VISTA Variables in the *Vía Láctea* (VVV): Current Status and First Results

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VISTA Variables in the *Vía Láctea* (VVV) is a public ESO near-IR variability survey aimed at scanning the Milky Way Bulge and an adjacent section of the mid-plane. VVV observations started in October 2009 during ESO science verification. Regular observations for the first year of the survey have been conducted since February 2010 and will cover a total area of 520 square degrees in five passbands and five epochs. Here we address the first results obtained from the VVV Survey as well as the current status of the observations.

Introduction

VISTA Variables in the *Vía Láctea* is one of the six ESO Public Surveys selected to operate with the new 4-metre Visible and Infrared Survey Telescope for Astronomy VISTA[1] (Emerson & Sutherland, 2010). VVV is scanning the Milky Way (the *Vía Láctea*) Bulge and an adjacent section of the mid-plane, where star formation activity is high. The survey will take 1929 hours of observations during five years (2010–14), covering ~ 10^9 point sources across an area of 520 square degrees, including 33 known globular and ~ 350 open clusters; the survey area is shown in Figure 1. The final product will be a deep near-infrared (NIR) atlas in five passbands and a catalogue of more than 10^6 variable point sources (Minniti et al., 2010). Detailed information about the VVV Survey can be found at the survey web page[2].

Science verification

Some VVV data were obtained on 19–30 October 2009, during ESO science verification (SV) of VISTA (Arnaboldi et al., 2010), following the same observing strategy as the VVV survey. The observations consisted of multi-colour imaging, *Z*- (0.87 μm), *Y*- (1.02 μm), *J*- (1.25 μm), *H*- (1.64 μm) and *Ks*- (2.14 μm) bands of a field at Galactic coordinates l = 2.2°, b = −3.1°. An additional thirteen epochs in *Ks*-band were also taken, since the variability study will be done only in this band. This is one of the most crowded fields in the Galactic Bulge, allowing us to test whether there are too many saturated stars. It is also known to contain numerous variable stars, allowing us to test their detectability. In addition to this field we also observed three other tiles (each tile corresponds to a sky field of 1 × 1.5 deg^2) in the Bulge in *Ks*-band to test different sky subtraction strategies.

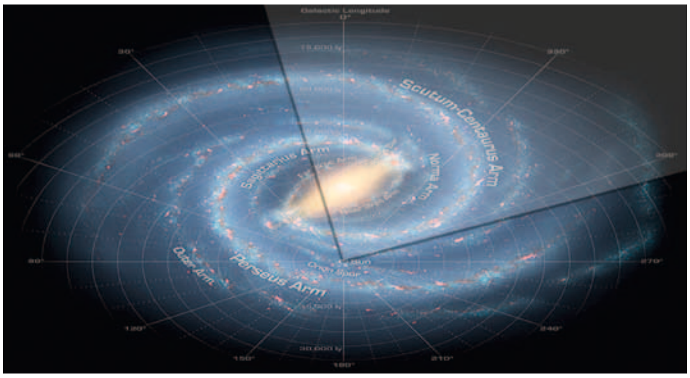


Figure 1. Illustration showing the Milky Way galaxy and the area being observed by the VVV Survey (based on Figure 16 of Churchwell et al., 2009).

Regular observations

Regular observations for the first year started in February 2010 and will cover the total survey area in the five passbands. An additional set of five *Ks*-band exposures will also be taken. Table 1 shows the number of Observational Blocks (OBs), each of which corresponds to one tile, scheduled for observation during the first period, as well as the current status of the observations. The OBs named "colour" contain observations in more than one filter.

Table 1. Overview of VVV observations: first year.

	Planned for 2010	Executed by 1 July 2010	Fraction %
Bulge			
Colour *ZY*	196	40	20
Colour *JHKs*	196	170	87
Variability *Ks*	1004	92	9
Disc			
Colour *ZY*	152	121	80
Colour *JHKs*	152	152	100
Variability *Ks*	760	507	67
Total	2460	1082	44

Pipeline processing and calibration of the VVV data are performed by the UK Cambridge Astronomy Survey Unit (CASU) using the VISTA Data Flow System (VDFS) pipeline[3]. The VISTA Science Archive (VSA) at the Wide Field Astronomy Unit (WFAU) in Edinburgh[4] performs: (i) image stacking to produce stacked and subtracted tiles; (ii) photometric and astrometric calibration; (iii) source merging; (iv) quality control; and (v) identification of variable sources. Photometric calibration on the VISTA system is done via thousands of unsaturated Two Micron All Sky Survey (2MASS) stars present in every VVV tile, including for *Z* and *Y* filters (not observed by 2MASS) where colour equations are used. The method is similar to that used for WFCAM (Hodgkin et al., 2009). Our project takes advantage both of the VDFS team's experience in handling the WFCAM/UKIRT and VISTA data, and the experience of the VVV team members, who are leading participants in other surveys such as OGLE and in routine data processing and delivery to ESO.

