 58 hrs/yr) is used by this DDF project, then it would take about 3 years to accomplish our goals. It will require concentration of the time in one year to cover the 4 LMC fields together. Of course, weather and engineering problems would extend this time, but it should not take the 10 years of the survey. One field could be done in 6 months (we recommend the SMC and 47 Tuc to give early results on variability that can be used for identifications throughout the 10 years of the main survey).

3 Other Required or Relevant Observations

3.1 Other Required Observations

There have been over 250 orbits of HST time spent on 47 Tuc, going down to magnitude 30 so the population is mapped well but not the variability as the time sequence is erratic and accomplished over several days.

To accomplish several of the science goals will require followup observations, either dedicated campaigns on the stars identified, or spectroscopy to identify the variables precisely. This will be the case for the pulsating white dwarfs and some of the cataclysmic variables. Since CVs have emission lines, it will be possible to obtain low resolution spectra of 22nd mag with the next generation of 20-30m class telescopes. The followup for white dwarfs can be accomplished with photometry on 8m class telescopes.

3.2 Other Relevant Observations

4 Specific Needs for LSST and for Deep Drilling

4.1 Need for LSST

The main advantage of the LSST for this work is the large field of view, which allows for an unprecedented probe of stars of different ages and metallicities and temperatures. The ability to set the cadence counters the past surveys that were done with random sampling. The added depth of the ddf co-added images pushes the CMDs to several magnitudes fainter than the main survey will accomplish.

4.2 Need for Deep Drilling

The primary goal of these Deep Drilling observations is to fill in the shortest timescales of variability for stars (and background objects) that the main survey will be insensitive to, concentrating on blue variables which are not well-served by the choices of filter and cadence in the main survey. In addition, the deeper imaging in the DDFs will allow deeper CMDs than achievable with the main survey for comparison with stellar evolution models. Finally, this Deep Drilling will allow early characterization of all types of variable objects early in LSST's operational lifetime, which will enable a more complete exploitation of the main survey than would otherwise be possible.

5 Feasibility

5.1 General Feasibility

The depth and number of stars covered will depend on the seeing conditions due to crowding in the central regions of 47 Tuc and regions of the LMC such as the bar. Given the large extent of coverage of these objects, we can choose the stars to match the nominal conditions of LSST. We have listed limits in a conservative sense, using typical conditions at the LSST site with airmass less than 2, seeing about 1 arcsec.

5.2 Bright Objects and Extinction

There are clearly objects both in the Magellanic Clouds and in IC4651 which exceed the saturation limits of 15.7 in g, and 15.8 in r, but the regions of the images that will be affected by these stars are reasonably small, and the science we hope to achieve is focussed on fainter objects. As we have no specific star that must be covered, we can eliminate any problem objects from our study.

The foreground extinction to all of the fields is quite low. E(B-V)=0.08 for the LMC amd 0.04-0.07 for the SMC and 0.116 for IC4651 from the literature (e.g.Schlegel et al. 1998; Meibom et al. 2002). As we are dealing with orders of magnitude of stars in each of these fields, individual objects are not vital. The extinction does not affect the variability aspect of the project other than the faint limits of the objects chosen.

5.3 Unresolved Feasibility Issues

There are no unresolved feasibility issues of which we are aware.

6 Other Issues

6.1 Relevance to LSST Commissioning

As these fields will determine the variability of a wide range of objects, they will be useful for the identification and separation of transients from the rest of the variable sky.

This program is of great significance to early observations of LSST, as it will allow us to establish the time variability behavior of all classes of variable object behavior. The datasets thereby obtained can be subsampled in various ways to assure that objects and object classes are not being misidentified.

6.2 Other Relevant Information

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