The Wide View of the Galactic Bulge as seen by the VVV ESO Public Survey

Oscar A. Gonzalez[1,7]
Dante Minniti[2,7,8]
Philip Lucas[3]
Marina Rejkuba[1]
Manuela Zoccali[2,7]
Elena Valenti[1]
Roberto Saito[2,4,7,9]
Jim Emerson[5]
Marcio Catelan[2,7]
Ignacio Toledo[6]
Maren Hempel[2,7]
Rodrigo Tobar[1]

[1] ESO
[2] Departamento Astronomía y Astrofísica, Pontificia Universidad Catolica de Chile, Santiago, Chile
[3] Centre for Astrophysics Research, University of Hertfordshire, Hatfield, United Kingdom
[4] Departamento de Física y Astronomía, Universidad de Valparaiso, Chile
[5] School of Physics & Astronomy, Queen Mary University of London, United Kingdom
[6] ALMA Operations Support Facility, San Pedro de Atacama, Chile
[7] The Milky Way Millennium Nucleus, Santiago, Chile
[8] Vatican Observatory, Vatican City State, Italy
[9] Universidade Federal de Sergipe, Departamento de Física, São Cristóvão, SE, Brazil

The first year of observations of the Galactic Bulge in the Vista Variables in the *Via Lactea* (VVV), one of ESO's public surveys with the VISTA telescope, have yielded a deep, near-infrared, multi-colour (*Z,Y,J,H,Ks*) photometric coverage of over 320 square degrees. Results based on this impressive dataset are presented, showing the global properties of the Bulge. Extinction has been mapped using the magnitude and colour of the red clump, revealing a large amount of small-scale structure. This extinction map has been used to de-redden the VVV stellar photometry to study the Bulge morphology from the absolute magnitude of the red clump and to derive photometric metallicities from the colour of red giant branch stars. The VVV survey continues to obtain multi-epoch data to investigate the variable stars in the Bulge.

The Galactic Bulge: An obscured past

The study of the central components of disc galaxies is a key step towards understanding the formation and evolution of spiral galaxies. The shape of the bulges embedded in galactic discs provides an important constraint on the different processes driving the history of galaxy assembly. The correlation between the structural properties of bulges and the properties of their stellar populations — namely the age and chemical abundances of bulge stars — has become an important factor in characterising the past history of the host galaxies, and is a basic ingredient for modern galaxy evolution models.

The main complication of such studies in external galaxies is the impossibility of resolving individual stars in the dense inner bulge regions. The Bulge of the Galaxy on the other hand, located at nearly 8 kpc, allows individual stars to be resolved and the detailed properties of the Bulge stars to be obtained. However, this possibility comes at a high price: we need to overcome the strong interstellar extinction due to the dust and gas across the intervening Disc of the Galaxy, so that we can cover homogeneously, and with a high spatial resolution, an enormous area on the sky. We also need to disentangle the stars in the Bulge from those distributed in the Disc along the line of sight towards the Bulge.

Until recently, spectroscopic and photometric studies had to base their efforts on investigating particular regions towards the Bulge that were not strongly affected by extinction, for example, the well-known Baade's Window. Studies in these regions provided important clues about the age, chemical abundances and morphology of the Bulge and they shared one common conclusion: the Bulge is much more complicated than previously thought, and thus the need for a global, deep and homogeneous study is undeniable.

Our group of investigators, led by Dante Minniti and Phil Lucas, accepted the challenge and using VISTA, the world's most powerful infrared survey telescope, started the Vista Variables in the *Via Lactea* ESO public survey.

The VVV survey

The VVV survey observations are carried out using the 4-metre VISTA telescope located on Cerro Paranal (Emerson et al., 2004), which, coupled with the high-sensitivity infrared camera VIRCAM, has the capacity to overcome the heavy extinction of the Galactic Plane in order to reach Bulge stars up to a limiting magnitude of *Ks* ~ 18 mag, with a median seeing of ~ 0.9 arcseconds. Furthermore, the high efficiency of VISTA allowed us to complete a set of single-epoch, multi-band observations of the entire Bulge region of ~ 320 square degrees using *Z*, *Y*, *J*, *H* and *Ks* filters within less than two Bulge observing seasons. Figure 1 shows the distribution of tile images across the Bulge area covered. Each tile is the result of six exposures (known as pawprints) used to cover a field of 1.48 by 1.18 degrees in size (Arnaboldi et al., 2007). The Bulge survey area consists of 196 of these tiles distributed as shown in Figure 1. Descriptions of the observing strategy, survey goals and first results are available from Minniti et al. (2010) and Saito et al. (2010). The first data release article, DR1 (Saito et al., 2012), describes the survey products in detail.

