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The VVV Survey: Globular Clusters and more

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Abstract. In the efforts to map the Milky Way structure, the central regions have remained very difficult to probe. The VISTA Variables in the Vía Láctea Survey (VVV) is a near-IR variability Survey that scans 560 sq.deg. across the Milky Way bulge and an adjacent section of the southern mid-plane. The main goal of the VVV Survey is to build a 3D map of the structure of the inner Galaxy and characterize its stellar populations. This survey has discovered different kinds of objects, such as globular clusters, Microlensing events, RR Lyrae stars, Cepheids, WITs, among others. The extension of the Survey (VVVX) is observing until 2020, tripling the areal coverage, and complementing the variability studies done by the VVV Survey.

Keywords. surveys, Galaxy: bulge, Galaxy: structure, stars: variables

1. Overview

Understanding the structure, formation and evolution of galaxies has been a challenge. Many efforts have been done to study in detail nearby galaxies, but it is still challenging to resolve their constituent stars down to the main-sequence turn-off. An efficient way to study galaxies is focusing on our own Milky Way (MW). However, as we approach the center of the Galaxy, telescopes that observed in optical bandpasses are unable to detect faint stars due to the severe crowding and interstellar extinction in the area. This can be partially overcome by observing in near-IR band passes, that penetrates the dust and allows us to study highly reddened regions.

The VISTA Variables in the Vía Láctea Survey (VVV) is a public ESO near-IR variability survey that scans the MW bulge and an adjacent section of the mid-plane. We use the 4-meter Visible and Infrared Survey Telescope for Astronomy (VISTA), located at ESO Cerro Paranal Observatory in Chile. The survey covers about a billion point sources across an area of 520 sq.deg. The single epoch observations are carried using the $ZYJHK_s$ filters spanning from 0.84 to 2.5 microns with multi-epoch observations in the K_s band (Minniti *et al.* (2010); Saito *et al.* (2012a); Alonso-Garcia *et al.* (2018)).

One of the advantages of VVV is the ability to find variable sources at the very center of the Galaxy for the first time. The VVV Survey seeks to make a 3D map of the Galaxy. To achieve the main objective, the survey focuses on the study of variable stars (such as RR Lyrae, Cepheids, Miras, Eclipsing binaries, Delta Scutis, Novae, among others), as well as Red Clump giants, as distance (and age) tracers.

The survey was recently renewed: the VVV extended survey (VVVX) is observing from year 2016 until about 2020, covering a larger total area of 1700 sq.deg (Minniti (2018)). The total area covered samples about 4% of the sky, but since is the densest area of the Galaxy, it includes about 3/4 of the MW stars. The Survey will enable further studies of the MW, its globular cluster system and the population census of the Galactic bulge and center, as well as the investigations of the star forming regions in the disk. In this limited space it is impossible to tackle all the VVV Survey discoveries that have been published in more than 200 refereed papers so far. Just to mention some of the most recent results, we briefly discuss below the new globular clusters (GCs), bulge RR Lyrae and Microlensing events.

2. New Galactic Globular Clusters

GCs are astrophysically useful because they give us information about the age of the universe and its chemical composition, galactic formation, structure and evolution, distance scale, stellar evolution, dynamics, etc. The bulge GCs in particular are very difficult to detect due to the high and differential extinction found the innermost part of the Galaxy. The deep near-IR VVV photometry is an excellent tool to extend the known sample. While the most prominent GCs are already known in the bulge, many of the small size and/or low luminosity ones might have been missed. We also should consider that some of them can be destroyed due to different dynamical process such as tidal disruption, bulge shocking, disk shocking, evaporation, dynamical friction, among others. These effects are stronger in dense environments such as the galactic bulge, deep in the potential well. Therefore, this is the best area to search for clusters on the verge of disruption and their debris. Thus, we argued that the inner census of GCs is incomplete in the inner Galaxy, and we started to search for new GCs (Minniti *et al.* (2017a)). Thanks mostly to the VVV survey, the number of known GCs increased the last years, with more than 50 new GC candidates discovered in the bulge (Minniti *et al.* (2011); Minniti *et al.* (2017a,b); Minniti *et al.* (2018b); Minniti *et al.* (2019); Moni Bidin *et al.* (2011); Borissova *et al.* (2014, 2018); Palma *et al.* (2019); Camargo & Minniti (2019), etc.). The majority of the new candidates have low luminosity, so they can be faint GCs at the tail of the luminosity function. The new candidates would be interesting even if they are not real GCs, like the debris of disrupted GCs or also low mass/intermediate age open clusters.

There are different ways to search for GCs, whether applying visual inspection or using automatic selection algorithms. In all cases, the goal is to detect round over-densities of stars above the background. The sizes of the GCs located in the galactic bulge range from $0.8''$ to $4.2''$ depending on their physical radii (typically $2 - 10$ pc).

Some of the new GCs found still need to be confirmed, and all of them need to be properly characterized in order to determine their physical parameters. Specifically, there are many techniques to discover/confirm GCs. Using the optical and/or near-IR color-magnitude diagrams, it is possible to characterize the new GC candidates, but first it is necessary to decontaminate the cluster color-magnitude diagrams by the field stars. Examples of the statistical field decontamination applied are illustrated by Palma *et al.* (2016) and Minniti *et al.* (2017b). Another way is using the distribution of stellar tracers such as RR Lyrae stars or Clump Giants. Metal-poor GCs are rich in RR Lyrae and type II Cepheid stars. Therefore, we should expect an over density of these objects in the presence of an old metal-poor GC.

