LSST Cadence Note: A census of dwarf satellites and substructure around the Magellanic Clouds

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Abstract

In this Cadence Note, we present survey strategy recommendations for Vera C. Rubin Observatory (Ivezić et al., 2019) observations to maximize the discovery of satellite galaxies, streams, and halo substructure in the periphery of the Magellanic Clouds, with focus on the region of the South Celestial Pole. This region is crucial for understanding the contribution and influence of the Magellanic Clouds, the Milky Way's most massive nearby companion galaxies, to the structure of the halo.

1 Science Case

The Magellanic Clouds (MCs) have always had outsized importance for astrophysics. They are critical steps in the cosmological distance ladder, they are a binary galaxy system with a unique interaction history, and they are laboratories for studying all manner of astrophysical phenomena, giving us front-row seats to observe the life cycles of galaxies.

Over the past decade, our view of the MCs has changed substantially. We now have evidence that they fell into our Galaxy's halo only recently (Kallivayalil et al., 2013), that they have a satellite galaxy system of their own (Bechtol et al., 2015; Koposov et al., 2015), that their mass is such that they have measurable effects on the Milky Way and its halo (Erkal et al., 2020; Garavito-Camargo et al., 2020), and that their binary interaction (Besla et al., 2013) has produced a field of stellar debris spreading over at least a 20 degree radius from their centers (Saha et al., 2010; Majewski et al., 2009; Nidever et al., 2018; Belokurov & Erkal, 2019). These discoveries increase the relevance of the MCs to the study of the Milky Way and galaxy formation and evolution generally, as they are probes of the effects of interactions on galaxy structure and star formation, of galaxy host properties on their satellite populations, and of group infall on the galaxies themselves and on the Milky Way system.

LSST has the opportunity to provide the ultimate map of the extent and structure of the Magellanic system. Our current maps are based on complete surveys of relatively rare red giant tracers or on partially filled surveys of the much more numerous main sequence turnoff (MSTO) stars, down to depths of $r \sim 24$. With photometry from image stacks as faint as $r \sim 27$, LSST will be able to detect extremely low surface brightness structure and dwarf companions of the MCs. From single-epoch photometry curves, LSST will detect both RR Lyrae and δ Scuti variables associated with this structure, giving us a 3D map of the MCs, their surroundings, and their satellite populations. Moreover, LSST's multiband coverage will characterize the ages and metallicities of these stellar populations, for the clearest possible view of the Magellanic system and its relationship to the Milky Way.

Because of their southern declination, coverage of the South Celestial Pole (SCP) region is crucial to detecting the satellite system and extended structure in the periphery of the MCs. Moreover, this region must be observed for us to have as complete a picture as possible of the Milky Way satellite system and its halo structure. Hargis et al. (2014) predicts that LSST may discover hundreds of low-luminosity dwarfs ($M_V > -3$), which would mean at least tens in the $\sim$1000 deg^2 of the SCP; however, DES has shown that dwarf discoveries may be higher in the neighborhood of the MCs, and non-uniform distributions of dwarfs are to be expected, making observations of the SCP especially crucial. In this note, we evaluate the families of LSST simulations from OpSim for their ability to discover dwarf satellites and streams in the SCP region.

2 Cadence comparisons and recommendations

The detection of dwarfs and streams in the SCP will be done by detecting overdensities of resolved stars against the sea of contaminating foreground stars and unresolved background galaxies. The typical approach is to use a filter in color-magnitude space with a profile targeted for metal-poor stars at a specified distance, over a specified spatial scale. Thus, to estimate our ability to detect dwarfs and streams with LSST, we:

1. Extracted the expected number of background galaxies in g and i using the `GalaxyCountsMetric`, and the expected foreground stellar density from the `StarDensityMetric`.

2. Computed the number of contaminants over an area of 1 arcmin^2, scaled for the area in $g - i, g$ color-magnitude space spanned by our matched filter and by the expected fraction of remaining galaxies after star/galaxy separation cuts are applied.