The final catalogue of the Bulge, as seen by the VVV survey, has a total of more than 84 million sources (Saito et al., 2012) and yielded a magnificent composite image of the Bulge area (ESO Release eso1242). Based on this dataset, we were able to study the global properties of the Galactic Bulge for the first time. An illustrative example is the VVV Bulge colour–magnitude diagram (CMD) shown in Figure 2, which, together with the VVV Disc CMD, are the largest CMDs to date. The CMDs yield important information about the Galaxy, showing the fingerprint of its structure and content.

The solution to the reddening problem

Towards the Bulge of the Galaxy, interstellar extinction effects are not only very strong, but also highly variable on small scales. As a result, sequences in colour–magnitude diagrams (see Figure 2) become very hard to identify and the properties of the Bulge stellar populations cannot be accurately characterised.

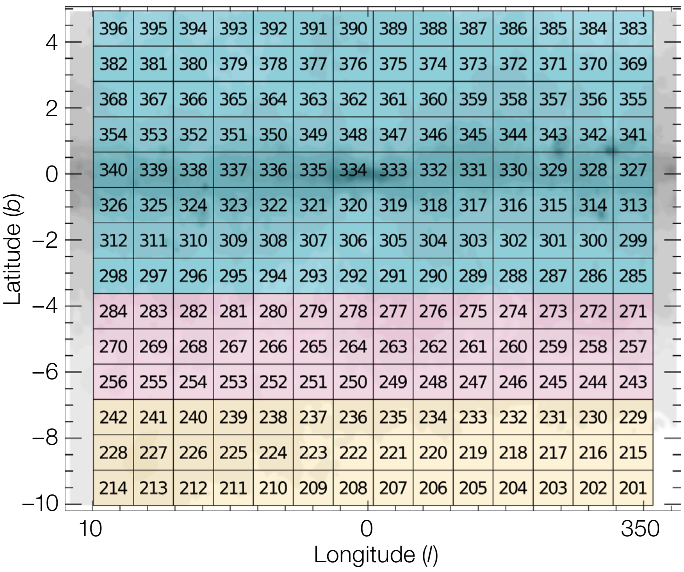

Figure 1. The distribution of tiles across the Bulge area between $-10° < l < +10°$ and $-10° < b < +5°$. Different background colours are used to emphasise the different resolution of our reddening map: 2 arcminutes for $-4° < b < +4°$ (cyan), 4 arcminutes for $-7° < b < -4°$ (pink), and 6 arcminutes for $b < -7°$ (yellow).

Extinction maps with enough resolution to successfully correct observations for reddening have so far been restricted to only a handful of Bulge regions. The only available extinction maps with enough coverage were those from Schlegel et al. (1998). However, these maps are only reliable in regions further from the plane of the Galaxy, meaning that no global studies could be carried out that included Galactic latitudes $|b| < 4°$.

In order to trace the effect of Galactic extinction, the main requirement is to identify a standard candle in the field, which is homogeneously distributed across the Bulge, with a high enough density to construct a high-resolution reddening map. When metal-rich giant stars ignite helium in their cores they concentrate at a relatively fixed position in the CMD known as the red clump (RC). Their average magnitude and colour are well known and have only a small and quite well understood dependence on internal population factors, such as age and metallicity, therefore becoming the ideal tracer for an external factor such as reddening.

In the Bulge, the RC is located at an apparent magnitude of *Ks* ~14 in low extinction regions, but it can reach up to *Ks* ~ 17 mag in the highly reddened innermost Bulge areas. The VVV survey is the first survey that provides photometry deep enough to reach the RC magnitude across all the Bulge regions. In Gonzalez et al. (2012) we measured the (*J–Ks*) colour of RC stars using a Gaussian fit to the colour distribution in a grid of varying spatial resolution dependent on the density of RC stars. The mean colour of RC stars was related to the intrinsic colour of Bulge RC stars in order to derive *E(J–Ks)* reddening values for each resolution element and to finally construct the high-resolution reddening map of the Bulge. We chose the grid size to maximise the resolution of the map, while having at least 200 stars in each resolution element necessary for an accurate mean colour estimate. The final resolution of our reddening map is 2 by 2 arcminutes for $-4° < b < +4°$, 4 by 4 arcminutes for $-7° < b < -4°$ and 6 by 6 arcminutes for $b < -7°$.

