The Milky Way's Box/Peanut Bulge: Measuring its Three-dimensional Structure Using the VVV Survey

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A three-dimensional map of the density of red clump giant stars (RCGs) in the Galactic Bulge has been produced from the Data Release 1 of the ESO public survey VISTA Variables in the *Via Lactea* Survey (VVV). From the magnitude distributions of the RCGs we infer line-of-sight densities and, because the VVV survey has good Bulge coverage, we can combine many line-of-sight density measurements into a complete three-dimensional (3D) map. The 3D density shows a prominent peanut shape when viewed from the side, which appears very similar to simulations of barred galaxies after the bar has buckled, and some edge-on barred spiral galaxies.

The Milky Way's barred Bulge

Despite the proximity of the Bulge of the Milky Way, our position within the disc and the intervening dust makes it difficult to ascertain its structure. We have known since the early 1990s that the Bulge of the Milky Way is barred, based on evidence from gas kinematics and near-infrared (NIR) photometry. Subsequently Cosmic Background Explorer (COBE) data and the Two Micron All Sky Survey (2MASS) star counts showed that the central Bulge had a boxy, perhaps slightly peanut-like, shape. An extensive recent review of the Galactic Bulge can be found in Rich (2013).

Recent excitement has been stimulated by the observation that along the minor axis ($l \approx 0°$) at high latitudes ($|b| \gtrsim 4°$) the distribution of red clump giants splits into separate bright and faint components (e.g., McWilliam & Zoccali, 2010). RCGs are metal-rich core He-burning stars (i.e., metal-rich horizontal branch stars) and provide a standard candle with a *K*-band dispersion ≈ 0.17 mag.

It was quickly realised that the split red clump would be a natural consequence if the Milky Way's Bulge was peanut shaped with many stars travelling along banana-shaped orbits, which, from the side, trace an X-shape. From our nearly end-on perspective of the bar, the split red clump results from looking through both arms of the "X". This type of box/peanut bulge is known to be associated with a bar (e.g., Combes & Sanders, 1981) and is commonly observed in edge-on barred spiral galaxies (e.g., Lutticke et al., 2000).

The motivation for our work was that the VVV survey covers the whole Bulge, but is also deep enough (≈ 4 magnitudes deeper than 2MASS) to allow the RCGs to be detected all through the Bulge. Therefore, because RCGs are good distance indicators and should also trace the major part of the mass, we could use VVV to obtain an approximate distribution of stellar mass in the Bulge. This is important in itself, but is also indispensable for understanding the kinematics and dynamics of Bulge stars.

Line-of-sight densities through the Galactic Bulge

Our work utilised Data Release 1 (DR1) of the VVV public survey accessible through the ESO Science Archive Facility[1]. The VVV survey was described in Gonzalez et al. (2013), along with extinction and photometric metallicity maps of the Bulge. The work described here is more thoroughly explained in Wegg & Gerhard (2013).

We downloaded the VVV DR1 source catalogue in the *J*-, *H*- and *Ks*-bands from the ESO Science Archive Facility (SAF). These source lists are available in Phase 3 format[2]. These catalogues were band matched and then extinction corrected. The extinction map was calculated directly from *J–Ks* reddening of Bulge RCGs in the VVV data in a similar way to the map described in Gonzalez et al. (2013).

At low Galactic latitudes, completeness becomes a significant issue for Bulge RCGs, despite the greatly increased depth of VVV compared to previous NIR surveys of the Bulge. In order to understand and correct for this we also downloaded all the VVV *K*-band images from the ESO SAF. With these images we conducted artificial star tests: modelling the point spread function (PSF), inserting stars at various magnitudes into the images, and testing whether they were detected using the same software as developed by the Cambridge Astronomical Surveys Unit (CASU) to create the original catalogues. The artificial star tests allowed us to understand and correct for these completeness issues.

Magnitude distributions were then constructed using the extinction and completeness corrected *Ks*-band data for 338 sight-lines though the Bulge region of the VVV survey (each of the 169 Bulge fields in DR1 of the VVV survey was divided into two). We excluded stars whose colour was inconsistent with being RCGs, however there is still a considerable "background" of stars which are not red clump giants in the Bulge. Fortunately this background is smooth and very close to a power law in luminosity and we therefore statistically identify Bulge RCGs as an excess over this background.

The entire process of constructing the line-of-sight density is shown for one sight-line in Figure 1. We fitted the background in the grey shaded regions giving the blue-shaded RCG magnitude distribution. This is then deconvolved from the intrinsic luminosity function (green line). The background-subtracted magnitude distribution results from both the RCGs, and the red giant branch bump (RGBB), which is less prominent and slightly fainter than the red clump in the *Ks*-band, but with a similar dispersion. We then estimate the line-of-sight density (red line) using iterative Lucy–Richardson deconvolution, stopping when our measured density produces a magnitude distribution consistent with the data (blue line).