Proper motions can also be used to detect and study stellar membership of the GC candidates (e.g. Smith *et al.* (2018); Contreras Ramos *et al.* (2018a)). The stars belonging to the GC can be detected as an over-density in the vector point diagram of the proper motions around the cluster region. Finally, with the addition of radial velocities one can better establish cluster membership and also compute the GC orbit. However, the bulge PMs can be at the same time a blessing and a curse. A blessing because they show bulge kinematics, indicating that the new GCs belong to the bulge, as opposed to halo or disk GCs that have very different motions. A curse because having bulge kinematics it is difficult to separate individual star cluster members from the bulge field population.

As mentioned, dynamics plays an important role when studying GCs. Using the VVV Survey together with Gaia DR2 it is possible to study the tidal RR Lyrae stars (e.g. Minniti *et al.* (2018a)). It is not surprising to find such tails, as the recent analysis of GC 56 GCs concluded that 20% of them show extra-tidal RRL stars (Kundu *et al.* (2019)).

With the VVV Survey we found many GC candidates covering a wide range of sizes and properties. For example, Minni22 is one of the smallest clusters found by the VVV (Minniti *et al.* (2018b)). On the other hand, we not only find faint GCs, but also some bright ones. For example, VVV-GC05 is a large GC, discovered by a concentration of RR Lyrae stars (Minniti *et al.* (2017b)). Follow-up radial velocities and proper motions allow to compute the orbital parameters, that show that this cluster must suffer from disruption processes (Contreras Ramos *et al.* (2018a)). As another example of a large new GC, FSR1758 was studied using VVV and Gaia data (Barba *et al.* (2019)). The vector point diagram of the proper motions of the stars around the cluster region shows a clear over-density departing from the normal distribution. The decontaminated color-magnitude diagram exhibits the typical sequences corresponding to a metal-poor GC with an extended blue horizontal branch. The stellar radial density profile gives a tidal radius $R_t = 0.35$ deg, size that is comparable with ωCen. Therefore, the object can be explained as a huge GC or as the remnant nucleus of an accreted dwarf galaxy. Spectroscopic studies with MIKE at the Magellan telescope reveal that is a metal-poor halo cluster in retrograde orbit (Villanova *et al.* (2019)). This interesting large GC can be the survivor of a dwarf accretion event called the Sequoia dwarf (Myeong *et al.* (2019); Evans *et al.* 2020 these proceedings).

With the new discoveries the final MW sample has $N = 220$ GCs in total, a number that is still much smaller than M31, that contains hundreds of GCs ($N = 600 - 700$). The VVV survey of the bulge along with future surveys of the halo (PanStarrs, LSST, etc.) would contribute to complete the census of the Galactic GC system.

3. And More Results...

RR Lyrae stars and Type II Cepheids: These are bright radial pulsators that are well-known tracers of old (~ 10 Gyr) and metal-poor populations. These stars are excellent distance indicators as they follow tight Period-Luminosity relations especially in the near-IR bands (Bono *et al.* (2001); Catelan *et al.* (2004); Clementini *et al.* (2019)).

The VVV survey has discovered thousands of new bulge and disk RR Lyrae stars (e.g. Gran *et al.* (2016); Minniti *et al.* (2017c); Majaess *et al.* (2018)). While RR Lyrae are common in the bulge, the central most reddened regions have remained unexplored. We searched for RR Lyrae and Type II Cepheids to complete their census in the Galactic center region. We initially discovered a dozen RR Lyrae in the Galactic center (Minniti *et al.* (2016)). A follow-up search revealed about a thousand RR Lyrae in the region within $R_G = 1.6$ deg from the Galactic center (Contreras Ramos *et al.* (2018b)), as well as dozens of Type II Cepheids (Braga *et al.* (2019)). This confirms that the innermost part of the Galaxy contains a non-negligible old and metal-poor component.

Bulge Microlensing events: Even though it is not the primary thrust of the VVV Survey, we have also searched for microlensing events in the inner MW. The study of these events gives us important information about the structure and dynamics of the bulge. Also, microlensing is a powerful tool to discover dark objects with a wide range of masses, from planets to black holes. In addition to discovering the first microlensing

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stellar mass Black Hole in a GC (Minniti *et al.* 2015), we have detected almost a thousand new microlensing events at low latitudes in the galactic plane (Navarro *et al.* (2017, 2018, 2019)). These studies help to complete the census of microlensing events in the galactic bulge.

Among the new results we found that the microlensing timescale distribution is shorter in the very center of the MW. We also find that their density distribution is steeply increasing towards the Galactic center, with an excess of events in the most central bins. We also detected a clear asymmetry with more events towards negative longitudes, likely due to the inclination of the bar. Furthermore, we studied the latitude dependence, concluding that the distribution along the Galactic minor axis is much more peaked than the distribution along the Galactic plane (Navarro *et al.* 2020). We also found many interesting objects such as binary events and long timescale events showing the parallax effect. Having found on average more than 4 events per night of observation, we can conclude that the VVV survey is also a very efficient microlensing experiment.

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