The complete map is shown in Figure 3, where both the general extinction patterns and the small-scale features are clearly traced. A web-based tool, the BEAM calculator, has been made available to the community[1], from which the reddening values of our map can be retrieved. The map has already been used not only for studies of the Bulge stellar populations, but also for studies on the extinction law, Bulge globular clusters and X-ray sources. We have used it to produce a complete set of reddening-corrected VVV catalogues, which can be used to study the Bulge stellar populations in great detail and with the wide coverage provided by the survey.

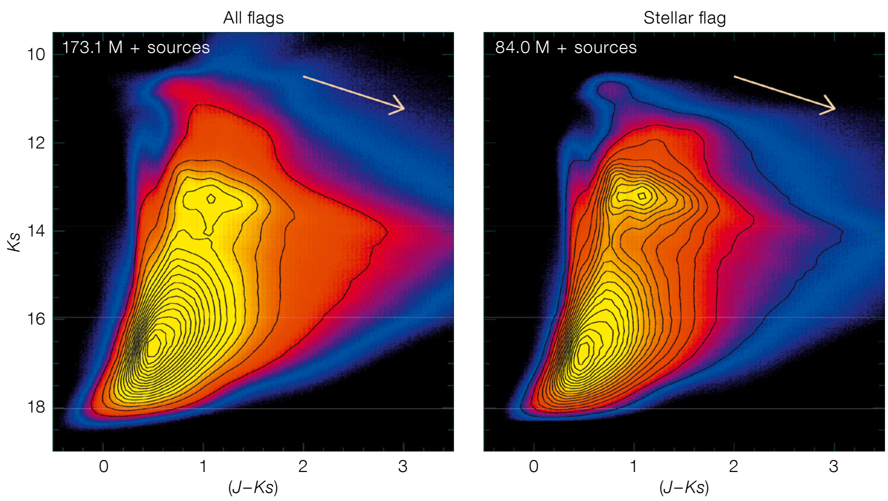

Figure 2. *Ks* vs. (*J–Ks*) colour–magnitude diagram for the VVV Bulge area. The left-hand panel shows the CMD for all point sources found with *J*, *H* and *Ks* photometry, a total of 173 150 467 sources. The right-hand panel shows only stellar sources found in the three bands, a total of 84 095 284 sources. The white arrow shows the reddening vector, which strongly affects the shape of the observed Bulge CMD.

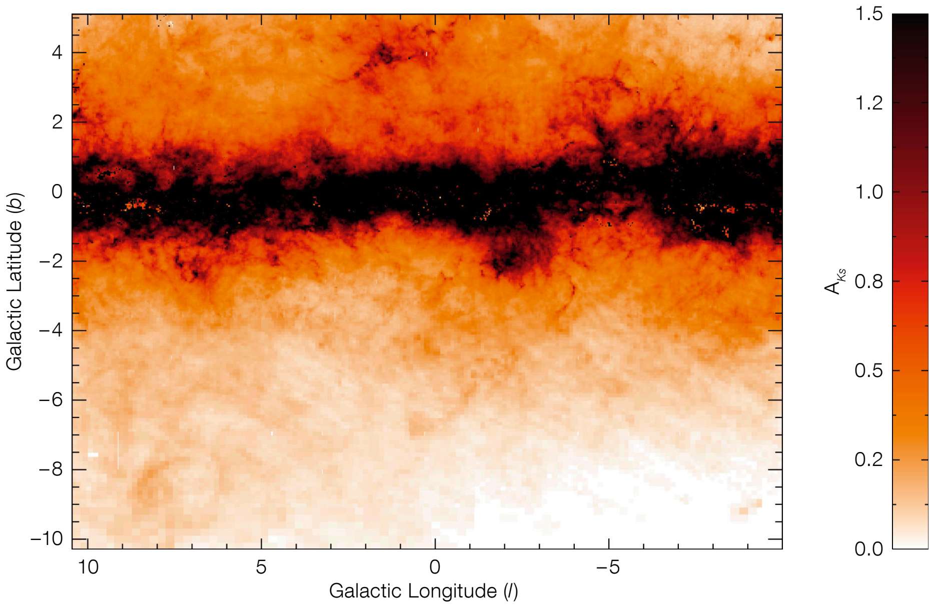

Figure 3. The complete high-resolution map of the Galactic Bulge. A_{Ks} values saturate the colour scale at A_{Ks} = 1.5 mag in this visualisation, in order to show better the extinction variations across the whole area. The central regions of the Bulge have A_{Ks} values extending to ~ 3.5 mag (corresponding to A_V ~ 30 mag).