Figure 2 shows a *J*-, *H*- and *Ks*-band colour-composite image centred on the Galactic H II region M8 (NGC 6523). Figure 3 (top panels) shows a small portion of a VVV image centred on the globular cluster Palomar 6, compared with 2MASS (Skrutskie et al., 2006). VVV images are usually a combination of *J*-, *H*- and *Ks*-band observations. However, some early images (including this one of Palomar 6) were created using *Z*-, *H*- and *Ks*-band colours. The higher quality of the VVV data stands out in this comparison. As another example of the superior quality of the VVV data, the lower panels of Figure 3 show colour images of the Bulge planetary nebula NGC 6629, located in a field centred at l = 9.8°,

Figure 2. VVV image of the Lagoon Nebula (NGC 6523), a giant interstellar cloud in the constellation of Sagittarius, towards the Bulge of our Galaxy. This colour image was made combining *J*- (blue), *H*- (green) and *Ks*-band (red) observations. Saturated objects show a black dot in the centre. Credit: Ignacio Toledo and Dante Minniti.

$b = -5.3°$. Clearly, even though the survey is not designed to detect or map emission line objects, it turns out that planetary nebulae (PNe) are also prominent in the VVV images. The colour is typical of most PNe, due to the intense emission lines present in our filters, particularly Paschen β in the *J*-band and Brackett γ in the *Ks*-band. We expect to identify a few hundred PNe in our fields in the inner Disc and Bulge.

Colour–magnitude diagrams

The left-hand panel of Figure 4 shows a colour–magnitude diagram (CMD) for the SV field in the Bulge located at $l = 2.2°$, $b = -3.1°$, in one of the most crowded regions of our Galaxy. In spite of the high stellar density and large number of giants, high precision photometry is possible over most of the field. This figure shows the dominant Bulge red giant branch along with the main sequence track of the foreground Disc, and it is evident that the VVV photometry is about 4 magnitudes deeper than 2MASS in this field, almost reaching the Bulge main sequence turn-off. About a million stars are measured in total in this 1.5 deg^2 field. CMDs like this can be used to study the stellar populations across the Bulge, as well as the 3D structure of the inner Milky Way.

The right-hand panel of Figure 4 illustrates the CMD of the first Galactic Plane field observed. Located at $l = 295.4°$, $b = -1.7°$ (in the outskirts of Carina), this field suffers from large and very inhomogeneous extinction. The Disc main sequence dominates and numerous reddened giants are also seen. We stress that 2MASS is very complementary to our survey, providing the external photometric and astrometric calibration, and photometry for the brighter sources ($Ks < 10$), which saturate even in the short (4 s) VVV exposures. The depth of the VVV allows us in many cases to see all the way through the Plane of the Milky Way. In fact, very often our CMDs show numerous background galaxies. CMDs like these can also be used to study the 3D structure of the Milky Way Plane, as well as the spiral arms, the edge of the Disc and the outer warp. About half a million stars are measured in this 1.5 deg^2 field. Taking into account that the VVV Survey covers over 520 deg^2 in total, we will provide photometry for ~ 5×10^8 sources in the Bulge and Disc of our Galaxy.

