Roadmap:
LSST Stars, Milky Way, and Local Volume Science Collaboration

Date: June 18, 2019

1 LSST Phase 1 Science Roadmap - Bulge subgroup v1.0, August 2013

Summary: This is version 1.0 of the LSST Bulge Science Phase 1 Roadmap. The Phase I document should identify the technical and scientific challenges for LSST Bulge work (without going overboard on the science) and to start to identify tasks for collaboration members in order to overcome these challenges on a timescale of a few years.

Based on input from the Bulge subgroup, we have identified a number of technical issues that are important to Bulge science with LSST. We also highlight some suggested investigations - mostly based on simulation and archival work - that we believe would allow LSST to become a unique machine for conducting scientific discovery about the Milky Way Bulge. This document is organized as follows:

1. Summary of Bulge LSST Science goals and match to LSST capabilities
2. Main technical issues these goals bring up
3. Investigations that should be performed / questions to answer at this stage.
4. Questions already arising for LSST development team
5. References cited
6. Figures
7. Appendix: more detail about the Bulge LSST Science goals

A note on editing: Feel free to email either the subgroup leads (Will Clarkson and Victor Debattista; wiclarkson@gmail.com and vpdebattista@gmail.com) or the mailing list (lsst-milkyway-bulge@lsstcorp.org) with suggested edits.

1.1 Overview of LSST Bulge science goals

These are kept deliberately broad at this stage (see Section 7 for more information), but point to the unique strengths of the Bulge as a test-case for Galaxy formation models:

1. Detailed balance of populations as traced by morphology, chemistry, kinematics and distance
2. The present-day mass distribution of the inner Milky Way as traced by Bulge star motions
3. Wide-field examinations of other sub-populations and objects of interest.

1.2 Match to LSST capabilities

If the numbers in Ivezic et al. (2008), the Science Requirements Document (SRD) and the LSST Science Book are realized for the Bulge populations of interest, these three science goals should be within the capabilities of LSST. For reference, those numbers are:

- Relative photometry: 5 mmag per-measurement rms (g,r,i), perhaps 50% larger for u,z,y (SRD Table 14)
- Absolute photometry: 10 mmag per-measurement rms, color zero-points accurate to 5 mmag rms (SRD Tables 15, 16)
- Relative astrometry: 10-15 mas per-measurement rms depending on separation (SRD Table 18)
- Absolute astrometry: 50 mas per coordinate (SRD Table 20)
- Pixel-scale and seeing: Pixel-scale $\leq$ 220 mas; at airmass 2, seeing-error 0.5 arcsec ($\gtrsim$ 2.3 pix; SRD Tables 10,11)
- Shortest possible exposure time: 5 sec, stretch-goal 1 sec (SRD Table 8)
- At r=20, predicted performance when measurements are combined over the 10-year baseline survey:
  - Proper motion accuracy: 0.14 mas/yr, Photometric error 0.005 mag (single-visit), 0.003 mag (stack)
  - These numbers come from from Table 6.6 and Figure 6.26 on Pages 193-195 of the LSST Science Book, v2.
  - Note that the 10-year baseline survey is likely to be rather more generous than Bulge observations (by a factor of several - see Section 2.3).
- For context, here are approximate apparent magnitudes for bulge populations of interest: MSTO roughly r$\sim$19.5 (r-band absolute magnitude about 4.0, plus distance and extinction), Red Clump giants roughly r$\sim$7.0 Note, however, that variations in the line of sight distance and extinction significantly broaden the observed distribution (X-shape alone leading to variation by 0.5 magnitudes or more; e.g. Saito et al. 2011).

However, most of the Bulge populations of interest are more crowded than the baseline LSST survey to which the above numbers apply (Section 2.1 and Figure 1). While a seeing-limited large-scale survey like LSST is likely to be transformative for Bulge science, to reach these science goals we do need to understand how the LSST performance numbers change towards the Bulge, and what strategy will successfully overcome any limitations of the current reduction plans.

1.3 Leading Technical Issues

1.3.1 LSST as complementary to Gaia towards the inner MW

LSST is supposed to smoothly extend the error-vs-magnitude curve of Gaia to fainter magnitudes (Ivezic 2008). Here are summary numbers for GAIA (de Bruijne et al. 2012 and Brown 2013), which are a bit more generous than Reyle et al. (2008; Figure 1).

- Gaia Astrometry OK up to about 1 million stars / sq. deg., corresponding to about 278 stars per square arcmin.

- Gaia Photometry OK up to about 200 stars per square arcmin
- Gaia Spectroscopy OK up to about 10 stars per square arcmin
- Brown (2013) indicates ∼800 stars / sq. arcmin "can be dealt with" - what does this mean for actual precisions in this regime?

For non-crowded regions (e.g. Science Book p193-195), LSST's precision starts to exceed Gaia's precision at r∼ 19.5 or so, comparable to the MSTO and sufficient to well-characterise red-clump giants already. However, this is unlikely to be realized in practice due to crowding; the GAIA - LSST handover magnitude may be somewhat brighter.

- Gaia performance: What will the true performance of Gaia be towards the MW Bulge in reality? See e.g. Figure 1.
- Gaia/LSST magnitude boundary: In crowded fields, at what apparent magnitude will Gaia's performance degrade and LSST be expected to "take over?" Is this transition magnitude fainter than, say, the fainter Red Clump Giants (RGC)s in most Bulge fields?
- Gaia's observing strategy: For those objects within Gaia's magnitude range of accuracy, how does Gaia's observing cadence map onto the science goals for LSST Bulge work?
- Gaia and LSST in overlapping brightness ranges: For the brightness interval in which Gaia and LSST overlap in coverage, what will LSST add to those objects? Should observations in this overlap magnitude range be scheduled for cross-calibration, in the crowded fields towards the Bulge?

1.3.2 Crowded-field Photometry and Astrometry

This was perhaps the most common technical response in the Survey amongst MWLV members! The performance specifications in the Ivezic et al. (2008) survey document and the SRD, are for regions that are not too crowded, although it does not appear that the collaboration has yet reached official consensus on what "crowded" really means. At the moment, the rule of thumb appears to be about 200 stars per square arcmin. This limit is reached before the Main Sequence Turn-Off in many fields towards the bulge (Figure 1).

Thus, reaching the MSTO will likely require pushing LSST's photometry and astrometry software to regions that are much more crowded than LSST's existing analysis stack was built to handle. Arising from this:

- What measurement approaches will work best for LSST Bulge crowded fields?
- Is rapid turnaround important for LSST Bulge photometry, or is a careful, if slower, analysis (taking, say, a few weeks to process) appropriate?
- Is rapid turnaround important for LSST Bulge astrometry?
- In what mode will crowded-field work be performed? Do we require optional tools that would be run on specific small regions, or is it essential instead to produce the photometric and astrometric catalog for all regions observed, no matter how crowded?

- What is the limiting depth required by the LSST Bulge science goals? To what source density (e.g. stars per square arcmin) does this correspond in real Bulge fields?
- Conversely, if we assume the baseline analysis software that will deliver photometry and astrometry for regions $<$ 200 stars / sq. arcmin, how does this impact the Science Goals? See e.g. Figure 1 in Section 6 below.
- If any science goals are precluded under the baseline scenario, does their resurrection deliver science of sufficient import to justify the extra effort developing crowded-field analysis tools?
- The LSST planning software already includes sophisticated tools to simulate stellar populations in the inner MW (its crowding predictions towards the plane were used to set the galactic latitude limits for the main LSST survey). How well do the predictions of these tools match reality? Are their predictions too conservative?
- One survey respondent recommended that astrometry not be treated as an afterthought, but be built in to analysis tools as a key requirement.

1.3.3 Observation setup (including total time, saturation issues)

How do the different science goals interact with each other when designing observations? Are some science cases excluded by others?

- Total observing time: Based on a quick query of OpSim (performed in June 2012), bulge fields were slated to receive one fifth the number of pointings per field when compared to the baseline survey (Figure 2). Assuming those numbers are still current, now is the time to advocate for a more suitable strategy. In particular:
  - Lower number of exposures per field is probably unimportant for deep stacks since the crowding is higher than baseline anyway.
  - However, for investigations requiring multiple exposures whatever the depth (e.g. proper motions, monitoring variable-object standard candles), the reduced total number of observations might prevent the desired science goal being reached.
  - How should observations be distributed along the total time allocation to maximize the science?
  - How many pointings per object are needed for a given science case?
  - Is there a strong enough case to request a larger total allocation time?
  - Saturation issues: What range of exposure times will allow both the bright and faint objects to be covered in the same campaign? What is the observing duty cycle as a function of exposure time? At what (if any) instrumental magnitude do persistence effects set in?
  - Cadence: How do the cadence requirements for the different science cases interact with each other? For example, can variable-object standard candles with very long periods (hundreds of days or longer) be monitored in an observing program that also

seeks short-period variables? In this example, if (say) a logarithmic cadence strategy is adopted, does this preclude other science?

  – What happens if the total allocation for Bulge science is reduced? Do we need to produce a contingency plan in this case?
  – Extinction and filter choice: Will extinction-correction rely on cross-matching to catalogs at other wavelengths? Or, does the requirement to correct for extinction drive a minimum number of filters for every observation?
  – Astrometry and filter choice: The Science book (Section 3.7) seems to suggest that the (r, i) filters will be best for astrometry. To pursue bulge astrometry, should a separate set of observations in a smaller number of filters be taken?

1.3.4 Calibration and calibration products

- What calibrations do we (the investigators) need to conduct our own specialized analyses of favorite regions?
- How will calibration products be made available to the community?
- For how long and in what format will supporting observational telemetry (e.g. telescope temperature, observed seeing, etc.) be maintained? WIll this be available to the investigator?

