Chapter 5
Photometric Surveys of the Galactic Bulge and Long Bar

O. Gerhard, C. Wegg, and M. Portail

Abstract The Galactic bar and box/peanut bulge can be studied in an unrivaled manner, star-by-star, with detailed chemical information and full 3D kinematics. Because of intervening dust this is greatly facilitated by the availability of wide field deep NIR photometric surveys. Here we summarize recent results on the three-dimensional structure of the bulge and the long bar region, based on 2MASS, UKIDSS, and particularly the ongoing VVV survey. We also summarize results from dynamical models for the Galactic bulge constructed with the Made-to-Measure method.

5.1 Photometric Surveys of the Galactic Bulge and Bar

It has been established from gas kinematics, near-Infrared (NIR) photometry, star counts, and stellar kinematics, that the Galactic bulge is barred [see 9, for an extensive recent review of the Galactic bulge]. Red clump giants (RCGs) are one of the primary tools used to establish the structure of the barred bulge. RCGs are core Helium burning stars and provide an approximate standard candle [13]. Large NIR photometric studies have now surveyed the entire bulge with sufficient depth to use RCGs as a probe. In Fig. 5.1 we show the deepest *K*-band surveys: the ongoing VVV survey [10] covers the central 10° and the southern galactic plane, UKIDSS [7] has surveyed the galactic plane at positive longitudes, while 2MASS remains the deepest survey away from the galactic plane. Only isolated areas remain without data of sufficient depth to use RCGs as a probe.

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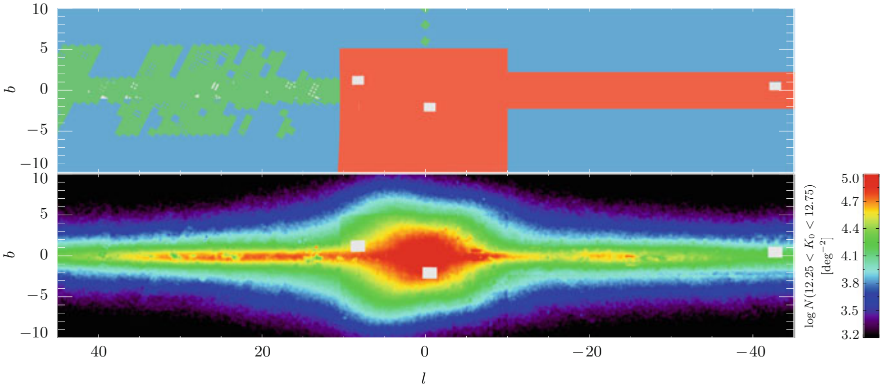

Fig. 5.1 In the *top figure* we show the deepest NIR surveys of the inner Galaxy: VVV DR2 in *red*, UKIDSS in *green*, and 2MASS in *blue*. *Grey regions* are those without data of sufficient depth to study clump stars i.e. close to the plane without VVV or UKIDSS data where 2MASS is insufficient. In the *lower panel* we show the resultant surface density of stars in the extinction corrected *K*-band magnitude range $12.25 < K_0 < 12.75$ (From [16])

5.2 The Structure of the Inner Milky Way

The VVV survey in particular is about 4 mag deeper and has a higher resolution than 2MASS. We exploited this in [14] to estimate the three-dimensional density using RCGs as a standard candle. We constructed extinction and completeness corrected magnitude distributions of VVV data for 338 fields covering the Galactic bulge. In these magnitude distributions RCGs were identified statistically as an excess over the otherwise smooth and nearly exponential background of non-RCG stars, which are mostly other giants in the bulge. The distribution of magnitudes of RCGs in each field arises from the convolution of the RCG luminosity function with the line-of-sight density. In each field we estimate the density by deconvolving using a variation on the Lucy-Richardson algorithm. The process of estimating the line-of-sight density is shown for one field in Fig. 5.2. These line-of-sight densities are then assembled into a non-parametric three-dimensional density assuming only eight-fold mirror symmetry about the principle axes of the bar with small symmerization errors. By varying details of the map construction process, such as the background fitting and the details of the luminosity function, we find the density seems robust at the ∼10 % level, while the symmetrization gives a bar angle of $(27 \pm 2)°$.