The Bulge morphology

One of the most common techniques used for studying the morphology of the Bulge has been the red clump method (Stanek et al., 1997). In this technique, the observed mean RC magnitude, corrected for extinction, is compared to the known intrinsic mean magnitude of the RC stars (M_{Ks} = –1.55 mag for the Bulge population) in order to derive the distance to the observed population. With our new high-resolution reddening map, we were able to apply this method at very low latitudes in the innermost regions of the Bulge, where it was not possible to measure it before, and to compare it to the outer Bulge regions.

Figure 4 shows the mean distance to the Bulge population, as traced by the RC stars, as a function of Galactic longitude at two different latitudes b = –1° and b = –5° (respectively 150 and 700 pc below the Galactic Plane). The distribution of Bulge stars clearly follows a downward trend with distance to the Sun for increasing Galactic longitude, tracing the position angle of the Galactic bar. Significant differences are observed between the distribution of stars at both latitudes, and in particular the inner Bulge shows a flattening of the slope between longitudes l = –4° and l = +4°.

These results advanced our understanding of the Bulge; the Galactic models were put to the test shortly afterwards in order to reproduce these observations. Gerhard & Martinez-Valpuesta (2012) compared their model to our results, finding that an axisymmetric concentration of stars in the inner Bulge is the cause for the different profiles that trace the bar position angle at low and high latitudes in Figure 4. Most importantly, the overall profiles shown in Figure 4 are fully consistent with a model of a boxy bulge formed as a result of buckling instabilities of the originally thin Galactic bar.

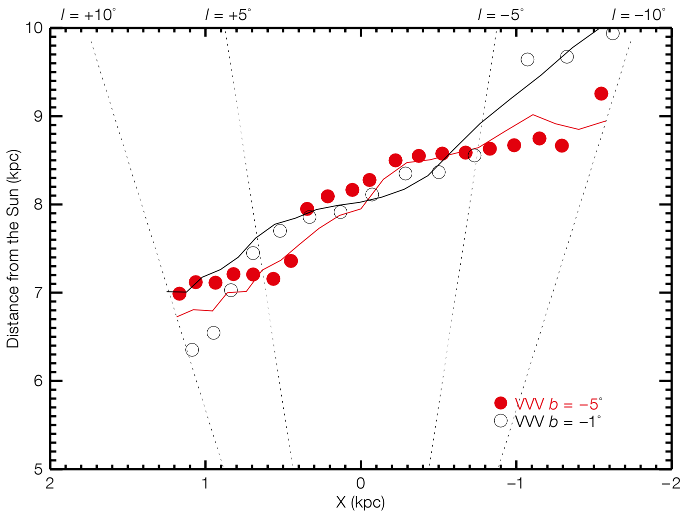

Figure 4. Distances derived using the RC method as a function of Galactic longitude at two fixed latitudes. Values for latitude b = –1° are shown as black open circles, and as red filled circles for b = -5°. Models for the corresponding latitudes are shown as thick lines in the respective colours.

Solving the mystery of the Bulge metallicity gradients

If there is one property of the Bulge that has been very well established by observations, it is the presence of a metallicity gradient along its minor axis (Zoccali et al., 2008; Johnson et al., 2011). The cylindrical rotation and morphology of the Bulge (Shen et al., 2010), the chemical similarity between Bulge and thick Disc stars (Gonzalez et al., 2011) and the suggested population of intermediate-age stars found in the Bulge (Bensby et al., 2013), have strongly pointed towards a secular evolution origin for the Bulge. However this conclusion is challenged by the presence of the metallicity gradient along the Bulge minor axis, which has always been considered to be a property of merger-built systems.

The need for a more general view of these gradients has increased but, unfortunately, a complete spectroscopic coverage of the Bulge, with the required resolution for such a study, remains infeasible. However, the colour of red giant branch stars in reddening-corrected CMDs, constructed using absolute mag-