3. Calculated the number of target dwarf/stream stars we would need to observe through our matched filter in order to reach a Poisson detection threshold of 10σ, at fiducial distances of 100 and 300 kpc.

4. Used a simulated luminosity function for a 10 Gyr stellar population with metallicity [M/H] $= -1.5$ to scale the number of target stars to the equivalent luminosity and

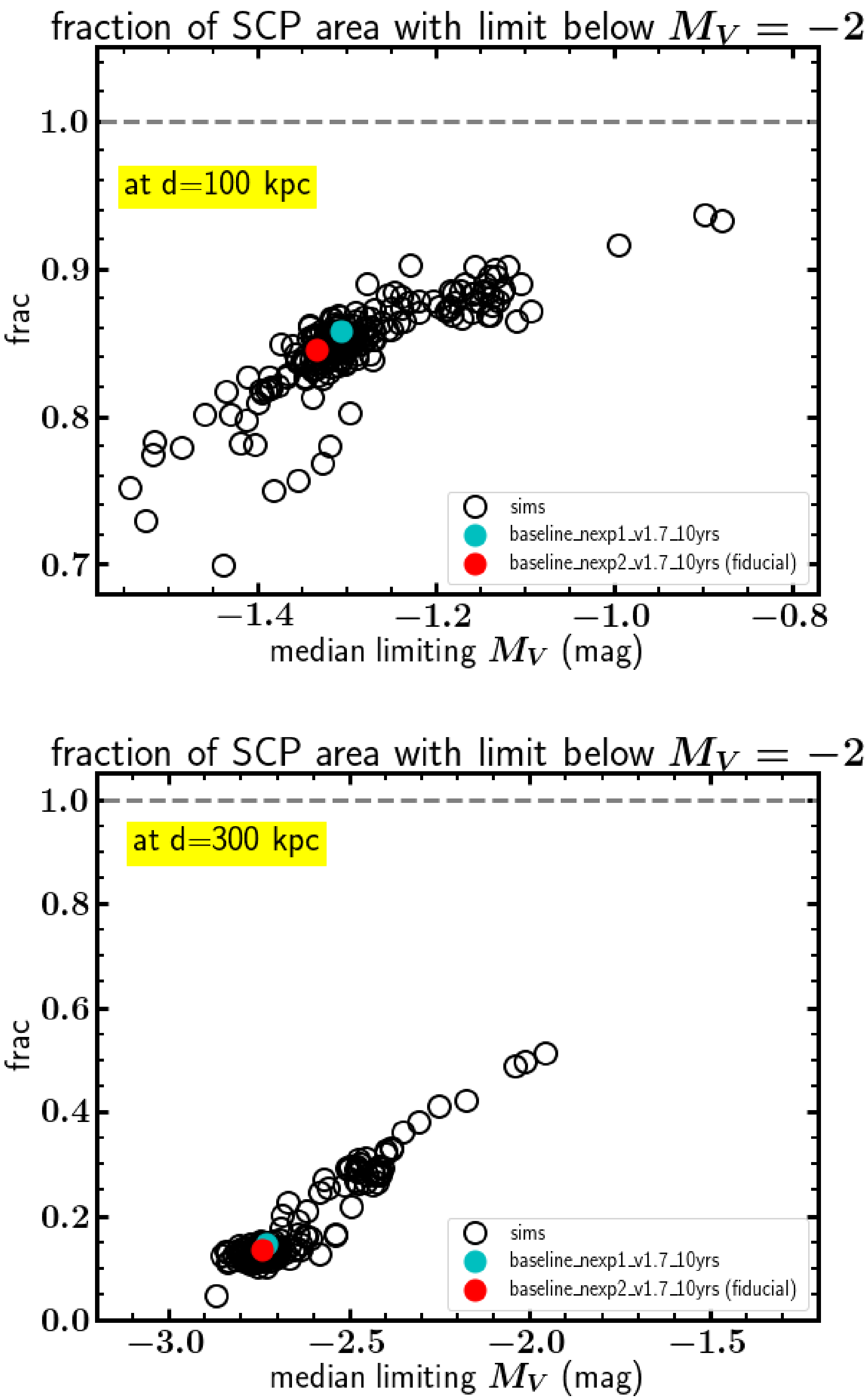

Figure 1: Both panels show the fraction of the SCP area (i.e., Dec$< -60°$) in which a given OpSim has limiting dwarf detection magnitude of $M_V > -2$. The top panel shows this fraction for simulated dwarfs at distances of 100 kpc, and the bottom panel shows the same for 300 kpc. Fiducial OpSims are highlighted as colored points.