The resultant 3D density is shown in Fig. 5.3. From above the bulge is barred with axis ratio (2.1:1) while from the side a strong peanut or X-shape is seen similar to some external galaxies such as the prototypical peanut bulge in NGC128 [15].

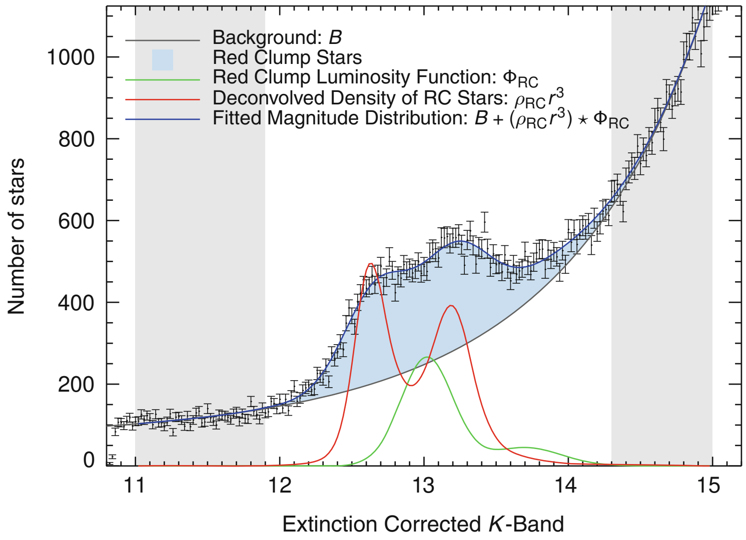

Fig. 5.2 The process of estimating the line-of-sight density of RCGs from the star counts in one bulge field. RCGs (*blue*) are statistically identified as stars above the smooth nearly exponential background of non-RCGs (*grey*). Then a variant of the Lucy-Richardson algorithm is then used to estimate the density (*red*) which when convolved with the luminosity function (*green*) is consistent with the data (Adapted from [14])

5.3 Made-to-Measure Dynamical Models of the Galactic Bulge

Because RCGs are good tracers of the stellar mass [11], their 3D density measurement can be used as a constraint on the stellar density in building dynamical models of the Galactic bulge. This has been done by [8] using the Made-to-Measure (M2M) modelling technique, which consists of adapting the N-body weights of an initial particle model until it reproduces a given set of data. We started from a set of five N-body models of a barred disk evolved in different dark matter halos, and fitted the stellar density to the RCGs density map as well as kinematic data from the BRAVA survey [6]. The kinematic data allow to recover the a priori unknown normalization factor between RCGs number density and the stellar mass density. This is shown in Fig. 5.4 where the velocity dispersion of the model matches the BRAVA data only for a specific value of the stellar mass in the bulge, which depends mostly on the dark matter mass present in the bulge. After M2M fitting, our set of models provides five equally good dynamical models of the bulge, even though their dark matter fractions range from 10 % to 30 %. We find that the total (stellar + dark matter) mass in the bulge, defined as the VVV RCG measurement box, is very well constrained by the RCGs density and the BRAVA data to $(1.84 \pm 0.07) \times 10^{10} M_{\odot}$.