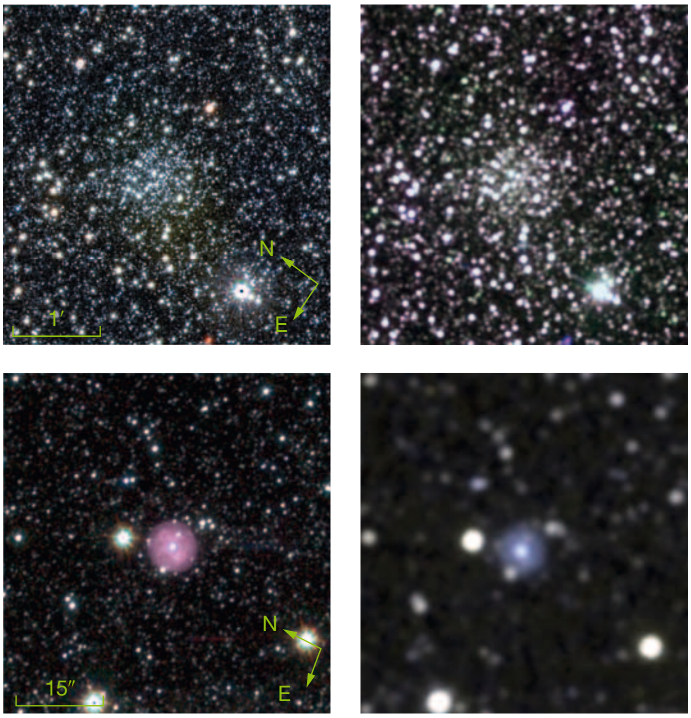


Figure 3. Upper panels: Comparison between VVV (left) and 2MASS (right) images of the globular cluster Palomar 6. Lower panels: VVV image (left) of the planetary nebula NGC 6629 compared with 2MASS (right).

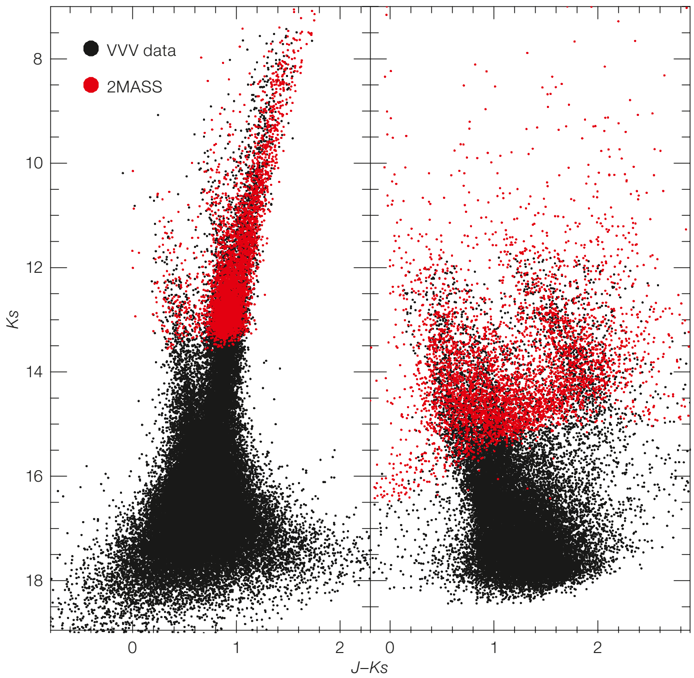


Figure 4. Colour-magnitude diagrams comparing VVV data (black) and 2MASS (red) for two extreme examples. The left-hand panel shows one of the most crowded Bulge fields (SV field), while the right-hand panel shows one of the Disc fields that are most heavily and inhomogeneously reddened (see text for further details).

First VVV RR Lyrae light curve

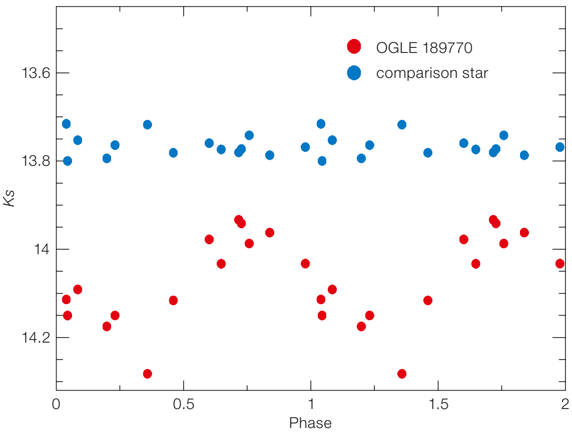
The detection of variable stars and the monitoring of their variability is the main goal of the VVV Survey. In Figure 5 we present the first, and preliminary, light curve of an RR Lyrae star obtained from the VVV SV data. The object, OGLE 189770, is an ab-type RR Lyrae star with a period $P = 0.72949$ days and an amplitude of 0.33 mag (Collinge et al., 2006). In *Ks*-band the minimum magnitude is $Ks \sim 14.2$ mag, with an amplitude of ~ 0.20 mag, smaller than that observed in *I*-band, as expected. The photometric accuracy of the data points in the light curve is ~ 0.05 mag. Our simulations show that, at a typical magnitude of $Ks \sim 15–16$ mag, we should be able to detect RR Lyrae stars with amplitudes down to 0.03–0.05 mag, using 100 phase points over the time frame of five years of the VVV Survey.