surface brightness of the parent dwarf galaxy/stream.

5. For each OpSim run, computed the fraction of the SCP area within which we can detect dwarfs with $M_V < -2$, the median limiting M_V over the SCP area, and the median limiting surface brightness.

Results of this calculation for all 200 available OpSim surveys are shown in Figure 1. As seen in the figure, at a distance of 100 kpc, many of the simulations are able to recover a substantial fraction of the faint dwarf galaxy/stream population, but with some significant variation. These differences are much starker at a distance of 300 kpc, and appear mostly to be related to depth in g and i. The best simulations for this science case are thus those with deepest g and i coverage of the SCP, e.g. `footprint_big_sky_nouiyv1.5_10yrs`. The worst are those with reduced WFD depth, e.g. `wfd_depth_scale0.80_v1.5_10yrs`.

Note that these estimates could be much improved in several ways, which will need to be explored over the next several months:

1. Verification of our assumptions about the ability to remove the contaminating foreground star and background galaxy population with the matched filter approach, using simulations and data.

2. Simulation of performance at a variety of spatial scales and shapes, particularly important for streams.

3. Inclusion of the ability to detect variable stars in the discovered dwarfs and streams, which will greatly improve the scientific return.

4. Consideration of the optimal filter set for isolation and characterization of dwarf galaxies and streams. In this note, we have focused exclusively on detection in two bands.

3 Question responses

Despite the imperfections, we can use the relative results of our current calculation to address some of the questions posed by SCOC.

[Q1] WFD footprint and [Q2] Use of additional time: The three simulations that have the highest detection fractions in both panels of Figure 1 are `footprint_big_sky_nouiyv1.5_10yrs`, `footprint_big_skyv1.5_10yrs`, and `footprint_big_sky_dustv1.5_10yrs`. This is unsurprising, as the purpose of the "big sky" strategies was to optimize high-latitude coverage by extending the WFD footprint further north and south, and de-emphasizing the Galactic plane. For the purposes outlined in this Note, the additional full-depth coverage in these "big sky" sims is ideal. The `footprint_tune` family of OpSims also perform well in our figure of merit.

Likewise, other simulations that extend the coverage further south in declination (e.g., the `bulge_heavy`, `rolling_exgal`, and `full_disk` sims) improve the completeness of satellite searches in the SCP region.

[Q3] u-band and [Q4] Changes in time allocation: Because the focus of this science case is on the SCP region of sky, changing the allocation of filters has little effect on the success at finding potential dwarf satellites of the MCs. Many of the sims with longer u-band exposures or changes in time allocation among filters are in the lowest tier of performance based on our FoM. However, in cases where the footprint is increased, allocating more visits to the g-band can be beneficial, as the depth in g is the primary driver of our detection limits. One relevant example is `filterdist_indx6_v1.5_10yrs`, which rates highly in our figure of merit for the 300 kpc dwarf search. A similar filter allocation (i.e., with increased g-band depth) combined with extended southern coverage would be helpful for the science goals of this Note.

[Q5] Visit pairs/triplets, [Q6] rolling cadence/season length, [Q7] dithering patterns: The choice of filters in pairs/triplets has little effect on our figure of merit. The rolling cadence simulations had a wide variety of outcomes, but in general seem to yield slightly worse performance for dwarf satellite detection in the SCP. Some rolling cadence exceptions that perform relatively well are the `rolling_exgal` sims. Dithering patterns are not necessarily vital to the detection of dwarf satellites.

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