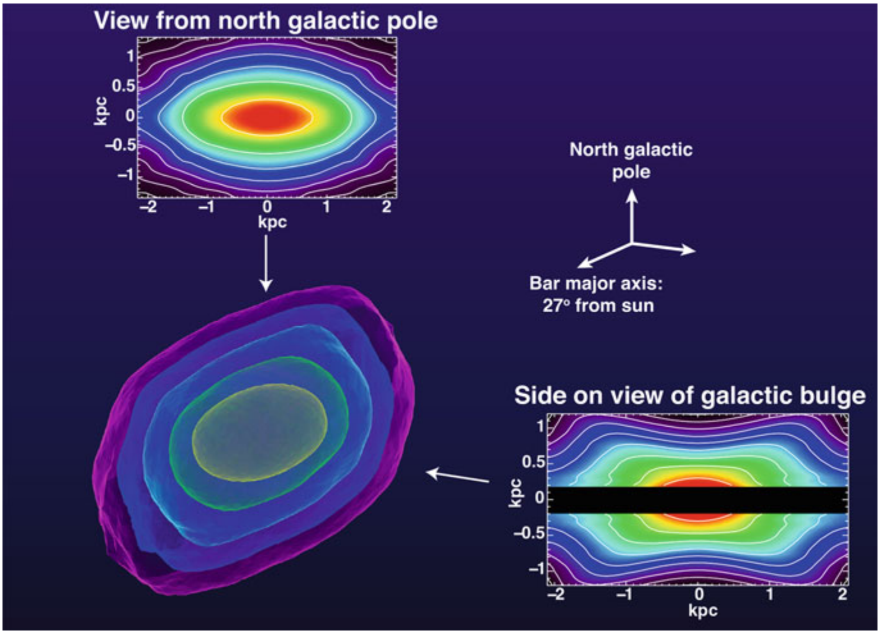

Fig. 5.3 The RCG density of the bulge. In the *center* we show the three-dimensional iso-density contours. The projections show the surface density from the north Galactic pole, where we see a bar with ≈2:1 axis ratio, and the view of the bulge from the side where we see a strongly peanut shaped bulge (Adapted from [15])

In addition, we used the COBE K-band measurements to compute the mass-to-light ratio of the models and compared them to predictions from population synthesis models. We measure stellar mass-to-light ratios ranging from 0.8 to 1.1, depending on the dark matter fraction. These are broadly consistent with predictions from the Initial Mass Functions (IMF) of [17] or [5], but are inconsistent with the [12] IMF that we therefore rule out for the Galactic bulge. The IMF from [17], directly measured from the bulge luminosity function, requires a large dark matter fraction in the bulge of about 40 %.

5.4 The Structure of the Bar Outside the Bulge: The Long Bar

While the structure of the barred bulge of the Milky Way has been extensively studied, the details of the bar outside this are very uncertain. The vertical scale height is smaller than in the bulge and it has therefore been termed the long bar. It can be seen in the surface density of stars in Fig. 5.1 as the enhancement close to the galactic mid-plane at positive longitudes. First investigated by [4] it has