The 3D density map

The measured line-of-sight densities for all 338 sight-lines were then assembled into a three-dimensional density map. Our 3D density is non-parametric, however we make one assumption: that the density is eight-fold mirror symmetric along the Galactic bar. This allows us to make a complete 3D map despite DR1 of VVV not yet having 100% Bulge coverage. It also has the desirable side

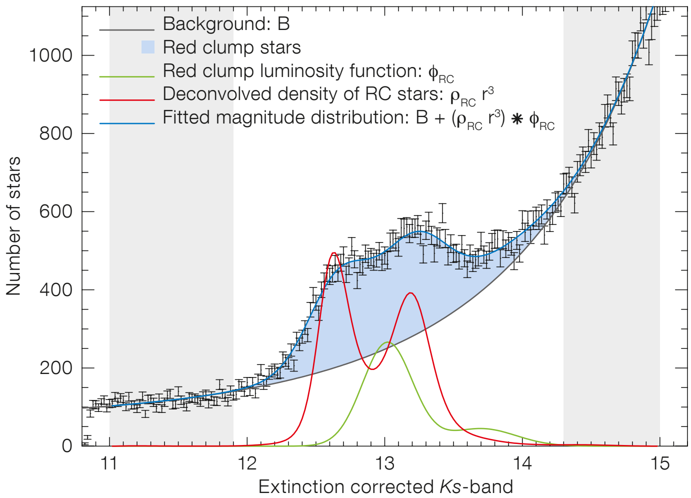

Figure 1. The process of constructing the line-of-sight density for one field at $b = -6°$, $l = 1°$ is illustrated. See text for details.

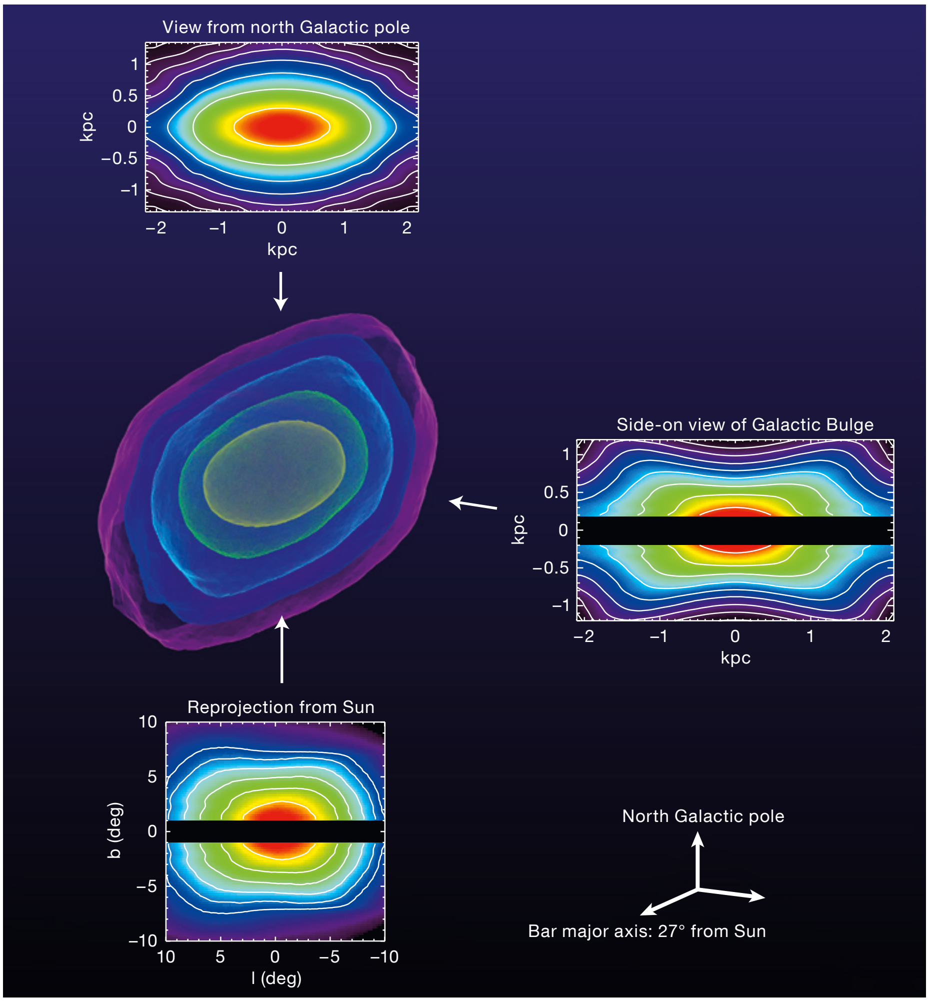

Figure 2. In the centre an image of the 3D iso-density contours of the measured Bulge density is shown, as projected by the VisIt Visualization Tool. Three projections are shown as surrounding plots: from above (i.e., from the north Galactic Pole), from the side (i.e. along the intermediate axis of the bar) and the re-projected surface density from the Sun. The three projections show the surface density of Bulge red clump stars with isophotes spaced by 0.5 mag.

effect of reducing dependence on the fitted background and intrinsic RCG luminosity function, and allows a simple error estimate for the density from the degree of departure from this eight-fold symmetry. This symmetrisation requires knowledge of the axes of the bar, which we find by minimising the differences between the eight assumed equal points. From this process we find the bar semi-major axis lies at 27° ± 2° to the Sun–Galactic Centre line-of-sight.

