THE VVVX SURVEY OF THE MILKY WAY: STATUS AND NEW RESULTS

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ABSTRACT: The ESO Public Survey VISTA Variables in the Via Lactea (VVV) has been mapping the Milky Way bulge and the Southern mid-plane in the near-IR since 2010. An extension of this survey started to map the gaps left between the coverage of the VISTA Hemisphere Survey and the VVV Survey. This VVV eXtended Survey (VVVX) would take about 200 nights in total in 2017-2020, covering 2x10^9 point sources within an area of about 1700 sq deg. The area survey includes about 50 known globular clusters and >1000 known open clusters, with many more clusters to be found. The final products will be deep JHKs-band images, and catalogues of variable point sources, and of proper motions. The main aims are to study the different stellar populations present in the inner Galaxy, and to produce a 3-D map of the surveyed region using well-known distance indicators (such as RR Lyrae, Cepheids, and red clump giants). In order to do all this, it is critical to do a variability search, and to have a good understanding of the effects of reddening and extinction in the near-IR. Within the existing bulge VVV area proper motions would also be available. In particular, the VVVX results will be an essential complement to forthcoming near-IR multiplexing spectrographs (MOONS, APOGEE). In addition, the VVVX survey results will complement the expected measurements from important space missions (GAIA, WFIRST).
Ground Based IR Surveys of the Milky Way

Spectroscopic IR Surveys
- Apogee (Majewski +)
- Moons (Cirasuolo, Gonzalez +)

Photometric IR Surveys
- 2MASS (Skrutskie, Cutri +)
- UKIDSS GPS (Lucas +)
- VVVX (Minniti, Lucas +)
The interstellar medium (ISM) reddens, dims and polarises the stellar light.
The ISM is more transparent in the near-IR.
The Earth’s atmosphere is opaque in the near-IR, except for a few Atmospheric Windows.
A WORD ABOUT GROUND-BASED IR PHOTOMETRY

Tricky...

because the sky background is very bright in the IR, and therefore we need to do mosaicing.
WHY THE NEAR-IR?

The Galactic extinction is much reduced: $A_k \sim 0.1 A_v$

The Cepheid and RR Lyrae PL relations are tighter in the near-IR

The red giants peak in the near-IR

Some problems:
— the near-IR sky background is very high
— the near-IR data rate is very large
— variable star amplitudes are smaller in the near-IR
— variations in the Galactic reddening law
— we see all the way through the MW
VISTA PUBLIC SURVEYS
VISTA VARIABLES IN THE VIA LACTEA (VVV)
VISTA Telescope

- 4m diameter
- IR optimized
- large field of view
- small pixel scale

Rio Webinar
Rio de Janeiro, Brazil, 22 March 2018
Dante Minniti (UNAB/MAS/CATA/VO)
- 16x 2048x 2048 VIRGO IR detectors
- many hot pixels & dead zones in detector 1
- sensitivity: 0.84 to 2.5 microns
- filters: Z, Y, J, H, Ks
- pixel scale: 0.34"
- active optics
- “tile” field of view: 1.0x1.5 deg (6 pointings)
- best image quality: 0.6" (incl. seeing, optics, sampling)
- image distortion: <15% PSF at field corners
What is the 3-D structure of the Milky Way

We use RRLyrae, Cepheids, and clump giants to investigate this.
OUR GALAXY, THE MILKY WAY
The photo album of the MW is not complete yet!!!
140 Gb single 25,000 Megapix image of ~300 sqdeg, made of ~400,000 images of 512x512pix each, scale 1pix = 0.4", JHKs filters, by Ignacio Toledo
Main differences with 2MASS

2MASS covers the whole sky, VVV only 1.3%

VVV has higher resolution (0.34''/pix)

VVV is deeper (Ks<18)

VVV has 5 filters (ZYJHKs)

VVV is a multiepoch survey (~100 epochs)
THE VVV EXTENDED SURVEY

Total Area 1700 sqdeg
Total Time 2000 hs

~50% of the MW stars

vvvsurvey.org
The VVVX survey: 1028 tiles

Our main scientific goal:

To unveil the structure of the inner bulge, disk and halo.

