The Vera Rubin Observatory Cadence Note
Milky Way Globular Clusters

R. Figuera Jaimes (San Sebastian University), Rosanne Di Stefano (Harvard-Smithsonian), Rachel Street (Las Cumbres Observatory), Yiannis Tsapras (University of Heidelberg), Markus Hundertmark (University of Heidelberg), and Etienne Bachelet (Las Cumbres Observatory)

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1 Introduction

Galactic globular clusters (GCs) have always been excellent astrophysical laboratories. These dense, gravitationally bound systems of $10^5 - 10^6$ stars are as old as the Galaxy, and can therefore inform our theories of star formation at the earliest times. They are also unique because, with central densities as high as $10^3 - 10^6$ stars per cubic parsec, they are hotbeds of stellar interactions. Stars interact singly, in pairs, or triples, to produce a wide range of interesting binaries, many of which are variable over long intervals, some of which become X-ray binaries (XRBs). Those with accreting neutron stars become recycled millisecond pulsars. Indeed, GCs with very high central densities, such at 47 Tucanae, which happens to lie in front of the SMC, have > 100 times the per-capita number of XRBs as is found in the field. The formed binaries, from cataclysmic variables (CVs) to XRBs containing neutron stars or black holes, tend to be highly variable and are therefore prime targets for Rubin Observatory variability studies. GCs contain important classes of short-period variable stars such as SX Phoenicis variables and RR Lyrae with pulsation time scales that can on the order of a day or significantly shorter, as well as long-period irregular and semi-regular variables.

The current census of variable stars in GCs is incomplete, and there are still many to be discovered and studied (Figuera Jaimes et al. 2016b,a, and references therein). The survey conducted by Rubin Observatory can provide unique time coverage, while the capabilities of the telescope and the planned data analysis techniques will mitigate the effects of blending. Rubin Observatory will not only discover new members of these important classes, but more important, it will provide opportunities for first-of-their-kind variability studies. Rubin Observatory data will be important on its own and can be used in even more powerful ways because we can access decades of HST and X-ray data to provide complementary information, while also employing new facilities, such as JWST.

The things we will learn include relative sizes of different stellar populations, as well as properties of individual members of these populations. Rubin Observatory will study accretion disks, stellar pulsation modes, eclipsing binaries, and even lensing by cluster members of stars in background fields (Di Stefano 2014). RR Lyrae stars, well-known distance indicators, are interesting examples. The Fourier analysis of RR Lyrae light curves, and the use of semi-empirical calibrations available in the literature make it possible to calculate effective temperature, absolute magnitude, distance, metallicity ([Fe/H]), and mass. This will provide measurements of distances and metallicities for the GCs and the magnitude of their horizontal branches as well. Through studying RR Lyrae and other GC variables we will improve models for the evolution of GCs, and develop a better understanding of Galaxy formation and evolution.

In addition to the studies one might have designed ten years ago, there are new possibilities based on recent research findings. The astronomy community has learned that globular clusters are more complex than previously thought. For example, some studies find evidence that globular clusters have multiple stellar populations (Piotto et al. 2015). Other studies indicate that globular clusters may host intermediate-mass black holes (Lützgendorf et al. 2016). Still others show that the cores of some clusters appear to be rotating on a fixed axis (Fabricius et al. 2014). Furthermore, one of the primary models for merging black holes invokes the dense environment of GC centers (Samsing & D'Orazio 2018). We note that Globular Clusters in general did not receive much attention in the 2018 White Papers, so we raise this consideration to ensure it is not overlooked.