We graphically illustrate the properties of the resultant density map in Figure 2. From above, the measured Bulge density displays highly elongated isophotes with axis ratio ≈ 2.1:1. When viewed from the side, along the intermediate axis of the bar, the Bulge surface density shows a prominent peanut shape. The density has a short scale height in the centre of the Milky Way of 180 pc, but this scale height increases rapidly along the semi-major axis of the bar. Projecting the density measurement from the position of the Sun shows boxy isophotes, similar to the 2MASS star count maps (Alard, 2001).

Overall the density map seems remarkably similar to generic simulations of bars in which an initially thin, pure exponential disc of stars forms a bar that then buckles and evolves into a three-dimensional boxy/peanut bulge (e.g., Martinez-Valpuesta et al., 2006).

Perhaps the most interesting image is the prominent peanut shape in the side-on Milky Way projection. Cuts though this image are shown in Figure 3 together with similar cuts though NGC 128, the prototypical edge-on galaxy with a peanut bulge. The shaded regions on this plot are estimated systematic errors, formed by varying: (i) our assumptions about extinction; (ii) the intrinsic red clump luminosity function; and (iii) the form of the background distribution. The density generally seems robust at the ≈ 10 % level.

Towards an understanding of the origin of the Galactic Bulge

The Galactic Bulge is unique in that we are able to study individual stars in detail in a manner impossible in other galaxies.

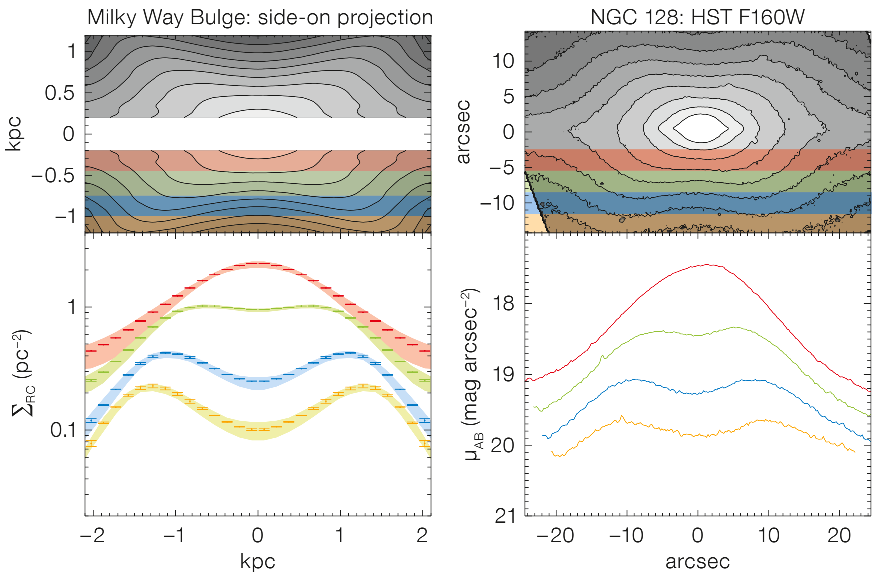

Figure 3. Cuts though the side-on projection of the Galactic Bulge density map on the left, and for NGC 128 on the right (data from Böker et al., 1999). In the upper plots isophotes are separated by 0.5 mag and the regions over which the density cuts are plotted in the lower figure are shaded. In the Galactic Bulge cuts, shown on the lower left figure, the shaded areas are the estimated systematic errors; the error bars are the internal errors of the fiducial density estimated from the departures from eight-fold symmetry. NGC 128 is the prototypical bulge with a peanut shape; although qualitatively similar it is in detail different. In particular, although the shape of the isophotes is quite similar, the Milky Way appears to be more centrally concentrated.

The density measured here, together with the kinematics which can be measured on a star-by-star basis, will allow a detailed understanding the dynamical structure of the Galactic Bulge. Meanwhile new spectroscopic surveys such as ARGOS (Ness et al., 2013) and the Gaia–ESO survey, are studying the metallicity, chemical composition, and kinematics of large numbers of stars across the Galactic Bulge. Comparing all this information to models should ultimately allow us to study and unravel its formation and evolutionary history to a level impossible in external galaxies.

Based on data products from VVV Survey observations made with the VISTA telescope at the ESO Paranal Observatory under programme ID 179.B-2002.

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Links

[1] Access to VVV data: http://archive.eso.org/wdb/wdb/adp/phase3_main/form
[2] Phase 3 format: http://www.eso.org/sci/observing/phase3/overview.html

ESO/J. Borissova

The VVV survey has discovered a large number of open clusters optically heavily obscured by intervening extinction and 30 of these new clusters are shown in this mosaic. Each image cut-out is a combination of *J*-, *H*- and *Ks*-band images (coded blue, green, red respectively) taken with VISTA. See Release eso1128 for more details.