1.4 Investigations suggested for LSST Bulge science

The above considerations suggest the following investigations. We are aware that in several cases this might be as quick as a literature or archive-search.

1.4.1 Simulation

Baseline capability of LSST in crowded fields with the currently-planned measurement software:

- Simulate observations towards a variety of regions towards the Bulge, at a variety of exposure-times, with input properties of interest (e.g. variability, proper motion, extinction), and attempt to recover these using the existing software stack.
- Use this to estimate random and systematic effects on photometric and astrometric completeness and precision as a function of the stellar crowding.
- This dataset might already exist - were these simulations performed to set the Galactic Plane avoidance limits for the baseline survey already?

1.4.2 Simulation + Archive

Science impact of crowding limit: Using crowding limits obtained from 4.1 above or otherwise, examine available source-catalogs towards the bulge to determine, under those crowding limits:

- What is the region of avoidance with current LSST software, in galactic coordinates, as a function of magnitude?

- What stellar populations in and towards the bulge become unavailable using this limitation?
- What science does this preclude?

1.4.3 Simulation

Observing strategy for saturated objects in crowded fields:

- Simulate observations for a well-chosen sample of fields towards the Bulge, at a range of exposure times from 1s to 15s, to estimate:
  - What range of exposure times is needed to attain high-precision measurements of the bright stars in the field of view?
  - What artefacts are bright objects expected to produce in the longer exposures, and how can their effects be characterized and mitigated?
  - How do measurement systematics vary with exposure time?
  - What is the tradeoff between observing efficiency and exposure time?

1.4.4 Literature, Simulation, ground-based data

Performance of existing crowded-field photometry and astrometry tools on likely LSST observations towards the Bulge:

- How do existing crowded-field measurement techniques scale to LSST-like applications?
- What scale of simulation is practical before LSST goes on-line? Can we expect to run a complete suite of imaging-sets under a variety of reduction strategies?
- How do changes to analysis software fit in with the LSST software pipeline as it currently exists?

1.4.5 Simulation combined with existing data and archives): Fidelity of LSST's simulation software applied to Bulge regions:

- Compare LSST simulation predictions with existing datasets towards the Bulge to determine how well these simulations reproduce actual data.
- A large number of potential comparison datasets, from broad-shallow to narrow-deep
- The ImSim/OpSim team might already be doing this...

1.4.6 (Simulation, literature, archives): Harder numbers for science requirements:

- Use existing archives / literature to map figures of interest across the bulge region (e.g. number of stars per square arcminute down to a limiting depth as a function of apparent magnitude and color). Do this for several populations of interest (e.g. Red Clump Giants).

- Modeling: To make further progress on (for example) mass models of the Bulge, what size of tracer-star sample is needed?

- Modeling: Under the current best bulge models, what is the prediction of proper motion as a function of line of sight distance for sight-lines towards the bulge? What does this imply for proper motion precision requirements?

1.4.7 (Simulation): Observing strategy to best meet science goals: dithering, pointings

- Simulate observations with different dithering strategies to determine the best strategy under likely time allocations.

1.4.8 (Archive, Simulation): Appropriateness of existing catalogs for LSST Bulge operations:

- Determine to what extent successful observations require information from external catalogs to succeed. Determine how the quality of these catalogs changes over the Bulge, and thus what (if any) effect variation in external catalog quality will hinder science observations towards the Bulge.

1.4.9 Literature, personal communication): Complementarity to GAIA

- Find out the current best estimate for GAIA's performance towards the Bulge. Do hard numbers exist from the GAIA team for what happens to GAIA's astrometric and photometric precision in highly crowded regions? What did Brown (2013) mean by "[$\sim$800 stars/sq arcmin] can be dealt with"?

1.4.10 (Observation, archive): Precursor data

- Determine what precursor data already exists to answer the questions raised in this document.

- As a sub-group, if necessary regions of parameter-space are NOT probed by these observations, determine a consensus plan to apply for further precursor data.

- We want to avoid the situation where members of the LSST Bulge sub-group submit proposals that compete with each other for similar precursor data.

1.5 Questions and wishlist arising for those developing the LSST facility and its software

1.5.1 Existing simulations:

- Improved knowledge desired on how to access simulated datasets.

1.5.2 Running custom simulations

- What computer hardware is required to run LSST simulations?
- What is the key factor determining the variation of time elapsed for a simulation on the same hardware – the total number of sources, or something else?
- Tutorials are desired on how to set up and run the simulation software.

1.6 Existing and planned analysis software

- Tutorials on the Data Management system
- Detailed understanding of the uncertainties (their production and propagation) through the LSST simulations and measurement routines
- Tutorial on running the LSST pipeline on non-LSST data
- What are the current capabilities of point-source software for LSST? What are its limitations (e.g. maximum array-size)?

1.6.1 External catalogs for LSST photometry

- How reliant is LSST calibration on cross-matching to external catalogs?
- What capabilities for cross-matching with external catalogs, can we expect?
- Bulge regions may have more sources per square arcmin than typical for the baseline survey. How does the time required to crossmatch scale with catalog size? How are multiple possible matches handled?

1.7 References cited:

1.8 Figures

1.9 Appendix

more detail about LSST Bulge science goals: To keep the focus of the Phase I document on technical investigations to be performed, much of the detail on the science goals in v0.2 has been moved here. Goals: i. Detailed balance of populations as traced by morphology, chemistry, kinematics and distance:

- Morphology: Uniform, accurate positions and magnitudes across sufficiently wide field to characterize X-shaped structure. Depth: at least 2 magnitudes below the red clump giants, and ideally down to the Main Sequence Turn-off (MSTO).
- Chemistry: Multi-color photometry, with uniformly calibrated photometric zeropoint in each region and filter. Depth as per Morphology. Cross-match with NIR catalogs (e.g. 2MASS, particularly VVV) to account for interstellar absorption.

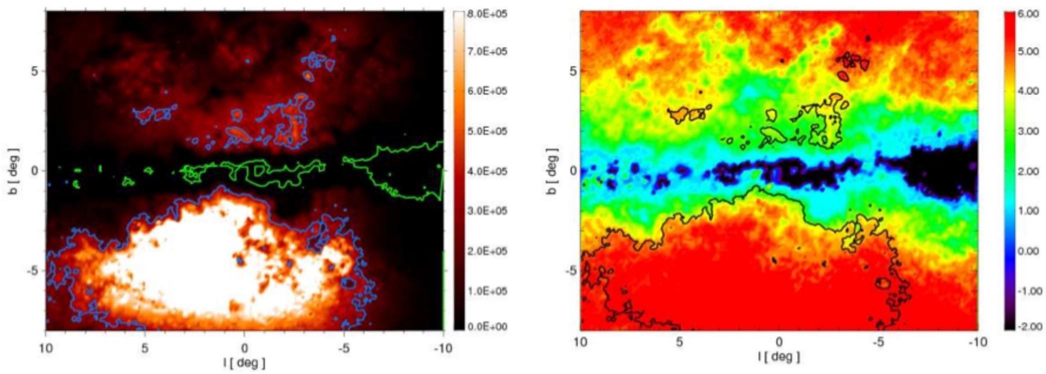

Figure 1: Figure 1a: This shows predictions of the Besancon model for the inner Milky Way, in the context of GAIA's performance estimates as of 2008. The left-hand panels show spatial density (stars per sq. deg.), the right shows the absolute magnitude (in G-band, approx SDSS r) of stars just reached at their assumed limiting magnitude. This figure shows GAIA's astrometric fields (the GRP and GBP instruments – limiting magnitude G=20). The blue contour shows the iso-density of 600,000 stars per square degree (167 stars per square arcminute, or a little less crowded than LSST's baseline limit at present). The green contour shows the iso-density of 100 stars per square degree, or 0.028 stars per square arcminute. Notice that in G-band, it is the bright area away from the plane that is in the region of avoidance, not the dark area covering the plane itself. This is Figure 3 of Reyle et al. 2008.

- Kinematics, particularly membership probabilities: Tracer stars (e.g. the Red clump giants) may overlap significantly with existing and planned spectroscopic catalogs. However, proper motions from LSST itself should allow all stars to be assigned membership probabilities. Requires proper motion precision better than 1 mas / yr, and ideally better than 0.5 mas/yr.

- Distance: Photometric variability will allow standard candles (including but not limited to RR Lyraes, eclipsing binaries) to trace the populations along line-of-sight distance. Requires monitoring cadence sufficient to characterize these tracers.