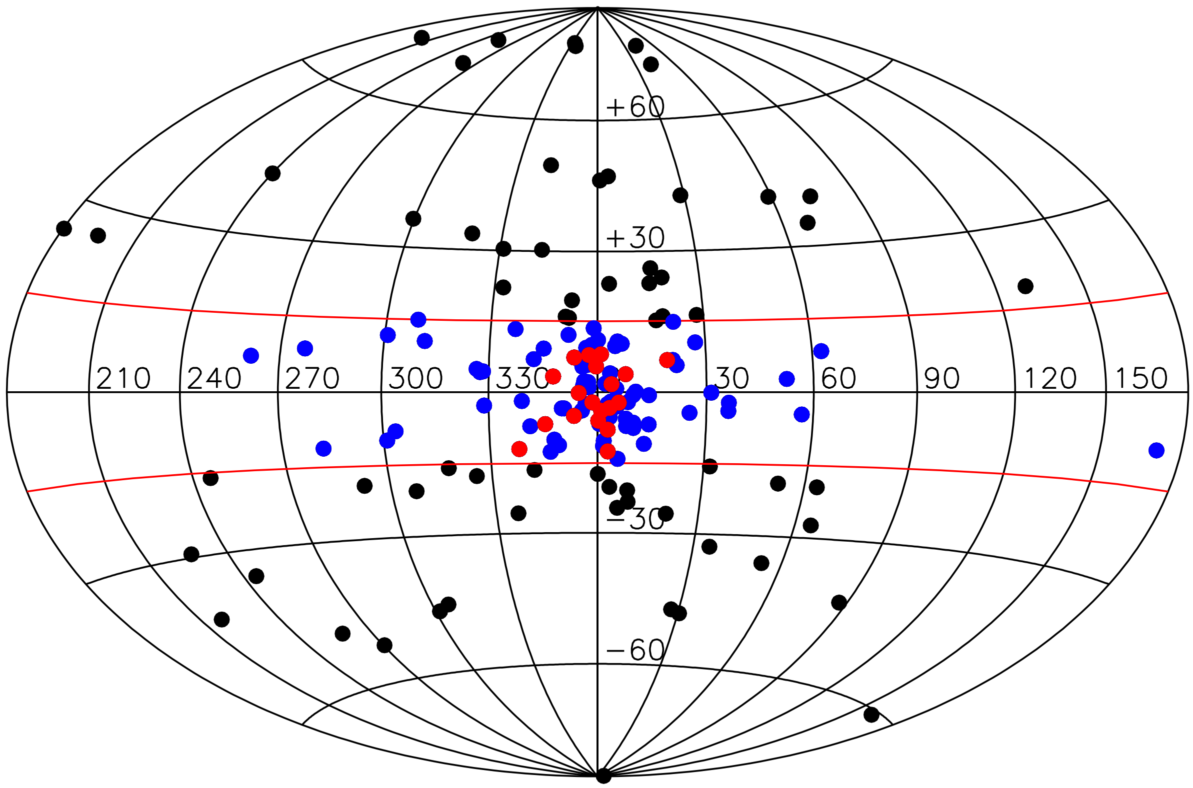

Figure 1: : Plot in Galactic coordinates showing the 157 globular clusters so far known in our Galaxy. The clusters in blue correspond to those with latitudes between +15 to -15 (red lines). Clusters in red correspond to those with the highest central luminosity density.

2 Globular clusters in the Vera Rubin Observatory-LSST fields

During the 10-year survey of the Vera Rubin Observatory a wide sample of globular clusters will be observed in the whole southern sky. So far 157 globular clusters are known in the Milky Way (Harris 1996, 2010 version). Their positions in the Galactic plane are shown in Figure 1 demonstrating that the majority of clusters (92) are found between Galactic latitudes $-15 < b < 15$ deg. The region in which most of the globular clusters with the higher central luminosity density $\rho_0 \geq 5$ are also located in this region (red points) and some of their physical properties listed in the catalogue of parameters for Milky Way globular clusters (Harris 1996, 2010 version) are shown in Table 1 for reference purposes. Covering the Galactic Plane region at reasonably high cadence in multiple filters is therefore essential in order to properly characterize cluster properties and their variable stars.