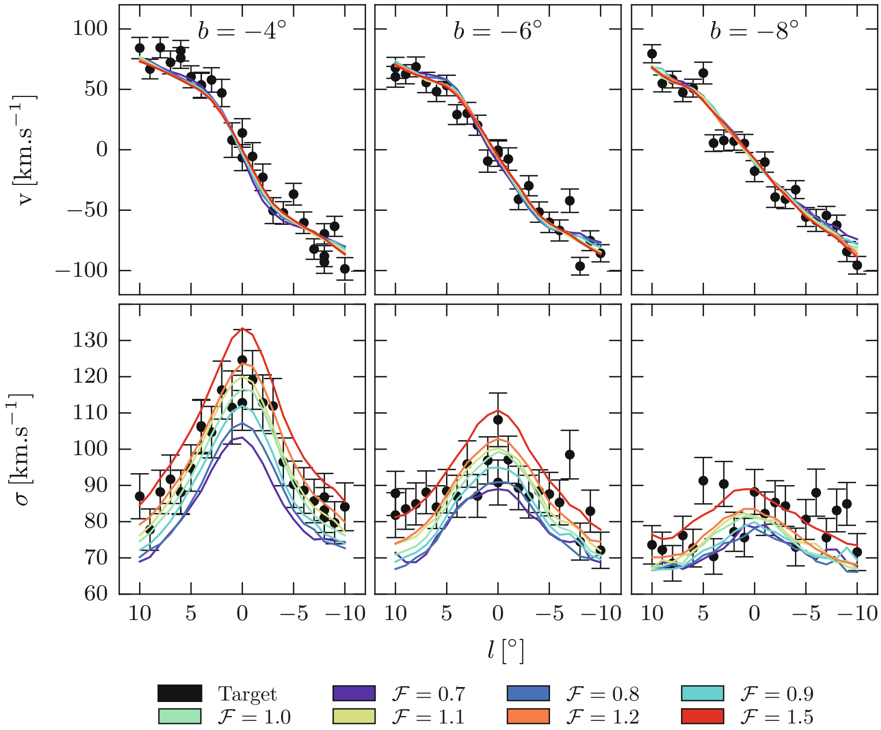

Fig. 5.4 Results of made-to-measure modeling of the Galactic bulge in [8] compared to the BRAVA data [6] in three latitude slices. The pattern speed of the bar and 3D density mostly determine the mean velocity in the *upper panels*. The stellar mass is varied by the $\mathcal{F}$ factor which primarily impacts the dispersion shown in the *bottom panels* (Adapted from [8])

subsequently been confirmed using RCGs with increasingly powerful NIR [e.g. 2] and longer wavelength GLIMPSE data [1]. Uncertainty remains however over the details of its structure and the relationship between the bar inside and outside the bulge.

We have matched and combined data from VVV, 2MASS and UKIDSS to get the widest possible view of the long bar covering $|l| < 40°, |b| < 9°$ [16]. By identifying RCGs in extinction free K-band magnitude distributions and using them as standard candles we have investigated the bar outside the bulge both directly in the data, and by constructing parametric density models which match the magnitude distributions. The combination of data allows us for the first time a large scale view of the long bar. A number of features are seen.

- The bar extends to $b \sim 5°$ at $l < 25°$, well outside the bulge region.
- Both in the data directly, and in our parametric density models, the bar outside the bulge has bar angle $\approx 29°$, consistent with alignment with the barred bulge.

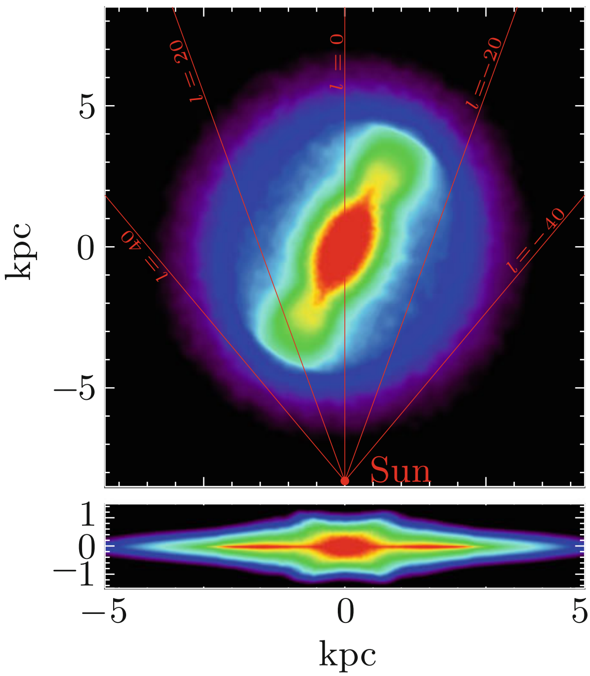

Fig. 5.5 The model density of the Milky Way viewed from above (*upper panel*) and from the side (*lower panel*). The density was constructed by adjusting the parameters of the density until the predicted magnitude distribution of RCGs matched the data across the region $-10° < l < 30°$ (Adapted from [16])

- The scale height of the RCGs smoothly transitions between a thicker scale height in the B/P bulge to the much thinner long bar. This scale height transition, and the alignment with the barred bulge, arises naturally in N-body models of barred galaxies and seems common in external galaxies [3].
- There is evidence for two scale heights in the long bar. We find a ∼180 pc thin bar component reminiscent of the old thin disk near the Sun, and a ∼45 pc super-thin bar component which exists predominantly towards the bar end.
- Constructing parametric models for the RCG magnitude distributions, we find a bar half length of 5.0 ± 0.2 kpc for the 2-component bar, and 4.6 ± 0.3 kpc for the 180 pc thickness bar component alone.

We show in Fig. 5.5 the face-on and side-on projections of one of our best fitting density models of the bar.

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