- Bulge, Thick Disk, inner halo, and Sgr Dwarf: A uniform multiband survey with high astrometric quality that spans the entire inner Galaxy will offer the quantitative means to define how the bulge is related to the inner disk and halo, and to settle whether any "classical" spheroidal-like bulge is separable from the bar. The complexity of the Sgr dwarf populations can be separated from the generally much closer Galactic populations.

ii. The present-day mass distribution of the inner Milky Way (MW), as traced by the Bulge star motions:

- Proper motions: Produce a catalog of proper motions accurate to ¡1 mas/yr (ideally ¡0.5 mas/yr) for all objects down to the MSTO. Use the wide-field, multi-sight-line nature of this catalog to test models of bulge formation and evolution. E.g. what size of "classical-bulge" population is consistent with the observed velocity dispersion as a function of position and depth? Are the putative kinematic substructures (e.g. Nidever et al. 2012, see also Howard

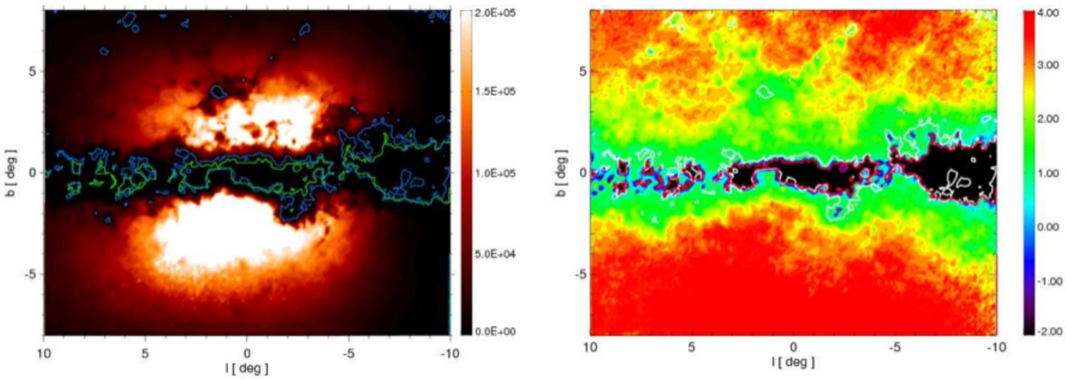

Figure 2: Figure 1b: As Figure 1a, this time for GAIA's spectrometer (RVS). This instrument has limiting magnitude G=17 and a much more stringent crowding limit: 30,000 stars per square degree, or about 8.3 stars per square arcminute. With these performance numbers, only the very inner (extincted) plane is accessible to GAIA's RVS spectrometer. This is Figure 4 of Reyle et al. 2008.

et al. 2009) real? What is the total mass felt by Bulge stars, as a function of cylindrical coordinates (R, theta, phi)? Requires carefully-designed survey strategy.

- Line-of-sight motions: Merging with existing and planned spectroscopic catalogs 3D measured motions for a massive sample of Bulge stars.

iii. Wide-field examinations of other sub-populations and objects of interest:

- Tidal streams and kinematic substructures that pass through the inner MW: With such a wide-field catalog, LSST should provide important tracer information for merger remnants and other discrete features in phase-space.

- How many Globular Clusters (GCs) exist in the inner MW? VVV is already uncovering more GCs in the inner MW, what scientific investigations will LSST enable for these objects?

- Hypervelocity stars: Observe rare, fast-moving objects ejected from the very inner MW, and use them to constrain stellar formation and ejection processes near Sgr A*.

- Is there a "nuclear" population?

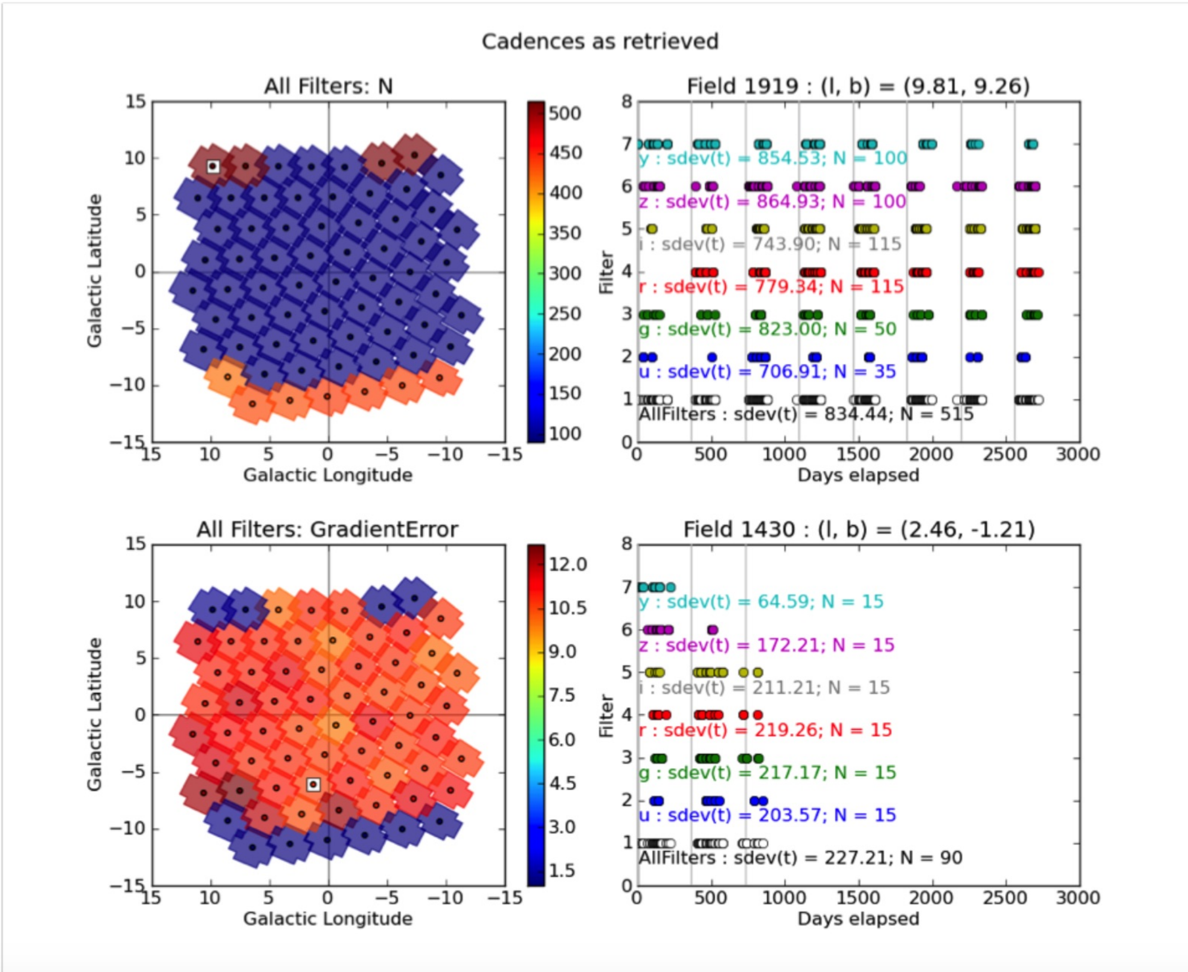

Figure 3: Figure 2a: This figure shows a basic example of the kind of strategy assessment that could be performed to optimize observations. OpSim was queried for all regions close to the galactic center (-15 ¡ l ¡ 15 degrees) using OpSim as of June 5th 2012, and the dates of all retrieved observations were used to estimate the impact of proper motion measurement due to time allocation and the concentration of observations under the retrieved strategy. Top-left: Map of fields in galactic coordinates, color-coded by the total number of observations per field. Bottom-left: Map of fields, this time color coded by the formal error on proper motion based on the samplings retrieved from OpSim. Top-right and Bottom-right show time-series for the samplings for example fields (top = baseline survey, bottom = example bulge field) under the OpSim strategy at the time. All else being equal, the proper motion precision for the Bulge strategy at the time is a factor 8 worse than the baseline survey just by virtue of the lower time allocation and its concentration, but there are obvious steps that could be taken to improve matters (such as spreading the same observations over the full time baseline of the survey).

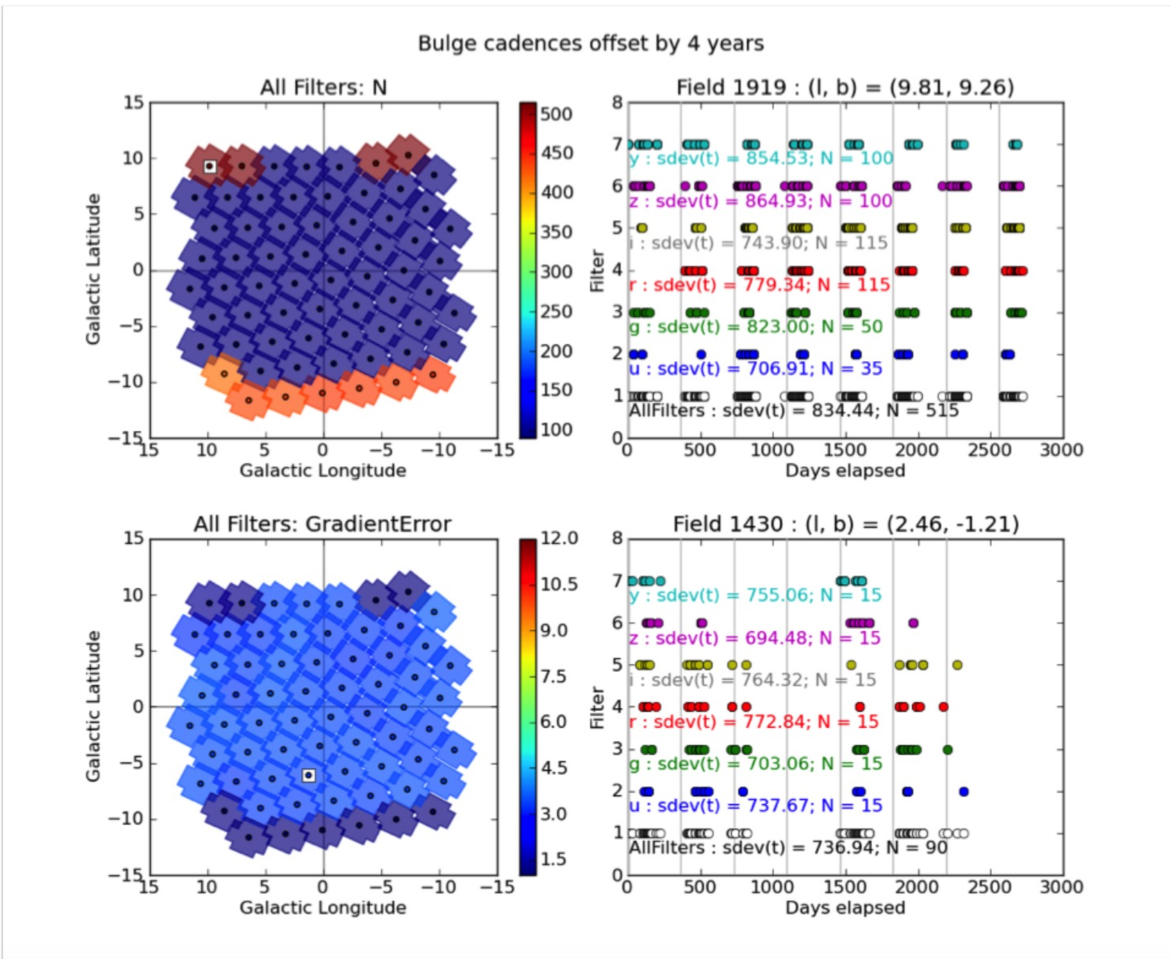

Figure 4: Figure 2b: As Figure 2a, this time with the original Bulge allocation spread along the same time interval as the baseline survey (note the total number of exposures for the Bulge is the same as for Figure 2a). The formal gradient error has already been reduced significantly, to a factor 2-3 over the baseline survey.