3 Survey Strategy for Globular Clusters

Some clusters are massive and have central regions of high density. 47 Tuc is one such and has been targeted for special attention by ground-based studies, by HST and by *Chandra*. This particular cluster and a small number of others are candidates for special programs, through either a minisurvey or through the use of rolling cadence. In addition to detailed studies of intriguing individual clusters, however, Rubin Observatory is a unique resource for comparative studies of GCs, given its wide-field coverage and ten-year duration. In this regard we note that the interaction processes discussed above are affected by stellar density profiles, metalicity, central density, and Galactic tidal interactions. Rubin Observatory will allow an unprecedented study of these effects. Not only can the results inform simulations of Galactic GCs, but they can provide insight into the more unusual types of X-ray activity observed in the GC systems of other galaxies, while at

Table 1: Some of the physical properties of the globular clusters with the highest central luminosity density. Column 1, is the name of the cluster as it is defined in the New General Catalogue, Columns 2 and 3 are the celestial coordinates (right ascension and declination), Column 4 and 5 are the Galactic coordinates (longitude and latitude), Column 6 is metallicity, Column 7 is V magnitude level of the horizontal branch, Column 8 is half-light radius, and Column 9 is central luminosity density $\log_{10}(L_\odot \mathrm{pc}^{-3})$.

Cluster NGC	RA J2000	Dec J2000	l degrees	b degrees	[Fe/H]	V_{HB} mag	r_h arcmin	ρ_0
1851	05:14:06.76	-40:02:47.6	244.51	-35.03	-1.18	16.09	0.51	5.09
6256	16:59:32.62	-37:07:17.0	347.79	3.31	-1.02	19.09	0.86	5.59
6266	17:01:12.80	-30:06:49.4	353.57	7.32	-1.18	16.25	0.92	5.16
6293	17:10:10.20	-26:34:55.5	357.62	7.83	-1.99	16.50	0.89	5.31
6325	17:17:59.21	-23:45:57.6	0.97	8.00	-1.25	17.90	0.63	5.52
6355	17:23:58.59	-26:21:12.3	359.59	5.43	-1.37	17.80	0.88	5.04
6388	17:36:17.23	-44:44:07.8	345.56	-6.74	-0.55	16.85	0.52	5.37
6397	17:40:42.09	-53:40:27.6	338.17	-11.96	-2.02	12.87	2.90	5.76
6440	17:48:52.70	-20:21:36.9	7.73	3.80	-0.36	18.70	0.48	5.24
6441	17:50:13.06	-37:03:05.2	353.53	-5.01	-0.46	17.51	0.57	5.26
6517	18:01:50.52	-08:57:31.6	19.23	6.76	-1.23	19.10	0.50	5.29
6522	18:03:34.02	-30:02:02.3	1.02	-3.93	-1.34	16.52	1.00	5.48
6540	18:06:08.6	-27:45:55	3.29	-3.31	-1.35	16.25		5.85
6544	18:07:20.58	-24:59:50.4	5.84	-2.20	-1.40	15.30	1.21	6.06
6558	18:10:17.60	-31:45:50.0	0.20	-6.02	-1.32	16.30	2.15	5.35
6624	18:23:40.51	-30:21:39.7	2.79	-7.91	-0.44	16.09	0.82	5.30
6681	18:43:12.76	-32:17:31.6	2.85	-12.51	-1.62	15.55	0.71	5.82
6752	19:10:52.11	-59:59:04.4	336.49	-25.63	-1.54	13.70	1.91	5.04
7078	21:29:58.33	+12:10:01.2	65.01	-27.31	-2.37	15.83	1.00	5.05
7099	21:40:22.12	-23:10:47.5	27.18	-46.84	-2.27	15.10	1.03	5.01

the same time having implications for our understanding of processes occurring near galaxy centers. It is therefore crucial that, in addition to selecting a small number of GCs for more intensive study, we establish observing criteria for a large number of the other GCs in fields covered by LSST.

Q1: Are there any science drivers that would strongly argue for, or against, increasing the WFD footprint from 18,000 sq. deg. to 20,000 sq.deg.? Note that the resulting number of visits per pointing would drop by about 10%. If available, please mention specific simulated cadences, and specific metrics, that support your answer.

We advocate for increasing the cadence of multi-filter observations of Galactic globular clusters. The simplest way to achieve this is to survey the Galactic Plane within $-15 < b < +15$ deg. with a WFD-like strategy. Alternatively, a selection of globular clusters could be included as regional minisurveys. For example, 47 Tuc could be included in any special coverage of the SMC. It is important to note however, that coverage of the Galactic Plane (GP) is essential to the serious inclusion of GC science. This is because, as Figure 1 shows, a large fraction of the GCs are in the GP.