In order to do this, we search for (discover, characterize, study) a variety of objects of astrophysical interest.
In Z, 667 million stars
In Y, 707 million stars
In J, 922 million stars
In H, 990 million stars
In Ks, 779 million stars
Color-magnitude diagrams of bulge and disk fields compared with 2MASS.

Oscar Gonzalez
The Mass of the Galactic Bulge
We first measure hundreds of millions of stars...
Limiting magnitudes

Completeness tests

Reddening maps

Then we make some corrections...

M. Hempel, E. Valenti

O. Gonzalez

Dante Minniti (UNAB/MAS/CATA)
... And we obtain the total bulge mass:

The mass of stars and remnants within

\(|b| < 9.5^\circ, |l| < 10^\circ\) is \(2.0 \pm 0.3 \times 10^{10} M_\odot\)
The global metallicity map of the MW bulge
Some Successful Models

Wegg & Gerhard, MNRAS 2016
Athanassoula et al., A&A 2017
Debattista et al., MNRAS 2017
Tissera et al., MNRAS 2018

The Future:

We need multi object NIR spectrographs

APOGEE-S
MOONS
Javier Alonso, Rodrigo Contreras, Istvan Dekany, Marcio Catelan, Joyce Pullen, Tali Palma, Felipe Gran, Roberto Saito, et al.

Galactic structure, stellar evolution, star clusters, interstellar medium, ...

VVV

RRLyrae

VVV

Survey
• RR Lyrae are pulsating variable stars.
• Their characteristic light curves make them simple to identify.
• They represent an old and metal-poor population.
• They are present in globular clusters.
• They follow a Period-Luminosity relation

• RR Lyrae are primary distance indicators.
• RR Lyrae represent an old and metal-poor stellar population.

• RR Lyrae stars are excellent distance indicators.


The distribution is not barred!
The VVV spatial distribution of known bulge RR Lyrae is different from the clump giants: 
there is no bar and there is no X-shape (Gran et al. 2016).
This contrasts with the inner bulge RR Lyrae from OGLE (Pietrukowicz et al. 2015).
The kinematics favor an axisymmetric population (Kunder et al. 2016)

**OUTER BULGE RR LYRAE**
GALACTIC CENTER RR LYTEAE

- Phase coverage (1 - max. phase lag) > 0.5
- Remove blends based on A(K)
- Remove runaways based on A(K)
- $\sigma_{TFF} < 0.05$
- min. points (after clipping) = 5

THE OLDEST STARS IN THE MW?
GALACTIC CENTER RR LYRAE

VVV Image of the Galactic center

1x1.5 sqdeg
VVV STARS CMD

outer bulge fields b209-b211
We found 10 RR Lyrae out of $10^7$ stars in the GC region.
- typical light curves
- clear discrimination from contact binaries
- somewhat noisier than VVV bulge RR Lyrae
- period distribution indicates an Oosterhoff type I population
red clump
bulge
RR Lyrae
galactic center RR Lyrae
shallow extinction law
(Nishiyama + 2009)

\[ A_{Ks} = 0.528 \, E(J-Ks) \]
steep extinction law
(Cardelli + 1989)

\[ A_K = 0.725 \ E(J-K) \]
RESULTS:

- We discovered a dozen RR Lyrae ab-type stars in the nuclear stellar bulge of the Milky Way.
- This suggests that Galactic center contains an old and metal-poor population, detected here for the first time.
- One implication is that the Galactic center is very old.
- Another implication is that the merger of primordial globular clusters could have contributed to building up the high stellar density in the Galactic center (R. Capuzzo-Dolcetta 1993).

- What next?
  - 1. Make a full census.
  - 2. Measure proper motions.
  - 3. Obtain spectra.
VVV Star Clusters

Star clusters are very important laboratories for stellar evolution. Their stars share the same distance, age and chemical compositions.
Discovery of >700 star clusters.

Make CMDs and measure their proper motions, sizes and reddenings.

Estimate their ages, masses, and distances.

Spectroscopic follow-up: measure their chemical compositions and VRs.

There are $N \sim 20000$ clusters estimated to be in our Galaxy.

We only know now $N \sim 3000$ clusters, and there are many many more waiting to be discovered.
STAR CLUSTERS IN THE MILKY WAY

VVV Survey

The globular clusters are astrophysically very important...

Age of the Universe, Chemical evolution Universe, Stellar evolution, Galactic structure, Formation of the Milky Way, Distance scale, Collisionless systems, Interestellar medium, ...