In parallel with the main VVV Survey, we are also obtaining a large database of high quality ("template") light curves in the *Ks*-band for different variability classes, using a variety of other telescopes. This will allow us to automatically classify an important fraction of the ~ 10^6 VVV *Ks*-band light curves. While automated classification is routinely accomplished in other variability surveys (e.g., Debosscher et al., 2007; 2009), the VVV Survey is the first of its type to be carried out in the NIR, where the required light-curve templates are, for the most part, not available in the literature.

First moving object

The VVV Survey will allow the detection of Solar System objects down to $Ks \sim 18$ mag. We are searching for Trans-Neptunian objects (TNOs), Jupiter Trojan asteroids (L5Js), Neptune Trojan asteroids (N5Js), Main Belt asteroids (MBAs), and near-Earth objects (NEOs). Since the VVV Bulge fields lie just on the Ecliptic, our search is limited to this region. Satellite tracks are also common and readily identified, even in the short VVV exposures.

As an example, Figure 6 shows MBA 199 Byblis, the first moving object detected by the VVV Survey while making the colour tiles. The sequence of observations (in this case taken on 23 October 2009) started with the *H*-band (green), 3 minutes later the *Ks*-band (red) was exposed, and finally 13 minutes later the *Z*-band (blue). The object was also recovered in *Ks*-band images acquired on 22 and 24 October 2009. 199 Byblis shows a magnitude of $Ks = 12.12$ mag and a motion of about 0.22 arcminutes/day. The excellent VISTA image quality (typically full width at half maximum < 1 arcsecond) and scale (0.34 arcseconds/pixel), also allows us to identify high proper motion stars with the survey baseline of 4–5 years



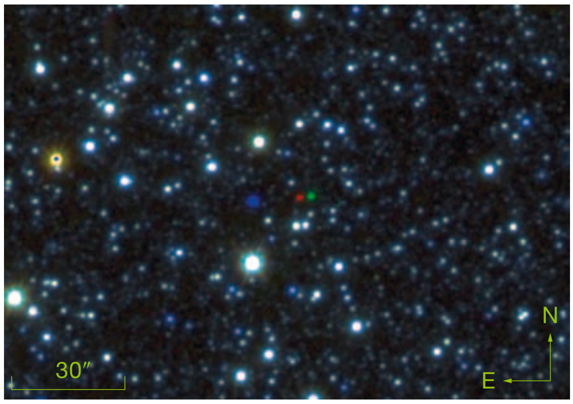


Figure 6. Main Belt asteroid 199 Byblis, the first moving object detected by the VVV Survey. It is the central object seen from left to right in filters *Z* (blue), *Ks* (red), and *H* (green). Bright saturated stars have *Ks* < 10 mag, and show a black dot in the centre.

Figure 5. (above) First VVV light curve for a Bulge RR Lyrae, obtained from the SV data. This ab-type RR Lyrae was identified from the OGLE sample, and has a period *P* = 0.72949 days (Collinge et al., 2006). The data are repeated in phase for better visualisation.

for faint objects, and with a baseline of more than ten years for bright objects with 2MASS. As a complementary project, we will also search for background QSOs in some selected fields, to provide an extragalactic frame for accurate astrometry.

Searching for new clusters and streams

Another goal of the VVV is to search for new star clusters of different ages. To trace the early stages of star cluster formation, we are carrying out a survey of infrared star clusters and stellar groups. These are found towards known massive star formation regions associated with methanol maser emission and hot molecular cores. Using the list of star-forming regions provided in Longmore et al. (2009), we have already identified 25 small star cluster candidates by visual inspection. Almost all of them seem indeed very young, because most of the mass is still concentrated in the gas. A typical example of a newly identified cluster candidate is shown in Figure 7. We are also studying the old metal-poor stellar population histories of the Milky Way Disc and Bulge, with the aim to find and study disrupted stellar streams produced during past accretion events.

Figure 7. Star cluster candidate identified in the VVV Survey. This cluster is located in a Disc field. The faintest stars in this picture have *Ks* ~ 17 mag.

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Links

[1] Visible and Infrared Survey Telescope for Astronomy (VISTA): http://www.vista.ac.uk
[2] VISTA Variables in the *Vía Láctea* project page: http://www.vvvsurvey.org
[3] VISTA Surveys page at the Cambridge Astronomical Survey Unit (CASU): http://casu.ast.cam.ac.uk/surveys-projects/vista
[4] Wide Field Astronomy Unit (WFAU) of the University of Edinburgh: http://horus.roe.ac.uk/vsa/