2 Roadmap for Star Clusters Subgroup

Kevin Covey, Jay Strader, Jason Kalirai, & Doug Geisler for the subgroup

2.1 A short summary of LSST science related to star clusters

Star clusters are a critical component of many of the science goals listed in the LSST Science Book (Ivezic et al. 2010). They offer unique environments where stars with a range of masses but similar ages and chemical compositions can be found. One class of studies aims to leverage these relatively simple stellar populations to understand the dependence of the stellar mass function and stellar evolution on metallicity and age (e.g., Sec. 6.5-6.6, 6.9-6.11; LSST Sci. Book). Their known properties and distances also motivate calibration work on many kinds of variable stars and transients (e.g., Sec 8.9; LSST Sci. Book).

A separate class of studies is focused on using star clusters to trace the star formation history, chemical evolution, and galactic structure of the Milky Way, nearby galaxies (including the Magellanic Clouds), and even more distant galaxies extending beyond the Local Volume (e.g., Sec. 6.2-6.3, 6.6, 7.2, 7.3, 7.8, 7.10, 7.11; LSST Sci Book).

2.2 Critical technical elements for LSST star cluster science

The unique advantage of LSST for studies of star clusters is the promise of deep, accurate, and homo- geneous multi-band photometry and astrometry for the entire southern sky. This directly enables both (i) an enormous sample of clusters and (ii) spatially complete data for each cluster, neither of which are generally possible in current datasets.

This promise can only be realized if LSST delivers photometric and astrometric measurements that are uniform, or at least well-behaved, over the wide range of crowding conditions and variable foregrounds and backgrounds that can occur within a single cluster and across different Galactic components.

Specifically, we identify the following critical technical elements as most relevant to star cluster science with LSST:

- The impact of source crowding and homogeneous backgrounds on the precision and depth of LSST photometry and astrometry.
- The performance of LSST's deblending and multi-epoch source association algorithms as a function of seeing and in crowded or nebulous fields.

2.3 Near-term investigations to retire risk for LSST star cluster science

Over the next year, the core members of the Star Cluster Working Group will use simulated LSST data products and precursor datasets to test the expected performance of LSST. Specifically, we plan to:

1. Use the ImSim pipeline to generate synthetic LSST images of crowded fields. Use these to establish the quality of star cluster color-magnitude diagrams—and their utility for testing specific aspects of stellar evolution models—using LSST's photometry and astrometry. Image morphology statistics will also be used to test star–galaxy separation. (J. Kalirai)

2. Obtain the best existing examples of overlapping ultra-deep ground-based starcluster photometry with HST images (e.g., NGC 5466; Beccari et al. 2013), using the "ground truth" provided by the HST catalogs to empirically assess the expected photometric uncertainties and incompleteness in LSST data. (J. Kalirai)

3. Calculate the proper motions uncertainties—both absolute and internal—that LSST will be able to return for typical Galactic star clusters, using both 10-year LSST baselines and longer HST to LSST baselines. These metrics will be compared to Gaia's expected performance as a function of magnitude and crowding to delineate the opportunity space for LSST in this area. (J. Strader)

4. Acquire new, wide-field multi-epoch ugriz photometry of dense and nebulous clusters in the Galactic plane. Process these images with the LSSTstack to quantify photometric precision as a function of local background and assess the fidelity of source association among the epochs. (K. Covey)

The primary person responsible for each task is listed above, but we expect that much of the effort will be collaborative both within the subgroup and with members of other relevant subgroups.

3 Notes towards a roadmap for the Galactic Structure and ISM sub-group

We have identified three major topics that came out of discussions among the Galactic Structure and ISM subgroup members. We present a number of specific questions that our subgroup would like addressed by the larger collaboration and/or project as well as some specific projects/goals that our subgroup plans to address over the next year.

3.1 Crowded field photometry

Technical overview: The stated limit from the project for the LSST processing is 200 stars/arcmin^2, or 0.056 stars/arcsec^2. Given that the median seeing at Cerro Pachon is 0.7 arcsec FWHM, the effective beam size is i π * $(0.7/2.35)^2$ = 0.28 arcsec^2.

Thus the proposed LSST limit is at 64 beams / source, or at $\sim$half the 30 beams / source confusion limit.

Implications for Galactic Structure science:

1. In what fields do we hit the proposed limit and the confusion limit as a function of band and Galactic coordinates for a single 15-second exposure? Action: We propose to organize an effort to estimate these values based on empirical data rather than simulated data, the latter of which are based on extrapolations.

2. What are the Galactic Structure science goals that require the fields having densities greater than 200 stars/arcmin^2 but less than the confusion limit? Action: This depends on how many fields are above that and where they are.

3. What model does ImSim use to create the Galactic Disk and Bulge stellar populations? Has this been tested at, e.g. low Galactic latitudes? Action: We can actually correct the ImSim using results from (1).

3.2 Astrometry [feedback from the DAWG]

The following questions came from members of the sub-group – we summarize the most important aspects of them in hopes of geting answers/feedback from the project:

1. Will the project assume responsibility for crowded field photometry and astrometry software?

2. Regardless of the project's support for crowded fields, should the science collaborations investigate alternative algorithms?

3. Should there be (or is there already) an ensemble of ImSims upon which the science collaboration members can try their algorithm and then compare their results against the "truth" (inputs to ImSim)?

4. What are the mechanisms for ensuring that certain features/capabilities are part of ImSim, the photometric pipeline or other project-wide software/tools?

Specifically, one of our members (D. Monet) reports that astrometric studies show that the ImSim does not mimic real data and that the astrometric errors grows as a function of separation. Also, the generation of 20 simulations that differ by only the seed used for the random number generator results in changes in the sky background of a factor of 30. They go from 0.1 to 3 times the value listed in the SRD.

3.3 Y4-band

There was some discussion in our sub-group about the performance of the y-band filter. Specifically, some users were concerned about the ability to calibrate out water vapor. Some of the specific cases where this may be important have clear overlaps with the low-mass star (and other) sub-groups but we summarize some of the discussion and specific questions below.

The main science cases that came up were motivated by the need for creating a color calibration of the M dwarf photometric metallicity scale and the identification of cool subdwarfs with the y-filter in combination with griz. These calibrations could directly lead to examining the distribution and scale height of M dwarfs as a function of metallicity and potentially probe the contribution from extragalactic streams and/or other halo object.

Potential Issues with the y-band filter:

1. Water vapor – an unresolved problem in the y4-filter is the highly time variable effect of water vapor and whether it can be removed – and if so, at what precision.

   Action: Members of our sub-group were curious if there exist time series spectra that would allow our sub group (or in tandem with others) to assess how easily the y4 band can be calibrated and what the empirical solution is to this concern. If these data don't exist, are there plans/ability to acquire these data? If the data do exist then one of our sub-group's action items will be to investigate the calibration and precision of the y-band filter (see (2)).

2. Metallicity calibration and identification of low-mass subdwarfs – our sub-group is committed to assessing how the y-filter (irrespective of (1)) will affect identifying and classifying the very metal poor halo M dwarfs accurately (disentangling temperature and abundance effects) as well as creating a useable photometric metallicity scale. The current SDSS gri color-color diagrams show significant overlap among metallicity classes of low-mass stars. And while most of the SDSS objects have spectroscopy, almost all of the extremely faint LSST stars will not.

   Action: Our sub-group has identified a number of questions that will lead some of our effort of the next year. These include (but are not limited to): Is there any way to increase the photometric accuracy in the classification and identification of metal-poor, low-mass stars? What are the quantitative limits to our precision with the current LSST setup (including the y4 filter)? Are there other observations that we can persue that might help answer these questions? Members of our sub-group have done some modeling using existing spectra. However, there are limited data for the coolest, lowest mass, and most extreme subdwarfs. These extreme stars are the ones near the hydrogen-burning limit that will ultimately tell us about the bottom of the mass function in the early history of the Galaxy. Therefore, one additional action item is to acquire additional low-mass subdwarfs to continue modeling LSST photometric products.

4 LSST Near Field Cosmology Roadmap

The LSST Near Field Cosmology subgroup focuses on using stellar substructure throughout the Milky Way and Local Volume as a probe of the underlying CDM cosmology. This includes searches for dwarf galaxies, tidal streams and other coherent features in phase space using the properties of individual stars. Examples include searches for ultra-faint galaxies based on overdensity of main sequence stars, searches for substructure using RR Lyrae variables, or searches for moving stellar groups using proper motions.