Rio Webinar
Rio de Janeiro, Brazil, 22 March 2018
Dante Minniti (UNAB/MAS/CATA/VO)
Globular clusters are the oldest objects in the Universe. There are $N=177$ globular clusters known in our Galaxy. Many more are hidden in the most obscured regions...
How many GCs missing in the MW?
The Galactic Globular Cluster System

M31 has $N=600-700$ GCs in total.

But our Galaxy only has
$N=157$ GCs (Harris 1996 catalog)
+20 recent discoveries (including 5 VVV)
$N=177$ globular clusters in the Galaxy.
How many more are missing?
$N_{M31} > 600$ globular clusters

$N_{MW} < 200$ globular clusters?

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NEW GLOBULAR CLUSTERS


Rio Webinar                                        Rio de Janeiro, Brazil, 22 March 2018                     Dante Minniti (UNAB/MAS/CATA/VO)

vvvsurvey.org
NEW GLOBULAR CLUSTERS

The GC distribution projected in the galactic plane is asymmetric within $|Z|<0.5kpc$ and $R_{gal}<3kpc$. The Sun is marked with S, the Galactic Center lies at the origin of the plot, and the dotted line shows the MW bar. The inset histogram shows the distribution of the GCs by Galactic quadrants, as seen by an observer located at the Galactic Center. The viewing angle is 0 deg in the direction toward the Sun, and bins are marked on the main plot with dashed lines. The shaded zone limited by the average levels of the outer and the inner bins corresponds to the expected number of missing inner GCs (10 +/- 3).
Variable stars in the VVV globular clusters

J. Alonso-Garcia et al. (AJ 2015)
Variable stars in the VVV globular clusters

2MASS-GC02

J. Alonso-Garcia et al. (AJ 2015)

cluster

field

Fig. 1.— $J - K_s$ vs. $K_s$ CMDs of 2MASS-GC02, out to its tidal radius $r_t = 4.9'$ (left), and of its surrounding region (right). The arrow shows the reddening vector according to Nishiyama.
EXTREMELY REDDENED GLOBULAR CLUSTERS

2MASS-GC02  Distance  4.9 kpc → 7.1 kpc

Using $A_k = 0.40$ Ej-k from Alonso-García (AJ 2015)

vvvsurvey.org
Dynamical processes affect the survival of Galactic globular clusters:

- dynamical friction,
- bulge shocking,
- disk shocking,
- tidal disruption,
- evaporation,
- ...

Fall & Rees 1977, 1985

These processes are stronger in the Galactic bulge, deep in the potential well.
Where would you find the clusters on the verge of disruption, and their debris?
— Dying clusters and their skeletons would be found in the elephant graveyard = the Galactic bulge.
— When a cluster gets disrupted, it yields its constituent stars to the field.

Some globular metal-poor clusters are rich in RR Lyrae and T2C variable stars. The bulge RR Lyrae and T2C can be used as tracers of the old and metal-poor stellar populations.
SEARCH FOR GLOBULAR CLUSTERS

GC searches are done by visual inspection or automatic selection algorithms. They appear as round concentrations of stars, showing up as overdensities above the background in the optical or near-IR images. At the distance of the bulge their typical sizes would be:

For $Ro=8.0 \text{ kpc}$

- $R = 2 \text{ pc} = 51'' = 0.8' = 151\text{pix}$
- $R = 5 \text{ pc} = 129'' = 2.1' = 379\text{pix}$
- $R = 10 \text{ pc} = 258'' = 4.2' = 758\text{pix}$

SEARCH FOR GCS IN THE BULGE

Searching for globular clusters in the Galactic bulge is very tricky! New Galactic globular clusters in the bulge are very difficult to find, due to

- high stellar density
- variable extinction
Why the Near-IR?
SEARCH FOR GLOBULAR CLUSTERS

We use stellar tracers (clump giants, RR Lyrae) in order to find new clusters.
We make density maps preselecting red giants from the Wesenheit colour-magnitude diagrams

New candidate clusters

Known globular clusters
Known GCs
New Candidates

KNOWN GCs
NEW GCS

Comparison

GCs

Minniti 01 – 22

Minniti et al. 2017 ApJL
Comparison

NEW GCS

Decontaminated CMDs

Minniti et al. 2017 ApJL
CONFIRMATION OF GLOBULAR CLUSTERS IN THE BULGE

How to decide if a candidate is a real globular cluster?