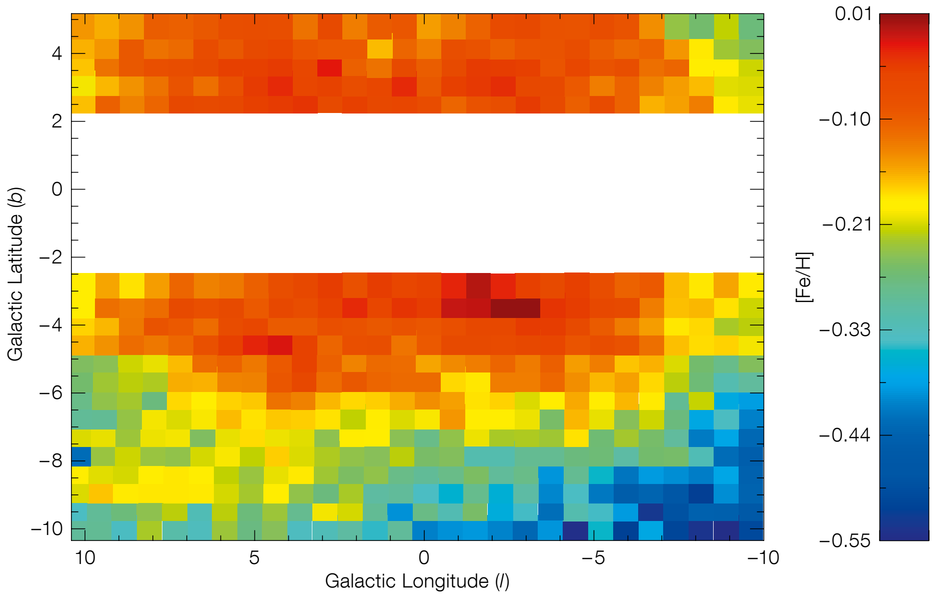

Figure 5. The complete metallicity map of the Galactic Bulge produced using the interpolation of $(J-Ks)_0$ colours of RGB stars between globular cluster ridge lines, with a resolution of 30 by 40 arcminutes.

nitudes, can be used to derive a photometric metallicity value by interpolation between globular cluster ridge lines of known metallicities. Although the photometric metallicities for individual stars are expected to have relatively large uncertainties, the average metallicity distribution for a sample of stars in a given field is a reliable proxy for the mean metal content, and it resembles strongly the mean metallicity derived spectroscopically (e.g., Valenti et al. 2007; Johnson et al. 2011).

Therefore, in Gonzalez et al. (2013) we used our reddening-free VVV catalogues to measure distances towards different Bulge lines of sight and produce a set of CMDs in the absolute plane from which we derived mean photometric metallicities. The end product was the first complete metallicity map of the Bulge, shown in Figure 5. We observe a radial metallicity gradient of ~ 0.28 dex/kpc and the clear domination of Solar metallicity stars in the inner Bulge. The observed metallicity map was recently also reproduced by a boxy-bulge formation model showing that, although other components might still be present, the general properties of the Bulge are fully consistent with a formation scenario where the Bulge is formed from the buckling instabilities of the Galactic bar (Martinez-Valpuesta & Gerhard, 2013).

Outlook

Great advances have now been made in our understanding of the Bulge properties, thanks to the general view provided by the multi-band products obtained during the first year of VVV observations. However, the revolution does not stop here. The VVV survey keeps accumulating data — it is now in the middle of its variability campaign. The multi-epoch observations in *Ks*-band, will allow us to further characterise the Bulge to a unique level of detail by, for example, studying the 3D morphology of the Bulge using RR-Lyrae variables and using proper motions for the bulge-disc decontamination required to derive stellar ages from the Bulge turn-off magnitude measured in decontaminated CMDs.

References

Arnaboldi, M. et al. 2007, The Messenger, 127, 28
Bensby, T. et al. 2013, A&A, 549, A147
Emerson, J. P. et al. 2004, The Messenger, 117, 27
Gerhard, O. & Martinez-Valpuesta, I. 2012, ApJ, 744, L8
Gonzalez, O. A. et al. 2011, A&A, 530, A54
Gonzalez, O. A. et al. 2012, A&A, 543, A13
Gonzalez, O. A. et al. 2013, A&A, 552, A110
Johnson, C. I. et al. 2011, ApJ, 732, 108
Martinez-Valpuesta, I. & Gerhard, O. 2013, ApJ, 766, L3
Minniti, D. et al. 2010, New Astron., 15, 433
Saito, R. K. et al. 2012, A&A, 537, A107
Saito, R. K. et al. 2010, The Messenger, 141, 24
Saito, R. K. et al. 2012, A&A, 544, 147
Schlegel, D. J., Finkbeiner, D. P. & Davis, M. 1998, ApJ, 500, 525
Shen, J. et al. 2010, ApJ, 720, L72
Stanek, K. Z. et al. 1997, ApJ, 477, 163
Valenti, E., Ferraro, F. R. & Origlia, L. 2007, AJ, 133, 1287
Zoccali, M. et al. 2008, A&A, 486, 177

Links

[1] BEAM calculator: http://mill.astro.puc.cl/BEAM/calculator.php