Searches for Milky Way substructure will allow critical new constraints in several areas. A more complete census and map of the distribution of satellites around the Milky Way sheds light both on the formation of satellite systems and the nature of dark matter halos that are able to host such low-mass galaxies. Finding tidal debris beyond 100kpc and out to the virial radius of the Milky Way will open a window on the more recent accretion history of the Galaxy, as well as the accretion of objects on more radial orbits in particular. Debris in the outer Galaxy also promises a powerful new probe of the mass distribution around the Milky Way in regions of a dark matter halo that have been largely unexplored for any galaxy in the Universe.

4.1 Overview of LSST NFC Science Goals

- Mapping Milky Way substructure, including dwarf galaxies and stellar streams using main sequence stars out to $\sim$300kpc
- Map of Milky Way substructure using more luminous tracers (BHB, RRL) out to 800 kpc
- Search for substructure in tangential velocity field out to 25 kpc (60 km s$^{-}1$ precision).

4.2 Scientific and Technical Issues

We discuss below issues that go beyond the LSST design specifications.

1. StarGalaxy Separation: For apparent magnitudes beyond $r \sim 22$, the number of unresolved galaxies relative to stars rises dramatically. StarGalaxy separation is critical and improvements in StarGalaxy separation will likely have the most significant influence on the degree to which the above science goals are achieved.

   StarGalaxy separation will be done using both color and morphological criteria. There is general consensus that these two type of criteria remain separate in the LSST catalogs, allowing users to combine them in different ways for different science goals. combined for specific science goals. There is a desire to see as many measures relevant to StarGalaxy separation as possible. Preferably as a probability, or some index like (χ^2, ν) that is transformable to probability.

2. AllSky Query Capability: Search for Milky Way substructure, particularly tidal streams, may be one of the few sciences cases that requires full survey data access and cannot be accomplished on smaller data chunks. This is unlikely to be possible in SQL on LSST servers. An SDSSLike Casjobs interface is both necessary and sufficient for this.

3. Variable Stars: The NFC group is primarily interested in RR Lyrae, but additional variable stars include W UMa stars, δScuti, Miras and Cepheids are of interest. There was general agreement that current LSST cadance is sufficient for these searches. Important flags to search for variable stars include the Stetson J, K, and L indices, as well as the median magnitude, skewness, kurtosis, von Neumann index, and linear fits to magnitudes vs. time.

4. Flags for diffraction spikes, ghosts, etc: Searches for substructure depend critically on photometric uniformity. Need to have a catalog flag indicating the degree to which a source may be a product of (or affected by) diffraction spikes or ghosts. It is important that these flags are provide for each data epoch.

5. Proper Motion Flags: Both straightline measurements as well as with parallax folded in, with a χ^2 for each. This would be good both to identify nearby stars as well as improve reliability of the proper motions of distant stars with too many fitting parameters.

6. Completeness Estimates: Many NFC science goals will require estimates of the sample completenesses as a function of magnitude for point sources in each color, at every position on the sky. This involves artificial star tests over an appropriate range of seeing, crowding, and for the appropriate number of exposures that go into each data release's average photometry. This will be particularly true for coadded data products.

5 Towards a Roadmap for LSST Magellanic Clouds Science

Knut Olsen, with direct contributions from Nitya Kallivayalil, Beth Willman, Doug Geisler, and Ben Williams

5.1 Introduction

The LMC and SMC are the nearest large galaxies to the Milky Way and represent fundamental testbeds for investigations related to many stellar astrophysical topics, from studying the star formation process, to the physics of variable star populations, to the physics of galaxy interactions, and to calibrating the cosmological distance scale.

The Clouds are some of the bestGstudied galaxies in the Universe, yet nevertheless consistently have the power to surprise. A recent surprise is that the Clouds, which have long been thought of as closely bound satellites of the Milky Way, appear to be on first infall, or at most have made a small number of close passages, based on proper motion measurements (Kallivayalil et al. 2006a,b; Besla et al. 2007, Piatek et al. 2008, Kallivayalil et al. 2013). We have also seen evidence that the LMC has accreted a significant mass in stars from the SMC (Olsen et al. 2011), which may indicate that the LMC and SMC collided directly with each other 100 Myr ago (Besla et al. 2012), a discovery that relied on the proper motion work. The HI tidal streamers that connect the LMC to the SMC and Magellanic Stream are kinematically linked to the accreted SMC stars, and thus may have formed in this collision; the streamers converge on the location of 30 Doradus in the LMC (Nidever et al. 2008), indicating that 30 Doradus may be an interactionGinduced star formation event. Moreover, the stellar debris left behind by the SMC could naturally explain the microlensing event rate (Besla et al. 2013) seen towards the LMC by e.g. MACHO and OGLE.

The Magellanic Clouds are also now known to extend to much larger radius than known before, through several pencilGbeam studies. Majewski et al. (2009) found spectroscopicallyGconfirmed KGgiant LMC stars at large distances (R $\sim$ 22 or 19 kpc), while Saha et al. (2010) found that the LMC exponential disk extends past 12 disk scale lengths. In the SMC, Nidever et al. (2011) traced K giants to $\sim$11, with possible evidence for a stellar halo. These studies are based on exploration of 1 of the relevant area of sky. There is thus a vast area that remains to be explored for hidden Magellanic Clouds structure, with implications both for understanding the history of the Clouds and the formation of the Galactic halo.

There are many other recent exciting discoveries in the Magellanic Clouds that have not been mentioned here. The point of mentioning the few above is to demonstrate that 1) in the Clouds, astrophysical problems are often connected across broad areas of study, 2) Magellanic Cloud populations cover a very large area of sky, and 3) highly precise measurements, such as produced by the work on LMC and SMC proper motions, have the power to fundamentally alter accepted understanding.

5.2 LSST:relevant Magellanic Cloud Science Objectives

Magellanic Clouds science potentially covers a very broad range of topics. Some of the topics that the MC working group suggested of being of greatest interest are:

1. Mapping the Magellanic periphery. Magellanic Cloud populations are now known to extend out to 20 degrees from the parent galaxies. Whether these populations are related to stellar

halos, extended disks, or tidal debris is not known. The HI Magellanic Stream extends over 200 degrees of sky (Nidever et al. 2010). LSST will excel at finding stellar populations down to very low effective surface brightness through deep photometry of individual stars. It will also provide a vast sample of RR Lyrae to trace potential structures in three dimensions.

2. Proper motions and internal motions. The most precise proper motions in the Clouds so far are those based on HST observations of narrow fields centered on background QSOs (Kallivayalil et al. 2006). LSST has the potential to deliver precise proper motions over large swaths of the Clouds. Given the complexity in the internal kinematics, these would be a boon for piecing together the effects of the LMC and SMC recent interaction history. As a demonstration of what is potentially possible, CasettiGDinescu et al. (2012) found a significant proper motion difference between the spectroscopically identified accreted SMC stars in the LMC and the general LMC background, using groundGbased measurements.

3. The star formation and chemical abundance history of the Magellanic Clouds. Linking detailed knowledge of these to detailed knowledge of the interaction history of the Clouds will be a big step forward in understanding what has driven the evolution of the Clouds' stellar populations.

4. Stellar variables. The Magellanic Clouds contain the full array of known variable stars, with the big advantage that their distances are well constrained. They also give important insight into variable star physics through their low metallicities compared to the Milky Way. Important variable star classes are regular variables such as RR Lyrae, irregular variables for which the Clouds provide complete statistical samples of events such as flares, variables which are discovered at wavelengths other than optical, such as xGray binaries, and stars which experience eclipses by other stars or, potentially, planets.

5. Star clusters. The Magellanic Clouds are thought to contain thousands of star clusters, only a fraction of which have been discovered and cataloged. Star clusters are very useful as precise markers in age and metallicity in the history of star formation in galaxies, and critical for understanding questions related star cluster dissolution and star formation mode. LSST has the potential to provide a complete catalog of Magellanic Cloud clusters to great depth, including clusters at large radius from the parent galaxies.

5.3 Scientific and technical issues

The first big scientific issue is to identify those science cases that are uniquely enabled by LSST. In the case of the Magellanic Clouds, the existence of other largeG scale optical surveys such as the Magellanic Clouds Photometric Survey (Zaritsky et al. 2000), DENIS, and the Dark Energy Survey, as well as the existence of wideGfield cameras such as DECam, can give the impression that the science cases outlined can be done by other means. While it is certainly true that past and current surveys are working on the problems above, LSST has the potential to open qualitatively new discovery spaces through:

1. Deep, multiepoch coverage of nearly the entire southern sky. We have already shown that the search for Magellanic Cloud populations is one that potentially covers thousands of square

degrees. While DES and the DECam survey SMASH (Nidever et al. 2013) will be potential bonanzas for the study of the Magellanic periphery, they probe only to g 24, the single'epoch depth of LSST, and have limited time information. LSST stacked photometry will go several magnitudes deeper, yielding the potential to discover structure with extremely faint equivalent surface brightness, and allow for the use of variable stars as three dimensional probes of structure.

2. Precise proper motions. Much of our recent advance in revealing the complexity of the Magellanic Cloud interaction history stems from the factor of 10 improvement in proper motion that the HSTGbased work provided. If enough attention is given to the Clouds in the LSST cadence, LSST has the potential to reveal the internal motions of the Clouds in unprecedented detail.