A comparative study of the effects of Galactic tides can be made by comparing GCs along directions to the Bulge with those in directions away from the Bulge. As a separate point, the GCs observed toward the Bulge increase the number of gravitational microlensing events. While the increase may be on the order of only tens of percent, events caused by cluster lenses map the distribution of stars and stellar remnants within the GCs. In summary, footprints with good coverage of the GP are preferred for GC studies. The footprint_gp_smooth provides the best coverage from the current subset of OpSims, as it includes the largest sample of Globular Clusters. We note that while the mwheavy_nexp2_v1.6_10yrs and footprint_6_v1.7_10yrs also cover some clusters, the lower cadence they provide at higher galactic longitude compromises the full sample and limits the scientific possibilities for comparing cluster populations in different regions. We futher note that Globular Clusters are included in the GalPlaneFootprintMetric described in a parallel Cadence Note by Street et al.

Q2: Assuming that current system performance estimates will hold up, we plan to utilize the additional observing time (which may be as much as 10% of the survey observing time) for visits for the mini-surveys and the DDFs (with an implicit assumption that the main WFD survey meeting SRD requirements will always be the first priority). What is the best scientific use of this time? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

At least a subset of GCs should each be afforded more frequent observations (every two to three days) for a significant interval (e.g. 1 year), presumably as part of a DDF or as part of a minisurvey. It is however important that, as selections of special fields be considered, the number of GCs that would be included, and the characteristics of the included GCs be considered. An optimal plan could achieve important science goals for GC science while simultaneously satisfying the needs of other science groups. We would like to be included in the discussions that take place at that stage.

In order to evaluate whether a given simulation provides observations at adequate cadence, we are evaluating the existing metrics for determining how well periodicities can be recovered from the data, e.g. periodicDetectMetric[1]. This work is underway and we expect to provide more detailed evaluations before the end of Q2, 2021.

4 Exposure time per visit

Q3: Are there any science drivers that would strongly argue for, or against, the proposal to change the u band exposure from 2x15 sec to 1x50 sec? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Time-series photometry is crucial for variable star detection. As mentioned above, globular clusters host several types of variable sources, from millisecond pulsars, short-period variables such as SX-Phoenicis stars with periods around 0.03 to 0.08 d, RR Lyrae stars with periods around 0.3 to 1.0 d to long-period variables such as the pulsating red variables with periods range between 35 to several thousand days.

Ideally, at least 4 exposures per night would help to better characterisation of short period variables, but previous studies for variable star detection on globular clusters (Figuera Jaimes et al. 2016a,b) have shown that it is possible to detect and a proper characterisation with less frequent observations.

5 Allocation of observing time per band

Q4: Are there any science drivers that would strongly argue for, or against, further changes in observing time allocation per band (e.g., skewed much more towards the blue or the red side of the spectrum)? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Multi-colour photometry (with visits in at least *gri* bands each night) are desirable as it will be helpful to corroborate variability detection and will help to update physical properties of each of the clusters observed.

6 Time sampling and revisit offsets

Q5: Are there any science drivers that would strongly argue for, or against, obtaining two visits in a pair in the same (or different) filter? Or the benefits or drawbacks of dedicating a portion of each night to obtaining a third (triplet) visit? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Some specific GCs, for example those with significant populations of XRSs, closely spaced observations on different filters would be advantageous.

Q6: Are there any science drivers that would strongly argue for, or against, the rolling cadence scenario? Or for or against varying the season length? Or for or against the AltSched N/S nightly pattern of visits? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

[1] https://github.com/lsst/sims_maf/blob/master/python/lsst/sims/maf/metrics/periodicDetectMetric.py

No.

Q7: Are there any science drivers pushing for or against particular dithering patterns (either rotational dithers or translational dithers?) If available, please mention specific simulated cadences, and specific metrics, that support your answer.

No

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