Confirming a globular cluster in the Galactic bulge is also tricky!

The requirements for globular clusters in the bulge should be stringent, due to the large extinction and background contamination.

There is not a unique recipe, but one can use one or a few of the following methods:

— Color-magnitude diagrams
— Radial velocities
— Proper motions
— Chemical footprint
— Stellar tracers (RRLyr)
The globular cluster Minni22 is classified as metal-poor based on the CMD. It also has 3 RRab within 2’ of its center.

We use the statistical field decontamination procedure of Palma et al. (2016) in order to clean up the VVV near-IR CMD.

The luminosity function of the decontaminated cluster shows a prominent RGB bump with $K_s=13.30\pm 0.03$ mag.
FOV = 6’x3.5’
**cl22** density maps made by Maren Hempel show a concentration of red giants.

2' = 352pix

**cl22** is one of the smallest clusters that we found

R = 1 pc = 25” = 0.4’ = 75pix
CONFIRMATION OF GLOBULAR CLUSTERS IN THE BULGE

The RR Lyrae are representative of old and metal-poor stellar populations. They are found frequently in the Galactic halo and bulge, and in globular clusters. The presence of RR Lyrae in a star cluster guarantees that this is a GC. They are also excellent distance indicators, as well as reddening indicators.

We can use tight groups of RR Lyrae variable stars in order to confirm a globular cluster. In the cases of the bulge fields the concentration of RR Lyrae has to be at the same distance.
There are 3 known OGLE RRab within 2′ of the cluster centre. They all have similar colors and magnitudes, and are located at the same distance. This matches the mean distance of the bulge.
There is also one RRc, but this is a background object.
Cluster 22 shows a well defined RGB, with a RGB bump. It appears to be a metal-poor globular cluster, consistent with the presence of RR Lyrae variable stars.
Comparison with Optical and Near-IR Theoretical Isochrones

The optical photometry is provided by the DECaPS Survey (E. Schlafly, D. Finkbeiner, et al. 2017)

We use the PARSEC v1.2S isochrones (Bressan et al. 2012, Marigo et al. 2017)

- age = 11.2 Gyr
- metallicities $z = 0.0001, 0.0008, 0.0125$

$[\text{Fe/H}] = 1.3 \pm 0.3$ dex
Proper motion decontamination works quite well eliminating foreground and background stars. The PMs show very well the RGBB, but do not reach the main-sequence TO.
We conclude that Minni22 is a real globular cluster located in the bulge. There are several lines of evidence.
— The near-IR CMD is similar to that of NGC6642.
— The optical and optical-IR CMDs resemble a metal-poor GC.
— It contains 3 RR Lyrae within 2’ of its centre.
We obtain $D=7.4$ kpc, $[\text{Fe/H}]=-1.3$, $E(B-V)=1.12$, $M_V=-6.2$.

Is this a new class of GC in the Galactic bulge? It is very small, it can be a low luminosity dissolving cluster. One of the skeletons in the elephant graveyard?
Not all the new GC candidates are faint. Some seem to be quite luminous…
How many globular clusters in the Milky Way?

Many GCs (~100) may be still missing in the MW. will find them!

CONCLUSIONS

- F. Gran +: Search for RR Lyrae in the bulge-halo transition region (A&A 2016)
9th VVV Science Meeting, Florianópolis, SC, Brazil, from April 04 to 06, 2018
Data Releases

New Imaging Data Release for the VVV Public Survey

Published: 25 Mar 2015

The VISTA Variables in the Via Lactea Survey (VVV) is a wide area, near-infrared (Z, Y, J, H, Ks), multi-epoch imaging survey with coverage of 540 square degrees. This new Phase 3 release (VVV DR4) contains observations up to 30 September 2013 with and includes images and single-band source catalogues. It replaces the previous releases that had been processed with previous new data, mainly increasing the number of epochs for the Ks band.

Images and source lists can be queried and downloaded from the Science Archive Facility. For more information please refer to the VVV DR4 release notes.
A new near-IR survey of the Milky Way

Discovering our own galaxy, promoting astrophysics at every level, fostering international collaborations, and securing resources for the future generations.