3. Precise photometry. All of the work described above depends on photometric measurements. Given the scale of typical PIGled projects and calibration efforts, it is rare for projects to achieve ¡2 photometric accuracy in the absolute sense. The LSST science requirement is to deliver 1 absolute photometric accuracy in single images, with a stretch goal of 0.5 . If these numbers can be achieved for the Clouds, and in particular improved upon by averaging multiple measurements, metallicities based on photometry, ages from comparison to isochrones, and reddening measurements all stand to improve by large amounts. As demonstrated by the phenomenal results from Kepler, the realm of high photometric accuracy has the potential to deliver many surprises.

Given the discovery spaces that will make LSST unique for Magellanic Clouds science, there are a number of technical issues that need to be addressed as part of a roadmap for the Magellanic Clouds:

1. What cadence is needed for full Magellanic Clouds coverage to achieve the desired gains in proper motion and photometric accuracy? The main bodies of the Clouds, in the current baseline, are not part of the WideGFastGDeep survey, but are covered at reduced frequency.

   (a) To evaluate the astrometric needs, we can quantify what HST/GAIA can do per single star, and what requirements that imposes on LSST observing in the MCs. Dave Monet has been doing a lot of work within the context of the DAWG to come up with metrics that best define astrometry errors. Nitya summarizes from Monet: we want to (a) give specific examples of good and bad parallax cadences, and also (b) develop metrics that can predict good and bad cadences so we can optimize. So far, the former has shown that there is a factor of 2 difference in recovered errors based on cadences that otherwise take the same amount of telescope time, and also as far as (b) goes, we don't have a good metric so far, and all the various metrics one could come up with seem to be correlated.

   (b) To evaluate the level of photometric accuracy that we achieve in the Clouds and the resulting cadence requirement, we can use the DECam observations that are getting underway to begin answering this question.

2. What limit on the photometric and astrometric accuracy is crowding going to impose on us?

(a) Past observations and the ongoing DECam surveys can help answer the question of the fundamental limit imposed by crowding.

(b) How crowded images will get handled by LSST DM is a separate question, and will require interaction with the DM Stack with comparisons to crowded field photometric packages such as DAOPHOT.

(c) A related question is whether there is the potential for a limited set of excellent seeing observations in the Clouds, and whether that would adversely impact the global cadence.

3. What is the best approach to starGgalaxy separation, particularly important for studying the Magellanic periphery?

   (a) The SMASH survey has begun to address this question to the level of r 24, but the growth in the galaxy luminosity function at faint magnitudes means that we'll probably need a dedicated effort to test this to the depths that LSST will achieve.

4. How do we accommodate the need for artificial star tests?

5. What other datasets need to be crossGmatched against the LSST catalog for the project to succeed? a. We can begin constructing a list pretty easily.

6. Are there particular projects that would be compelling/easy to do early in the survey, perhaps during commissioning?

7. What are the typical database queries and data services that we will be using? a. This will need to be explored. There are efforts underway to provide a testbed for potential services that would be useful to interact with here.

6 LSST Solar Neighborhood Collaboration Roadmap Planning Document

Adam Burgasser, John Gizis, Todd Henry, Sebastien Lepine, Michael Liu, Keivan Stassun

6.1 Purpose of this Document

- Identify the technical and scientific challenges for LSST in studying low mass stars and the solar neighborhood
- Identify tasks for collaboration members that can overcome these challenges on a timescale of a few years.
- Organize collaboration members to perform assigned tasks before data delivery

6.2 History

- 22 October 2013 (AJB): Version 1 released to working group
- 1 November 2013 (AJB): comments integrated and sent to leads
- 2 January 2013 (AJB): comments from WIllman
- 14 August 2014 (MCL): cleanup of edits

6.3 Introductory Material

6.3.1 Key target populations:

- Solar neighborhood: classically d $<$ 10-25 pc, extend to $\sim$100 pc in LSST era
- Young stars: clusters, moving groups & associations
- Old stars: subdwarfs, thick disk and halo objects, globular clusters (??)
- Brown dwarfs: $<$0.07 Msun, including free-floating planets
- White dwarfs (and other remnants?)
- Binaries and higher order multiples: q $>$ 0.1, resolved and unresolved
- Low mass companions: q $<$ 0.1, resolved and unresolved

6.3.2 Definitions & Acronyms used in the text

Mass scales:

- $>$ 2 Msun = “massive” 0.5-2
- Msun = “solar type”
- 0.1-0.5 Msun = “low mass” (LM)
- $<$ 0.1 = “very low mass” (VLM)
- $<$ 0.07 Msun = “brown dwarf” (BD)
- $<$ 0.013 Msun = “planetary-mass object” (PMO)

CPM = common proper motion DBMM = deuterium burning minimum mass, nominally 0.013 Msun for solar Z GC = globular cluster HBMM = hydrogen burning minimum mass, nominally 0.07 Msun for solar Z LBMM = lithium burning minimum mass, nominally 0.06 Msun for solar Z [M/H] = metallicity MF = mass function MG = moving group MS = main sequence star NIR = near infrared PM = proper motion PMS = pre-main sequence star RPM = reduced proper motion RV = radial velocity SED = spectral energy distribution SpT = spectral type ToO = target of opportunity WD = white dwarf YA = young association YMG = young ($<$100 Myr) moving group

6.4 Roadmap Plan

- Phase 1 (deadline: 1 Nov 2013): Highlight technical/scientific challenges that must be worked on to conduct our science with LSST.
- Phase 2 (deadline: TBD): Develop a strawman path towards overcoming those challenges before LSST data start flowing.
- Phase 3 (deadline: TBD): raise interesting precursor science that can be done by you/can get grant support now.

6.5 Identified inputs required for planning (priorities TBD)

- precise LSST filter definitions
- photometric sensitivity per band for single and deep pointing
- astrometric performance (proper motion & parallax) per band as a function of brightness, spectral type, # of epochs, time baseline and sky location (see preliminary results from DAWG = Differential Astrometry Working Group)
- LSST imaging cadence(s)
- LSST PSF shape model (including saturation)
- galactic model

- spectroscopic followup resources
- theoretical atmospheric models of LMs/VLMs/BDs as a function of Teff, log g, [M/H], clouds, circulation that span LSST bands
- empirical templates of sources (MLTY standards, subdwarfs and young dwarfs)
- evolutionary models and forward modeling samples for BD population
- flare emission model to determine LSST response/sensitivity to LM flares
- cloud spot model to determine LSST response/sensitivity to BD weather patterns
- An (updateable) list of currently nearby LMs/VLMs/BDs (ra, dec, spt, distance, predicted LSST mags, age/cluster, etc)
- Quantification of completeness as a function of SpT and distance

6.6 Primary science investigations: Objectives, issues and tasks

6.6.1 Volume-complete (astrometric) sample of extended solar neighborhood

definition: all sources for which parallax measurements can be made with LSST

interested collaborators: Adam Burgasser, John Gizis, Todd Henry, Michael Liu, Keivan Stassun, Sebastien Lepine.

interface with other collaborations: Galactic Structure and ISM:

objectives:

- distance-limited sample of solar neighborhood (to be defined)
- 6D phase space determination (XYZUVW)
- LM/VLM/BD MF determination
- Full physical, atmospheric, multiplicity characterization of complete sample
- map evolution of ultracool objects through the M/L, L/T, and T/Y transitions.

issues:

- number of epochs and cadence required to distinguish proper motion and parallax
- overlap with GAIA (minimal/non-existent for L/T/Y dwarfs)
- astrometric calibration and astrometric uncertainties
- distance limit for completeness
- brightness limit for completeness (e.g., astrometric accuracy vs. brightness)
- detection of/contamination by astrometric binaries and unresolved binaries

- followup spectroscopy: science goals & data needs (sample size, resolution, etc.)
- RV measurements
- kinematics (statistical) ages?
- handling crowding along Galactic plane (e.g. image differencing, pixel-level modeling)

tasks to do:

- need a current list of stars (perhaps broken down by SpT) w/in XX pc to assess where the big holes in completeness are - both X and SpT regime that we care about will need to be defined (Todd?), will require some "population synthesis" modeling for BDs (Adam?), as well as kinematic considerations (Paul Thorman?)
- summarize existing compliations from Pan-STARRS solar neighborhood work (Mike)
- model astrometric binary contribution/contamination
- comprehensive follow-up of sources - RV, high resolution imaging
- examine model parameter sensitivity through LSST photometry
- Lists of proper motion selected M dwarfs already exist to at least 100 pc. A local kinematics model (velocity space distribution), combined with luminosity function, will determine how many stars are missing from the current census as a function of magnitude, and e.g. what the distance range of GAIA will be for stars of different magnitudes. This will determine the "sweet spot" (in distance/luminosity) for LSST to reap the most results.

tasks completed:

6.6.2 Deep sample of LM/VLM/BD dwarfs

definition: sources inaccessible to parallax

interested collaborators:

interface with other collaborations: Galactic Structure and ISM: The Galactic Bulge: Near Field Cosmology:

objectives:

- extremely large sample (10^6?) for population analysis
- galactic stratigraphy - chemical abundances, kinematic "heating", structural features out to XX kpc
- galactic scaleheight as a function of mass (constraint on potential and formation mechanisms)
- search for thick disk/halo objects

issues:

- spectroscopy won't be viable for whole sample - photometric selection criteria, RPM (limits)
- most sensitive filter likely to be Y(4): will single-band detections(+astrometry) be useful?
- limit to which PM is viable
- metallicity characterization through photometry alone

tasks to do:

- simulate yield along different sitelines, with variations in scale height, MF, etc.
- calibration sample for metallicity effects tasks completed:

6.6.3 Ultracold brown dwarfs (late-T and Y dwarfs)

definition: BDs cooler than $\sim$1000 K =¿ T5 and later, any distance
interested collaborators: Adam Burgasser, Michael Liu
interface with other collaborations: Galactic Structure and ISM:
objectives:

- detect a significant population of T and Y dwarfs for MF determination
- kinematic characterization (6D phase space)
- identify extreme TY populations (halo, young, cloudy, etc.)
- measure how optical SEDs change across K$->$KCl, Na$->$NaCl/Na2S transitions

issues:

- sensitivity of LSST filters to cool T and Y dwarfs - detection limits, expected numbers assuming an MF
- compare expected performance to WISE. e.g. LSST will not be competitive in this area, at least for discovery of the coolest objects.
- most sensitive filter likely to be Y(4): will single-band detections(+astrometry) be useful?
- possible to spectroscopically follow these up? (necessary for classification, RV)
- minimal information set required to eliminate contaminants (e.g., RPM, color sets, necessary filters)

tasks to do:

- examine photometric classification and contamination

tasks completed:

6.6.4 Halo dwarfs across the substellar limit

definition: dwarfs with halo kinematics and/or $[M/H] \leq -1$

interested collaborators: Pat Boeshaar, Adam Burgasser, John Gizis, Michael Liu, Sebastien Lepine

interface with other collaborations: Galactic Structure and ISM:

objectives:

- Halo mass function across substellar limit
- measurement of H-burning "age gap" (z-dependent HBMM)
- confirmation of BD formation in low metallicity environment
- metallicity effects on low mass spectra/photometry
- multiplicity of halo LM/VLM/BD dwarfs
- map out velocity space distribution
- search for substructure in LM halo
- discovery of extremely metal poor ($[Fe/H] < -3$) VLM dwarfs
- Pop III VLM dwarfs?

issues:

- game selection: target max V (anticenter and vertical ring)
- efficient and robust selection: RPM, metallicity effects, contaminants
- mapping LSST photometry to physical properties - templates? models?
- spectral characterization?

tasks to do:

- model discovery rate using MF forward modeling + atmosphere models (colors)
- identify templates for SED characterization
- estimate the local density of halo subdwarfs and their expected magnitude/color distribution, based on the existing census.
- Calculate the distance range over which LSST will be detecting M subdwarfs of different subtypes, what can be expected of their proper motion distribution, and determine the distance range required to assemble statistically significant samples of various metallicity classes (i.e. halo sub-populations).

tasks completed:

6.6.5 Co-moving populations

definition: members of well-defined clusters, young associations, and moving groups in the Solar Neighborhood

interested collaborators: Michael Liu, Keivan Stassun, Sebastien Lepine

interface with other collaborations: Star Clusters

objectives:

- complete MFs for YAs/MGs in VLM/BD regimes]temsearch for new YAs/MGs, associated with “isolated” stars or as completely new groups.
- identify ultracool dwarf benchmarks over a broad range in age ($\sim$1 Myr to $\sim$1 Gyr)
- build up sample of ultracool dwarf benchmarks (i.e. with well constrained ages, compositions, distances)
- disk/jet/accretion properties of young group members (e.g., TWA)

issues:

- probability of cluster membership: CPM, π/Dest, phot/spec properties, UV/X-ray, variability?; are RVs necessary?
- how to we obtained activity diagnostics to examine youth? (e.g., Halpha)
- Will u photometry be sufficient to characterize UV emission excess?
- disentangling multiple memberships (overlapping nearby groups)
- what is lowest mass we can probe to in a given group?
- mapping observations to physical properties (Teff, logg, masses, ages)
- mass sensitivity limit for nearest GCs, older clusters (including age effects)
- The young local pop will start to merge with ScoCen - how do we interface with the Star Cluster subgroup?

tasks to do:

- determine requirements on RV measurement for cluster association
- confirm and compile properties of nearby YAs/MGs/GCs
- predict mass limits for various groups item characterize impact of disk/jet emission/envelope obscuration on LSST (+2MASS +WISE?) photometry, map color terms to physical measures

tasks completed:

6.6.6 VLM Multiples

definition: all multiples with a VLM/BD primary, including PMOs
interested collaborators: Adam Burgasser, Michael Liu
interface with other collaborations
objectives:

- measure the wide separation binary fraction and separation distribution via CPM
- measure the small separation binary fraction via astrometric binaries
- detect eclipsing binaries; if sufficient number, measure binary fraction at close separations
- use these measurements to constrain separation and mass ratio distributions, binary fraction all as a function of mass/SpT
- use astrometric and transit binaries to determine orbital distributions (eccentricity, mass ratio)
- use transit binaries to test VLM/BD structure models
- robustly determine higher-order fractions for LM/VLM/BDs
- measure planetary companion fraction to VLM/BDs

issues:

- what is the transit detection rate for various cadences? what cadence would optimize?
- what are the astrometric requirements for CPM assessment as a function of binary separation, distance, mass ratio?
- how can color/photometry winnow candidates for wide binaries?
- how reliable is photometric information for constraining mass ratios? separate question for */*, */BD and BD/BD pairs
- what constraints can wide VLM binaries have on DM distribution?

tasks to do:

- ensitivity limits for these three cases
- simulate discovery fraction and efficiency for each class of systems (simulations of population, detectability for eclipsing/astrometric/resolved binaries)
- interface astrometric requirements with halo PM, parallax requirements
- false positive simulation for wide binaries
- RV followup of astrometric, transit binaries

- compile specific predictions of VLM formation models on binary stats (e.g., co-ejection for wide multiples)
- model wide separation limits due to DM substructuring, differential tests with massive, LM, & VLM wide binary distributions

tasks completed:

6.6.7 VLM/BD companions to stars

definition: resolved LM/VLM/BD/PMO companions to stars
interested collaborators: Michael Liu
interface with other collaborations:
objectives:

- measure the companion fraction at low q to various stellar types
- characterize "BD desert" at wide separations
- build up sample of ultracool dwarf benchmarks (i.e. with well constrained ages, compositions, distances)
- test brown dwarf evolutionary models and model atmospheres using benchmarks
- identify wide companions to planet-hosting stars (Kozai mechanism)

issues:

- confirmation: CPM (limits), color, other?
- how to deal with saturated primaries
- what is the companion volume sampled as a function of separation (distance effects)?
- what is the minimum resolving angle?
- sensitivity as a function of angular separation from a star and brightness?
- how to account for orbital alignments in detectability, separation distribution
- defining robust search samples - PM-selected?

tasks to do:

- simulate discovery fraction with various assumptions of companion fraction, separation distribution, orbital properties
- CPM limits
- define input search sample; resources to characterize primaries
- contamination rate as a function of separation (w/ & w/o CPM confirmation)
- resources for follow-up

tasks completed:

6.6.8 Magnetic, atmospheric and structural photometric variability in cool dwarfs

definition: analysis of photometric variability associated with magnetic and atmospheric phenomena (separating off eclipses/transits)

interested collaborators: John Gizis, Keivan Stassun

interface with other collaborations: transients and variables working group

objectives:

- characterize period distribution of VLM dwarfs
- characterize flaring rate and flare energy distribution of M and L dwarfs
- characterize spot properties: covering fraction, Tspot-Tphot
- distinguish between magnetic emission mechanisms (spots/aurorae)
- characterize weather-related phenomena

issues:

- relation of (lower-precision) LSST results to (higher-precision) Kepler & TESS results?
- cadence necessary for typical flare and rotation rates
- what follow-up is required to characterize flares and/or quiescent emission?
- Will targets of opportunity be needed to catch flares in action (is there even time to do this? what can we learn from GRB community?)
- photometric precision required for detection of X% spot/cloud var
- what different bands sample in terms of cloud and flare properties
- how could multi-color photometry constrain properties of flare source
- can multi-color photometry constrain cloud properties (e.g., grain size distribution)
- follow up to directly measure magnetic activity indicators (RAVE?)

tasks to do:

- use a list/database of currently known VLMs within X pc, and use this as in input catalog to see what the cadence of these sources would be.
- model flares in LSST photometric bands as function of flare temperature
- predictions of "magnetic" variability for spot vs. auroral models
- model cloud variability in LSST photometric bands as function of v sin i, covering fraction, Tcloud-Thole, viewing angle, latitude distribution, differential rotation
- discovery rate of flares for a given flare rate/energy model and cadence

tasks completed

6.6.9 White dwarfs

definition: all degenerates, including those not identified by parallax

interested collaborators: Sebastien Lepine

interface with other collaborations: Galactic Structure and ISM

objectives:

- identify and characterize halo WD population
- characterize the luminosity function across populations
- identify main-sequence + WD binaries

issues:

- Are u-g/g-r colors sufficient to identify most field white dwarfs?
- To what extent will the search for WDs have to rely on proper motions (i.e. reduced proper motion detection).
- How efficiently can WD+MS binaries be identified based on color alone?

tasks to do:

- Calculate the local WD density based on the current census, and estimate how many WD can potentially be detected by LSST as a function of magnitude.
- Build expected color-magnitude distributions based on predicted luminosity functions.
- Estimate proper motion detectability of halo WDs, how deep one needs to go to assemble a statistically significant sample.

tasks completed:

7 Roadmap for the Variable Stars subgroup of the LSST Stars, Milky Way, and Local Volume Working Group

Joshua Pepper (Lehigh University) and Leslie Hebb (Hobart and William Smith Colleges)

7.1 Context

The science of variable stars is effectively split between the Transients & Variable Stars (T/VS) Work- ing Group and the Stars, Milky Way, and Local Volume (S/MW/LV) Working Group. This subgroup will serve as a bridge between the two Working Groups to maintain a focus on this important scientific area.

7.1.1 Collaboration with Transients & Variable Stars Working Group

One of the key questions about our subgroup is what science will be primarily covered by the S/MW/LV group versus the T/VS group. In general, extragalactic transients like supernovae and GRBs will be dealt with by the T/VS. That still leaves eclipsing, rotational, pulsating, and flaring stars. So far most of the work on pulsating stars (i.e. RR Lyrae) has taken place within the T/VS group, and so we will only briefly discuss such variables in this roadmap. However, we should remain careful to prevent any scientifically interesting variable type from falling through the cracks between the two working groups.

7.1.2 Classification of Variables

A very broad issue that both Working Groups (T/VS and S/MW/LV) will have to deal with is the nature of LSST classification. No science can be accomplished in the area of variable stars unless we resolve the question of how the LSST pipeline will classify the enormous variety of variable stars, and at what level. Will stars be simply identified as Variable or Not Variable based on some confidence level of a given statistical test? Or will the classification go deeper, into identifying stars as periodically versus non- periodically variable, or even further into sorting them into specific categories, such as eclipsing, pulsating, etc.? This is arguably the single most important question for variable star science with the LSST. There are existing efforts to approach this problem, including the EB Factory project (Stassun et al. 2013) at Vanderbilt University1, and efforts led by Josh Bloom (Bloom et al. 2012). However those efforts will have to be more fully developed for the variable star science goals of LSST. Current variability surveys such as the Palomar Transient Factory and the Catalina Sky Survey offer precursor data sets that can be used for testing classification methods.

We have included in this document the basic science questions that we hope to address with LSST, many of which were included in the Science Book. The majority of these science questions require large populations of the following variability types:

- Eclipsing binaries
- Rotational variables
- Flaring stars

- Transiting Exoplanets
- Non-periodic variables
- Pulsating stars (including RR Lyrae, Cepheids, etc.)
- Serendipitous variables

Each science area has a set of technical questions that need to be answered or criteria that need to be met in order to achieve the stated aims. In general, we need to understand the technical capabilities of the LSST pipeline, the various limits on the data and the tools available for analysis.

7.1.3 Stellar Properties

Additionally, what information will be provided by the default LSST stellar characterization process? Will the system only provide LSST coordinates, magnitudes, and colors for stars, or will any effort be made to extrapolate effective temperatures or other properties, even at a crude level? Especially important will be the incorporation of data from previous catalogs, including SDSS, 2MASS, and GAIA into the LSST catalog. That being said, we have listed below specific questions related to different types of variable stars. Many of the issues raised in the first section, eclipsing binaries, are broadly relevant for all variability types.

7.2 Technical questions needing answers

7.2.1 Eclipsing binaries

- Eclipsing binary classification: Are variability classifications being made by the LSST software? How detailed and reliable will that classification software be? What level of detail will be provided (i.e. eclipsing versus pulsating variable, or down to determination of detached or contact EBs?)
- Photometric precision: What will be the per-exposure and per-visit photometric precision of the observations as a function of apparent magnitude for all filters? The details are especially at the bright end and faint end.
- Spectroscopic follow up: How many EBs will be bright enough to follow up spectroscopically? What resources are required to derive masses for these systems, and how will that effort be organized? Does a prioritization system need to be developed?
- Clusters targeted by LSST: What known open clusters, globular clusters, and young associations will LSST target? Coordination with the S/MW subgroup on clusters to determine the list of probable cluster members. Do we need to set up a system to investigate these cluster stars specifically?
- Photometric precision in crowded regions: What are the effects of crowding expected to be on photometric precision and the ability to confidently identify sources of variability?

7.2.2 Rotational variables

- Same technical questions as EBs
- Long-term systematics: It will be important to investigate what possible long-term systematics might be present in the LSST photometry at the relevant periods.

That includes especially diurnal and monthly timescales, since the non-continuous photometry means that we need to be concerned about identifying period aliasing.

7.2.3 Flaring stars

- Reliability of the uncertainties on individual data points: Properly identifying flare events and distinguishing them from non-astrophysical sources (like cosmic rays) will be crucial. Therefore, having reliable uncertainties that are realistic and believable for all data points is important. How do we achieve this?

7.2.4 Transiting Exoplanets

- Photometric precision even more important: Photometric systematics will be an even bigger prob- lem for transit detection that EB detection. While the long gap between subsequent observations will make red noise less of a concern, it should still be examined and characterized.
- Understanding the uncertainties: The small number of in-transit observations from an LSST light curve will necessitate a great deal of confidence in every observation, so the LSST systematic noise in every filter must be carefully characterized.
- Cadence and total number of data points: Which fields will have enough data points to detect exoplanets? Will there be sufficient observations of the regular survey field or are the deep drilling fields the only ones of relevance? Simulations will be required to determine this.

7.2.5 Non-periodic variables

- Real-time alerts: A question for those interested in such cases is whether LSST will provide alerts regarding the possible beginning of major, previously unknown eclipsing or brightening events to allow other telescopes to target these objects in real time.

7.3 Science Questions: Detailed

7.3.1 Eclipsing Binaries

According to simulations by Prsa et al. (2011), LSST will observe $\sim$24 million EBs over the course of the mission. For $\sim$28% (or 6.7 million), LSST photometry alone can be used to characterize the system. The properties derived from the LSST photometry alone are Period, T2/T1, (R1 +R2)/a), ecos(ω), esin(ω), and sin(i). However, the vast majority of targets will be too faint for spectroscopic follow up. Therefore, no mass information will be available for these systems.

The analysis by Prsa et al. (2011) was preliminary, using an early version of the OpSim, without the deep drilling fields, and without an analysis of the multiband photometric capabilities of LSST. It also employed a crude method for detecting binary periodicities, and was not tested for false-positive results. It should therefore be updated in a number of ways.

The primary value of LSST for EB science is threefold. The enormous numbers of EBs detected will permit thorough statistical analysis of EB properties across a number of stellar populations. It will also permit the detection of very rare or extreme systems. Previous studies such as Raghavan et al. (2010) or Pojmanski et al. (2005) typically include at most tens of thousands of EBs, so the LSST EB catalog will include objects three orders of magnitude rarer than those known.

LSST will enable the astronomy community to probe the following stellar populations: (1) Open clus- ters and young associations, (2) Extremely metal-poor or metal-rich populations, including the thick disk and the Halo, (3) Certain populations in the LMC and SMC, (4) Globular clusters, (5) Low-mass stars, and (6) Brown Dwarfs.

With access to the populations listed above, LSST will permit astronomers to examine questions such as:

- EB period distribution within and across the populations.
- Evolution of binary fraction.
- Fundamental stellar properties for the bright end of the discovered EBs, testing structure and evolutionary models.

7.3.2 Rotation periods of stars

Gyrochronology is becoming a mature discipline for age determinations of stars. Rotational modula- tion may be detected by LSST for stars in clusters or other populations that have as yet been too faint for gyrochronological analysis.

7.3.3 Flare stars

The SDSS and Kepler flare studies can be replicated to an extent with LSST.

7.3.4 Exoplanets

There is some potential for LSST to discover large numbers of transiting exoplanets (Beatty & Gaudi 2008). There is both enormous potential in this area but also tremendous difficulties. In general, the LSST photometric precision will only allow the detection of gas giant planets, and effectively none of the stars observed by LSST will be bright enough for radial velocity confirmation. Furthermore, there will be huge numbers of false positives.

On the other hand, if these difficulties can be managed, statistical analysis would allow the discovery of planets in many of the stellar populations described in the EB section above. Of particular interest would be low-metallicity populations, very low-mass stars and brown dwarfs, and potentially even extragalactic populations such as the LMC. Even tentative discoveries, if carefully considered, can provide insight into planet formation and evolution mechanisms (see http://arxiv.org/abs/1302.6244).

One intriguing possibility is that some number of tentative LSST planet detections can be followed up via ground-based photometric tools (see an analysis of that possibility in Dzigan & Zucker (2013)). Also, even though the stars will be too faint for RV confirmation of the planetary orbits, low-precision RV can help eliminate false positives and determine some host star properties. However, just how many resources would be needed, even for a sliver of the LSST transit candidates? That question must be addressed. Also, statistical validation of LSST transit candidates will require a tool similar to the BLENDER method developed for Kepler, but extensively adapted for LSST.

7.3.5 Non-periodic variables

In addition to the broad categories of supernovae and GRBs, there are other types on non-periodic variability worth investigating. Flare stars are one type, and another is apparently singular, non-repeating eclipse events. Cases of those have been observed a number of times in the past, but their non-repeating nature complicates efforts to understand them. However, some recent detections, especially Mamajek et al. (2012) and Rodriguez et al. (2013), suggest that these events hold a great deal of promise, providing insight into star formation, binarity, and exoplanets.

7.3.6 Pulsating Stars

As stated at the beginning of this document, it appears that the T/VS working group is taking the lead on covering pulsating stars. That certainly includes categories of perennial interest, such as Cepheids and RR Lyrae. It will be the responsibility of this subgroup to take the lead to liaise with the T/VS working group to convey information between the working groups and seek cooperation, and also to ensure that no variable type of interest is ignored.

7.3.7 Serendipity and the Unknown

Finally, an unprecedented survey like LSST will inevitably discover some kinds of new and completely expected phenomena. We should plan for such discoveries in whatever way practical. Most importantly, the native classification tools that LSST ends up employing must be prepared to recognize objects whose variability does not fit into any known category and set them aside for further investigation. Crucially, the system must be tuned so as to not overwhelm the community with slight variations on known object types, but not to be so stringent as to miss potentially exciting discoveries. The process will certainly require extensive testing and optimizing, but one of the crucial early steps in such a process will have to be the assembly of all types of known variability, both to aid the classification process and to define the regime of "unknown". It will be necessary to work closely with the LSST OpSim and ImSim teams to explore this task.