Formation Models of the Galactic Bulge

Ortwin Gerhard

1Max Planck Institute for extraterrestrial Physics, PO Box 1312, Giessenbachstr., 85741 Garching, Germany

Abstract. The Galactic bulge is now considered to be the inner three-dimensional part of the Milky Way’s bar. It has a peanut shape and is characterized by cylindrical rotation. In N-body simulations, box/peanut bulges arise from disks through bar and buckling instabilities. Models of this kind explain much of the structure and kinematics of the Galactic bulge and, in principle, also its vertical metallicity gradient. Cosmological disk galaxy formation models with high resolution and improved feedback models are now able to generate late-type disk galaxies with disk-like or barred bulges. These bulges often contain an early collapse stellar population and a population driven by later disk instabilities. Due to the inside-out disk formation, these bulges can be predominantly old, similar to the Milky Way bulge.

1. Introduction: the barred Galactic bulge

The Galactic bulge, subject of many studies here at CTIO observatory, is now considered to be the inner three-dimensional part of the Milky Way’s bar. Its triaxial shape was first established by the COBE NIR photometry (Blitz & Spergel 1991; Dwek et al. 1995; Binney et al. 1997; Bissantz & Gerhard 2002). Star counts confirmed this but also pointed to a larger, in-plane bar, the so-called ‘long bar’ (Stanek et al. 1994; López-Corredoira et al. 2005; Skrutskie et al. 2006; Benjamin et al. 2005; Cabrera-Lavers et al. 2007). Comparing the observed HI and CO lv-diagrams with hydrodynamic models showed that many of the observed features could be naturally, sometimes even quantitatively interpreted with gas flow models in barred potentials, modeled on the COBE data (Englmaier & Gerhard 1999; Fux 1999; Bissantz et al. 2003; Rodríguez-Fernández & Combes 2008).

In recent years, Galactic bulge studies have been revitalized by new large photometric and spectroscopic surveys. With these new data, the density and metallicity structure of the Milky Way’s bulge and its kinematics and dynamics have been mapped in much greater detail than possible before. Comparison of this information with models of bulge formation is promising to give us a better understanding of the origin of the Galactic bulge.

2. Box/peanut bulge models from disk instability

N-body simulations following the evolution of isolated disk galaxies have shown that stellar disks are often unstable to bar formation (Sellwood 1981; Athanassoula 2002; Debattista et al. 2006). Subsequently, the bar may quickly go through a second, so-
called buckling instability, resulting in the formation of an inner boxy bulge (Combes & Sanders 1981; Combes et al. 1990; Raha et al. 1991). The bar may then evolve by losing angular momentum to the dark matter halo, grow in size, and eventually go through a second buckling instability. This results in a a strongly peanut-shaped bulge (Martinez-Valpuesta et al. 2006) much like those seen in barred galaxies (Athanassoula 2005), which is supported by three-dimensional 2:1:2 resonant orbit families that support a characteristic X-shape (Pfenniger & Friedli 1991).

Recent star count and stellar kinematics data have shown that the predictions of these idealized models characterize the properties of the Milky Way bulge surprisingly well. The apparent magnitude plot for red clump stars in high-latitude pencil beams shows a clearly bimodal distance distribution, termed the 'split red clump'. This was first seen in 2MASS data (McWilliam & Zoccali 2010; Saito et al. 2011) but has also been confirmed with OGLE data (Nataf et al. 2010) and the ARGOS spectroscopic bulge sample (Ness et al. 2012). The split red clump is a signature of the X-shaped stellar orbits in the bulge. Recent deconvolution of the VVV DR1 star count data has shown that the Galactic bulge has the shape of a highly elongated bar with a strong peanut shape (Wegg & Gerhard 2013). The measured angle of the barred bulge to the line of sight is $(27^\circ \pm 2^\circ)$. Along the bar axes the density falls off roughly exponentially, with axis ratios $(10 : 6.3 : 2.6)$ and exponential scale-lengths $(0.70 : 0.44 : 0.18)$ kpc, but along the major axis the profile becomes shallower beyond 1.5 kpc.

N-body models with box/peanut bulges grown from unstable disks have been used to interpret not only the structure, but also the stellar kinematics and metallicity distribution of the Milky Way bulge. Gerhard & Martinez-Valpuesta (2012) showed that the flattening in the longitude profiles seen for $|l| < 4^\circ$ in low-latitude star counts (Nishiyama et al. 2005; Gonzalez et al. 2011) is naturally reproduced by the density distribution in a simulated box/peanut bulge. Li & Shen (2012) showed that their N-body model shows a similar split red clump as the Galactic bulge when viewed at an appropriate orientation. N-body bulges also explain the near-cylindrical rotation and the velocity dispersion profiles seen in the BRAVA (Kunder et al. 2012) and Argos (Ness et al. 2013a) spectroscopic surveys (Shen et al. 2010; Ness et al. 2013b).

The match of the models to the kinematic data is very good and Shen et al. (2010) concluded that it would be worsened even by a fairly small additional classical bulge. Such a classical bulge could have arisen from an early merger episode that preceded the growth and subsequent instability of the early disk. Saha et al. (2012); Saha & Gerhard (2013) showed that angular momentum transfer from the bar and boxy bulge can spin up the preexisting bulge, so that it too develops cylindrical rotation. The radial dependence of the rotation is different between the two bulges though; thus some more work is needed on this issue.

The strongest argument for a classical bulge in the Milky Way has been the observation of a strong vertical metallicity gradient (Zoccali et al. 2008; Johnson et al. 2011; Gonzalez et al. 2013). However, a recent analysis of an N-body bulge showed that this argument is not compelling. If the Milky Way’s bar and bulge formed rapidly from the disk at early times, then any preexisting metallicity gradients are preserved as vertical gradients in the final bulge, because of the incomplete violent relaxation during the instabilities (Martinez-Valpuesta & Gerhard 2013). Therefore, at present there is no strong evidence for a classical bulge in the Milky Way. Further chemodynamical analysis of the metallicity distribution and kinematics will be needed to clarify whether the Milky Way has a small classical bulge underneath its dominant peanut-shaped bulge,
and if so how this is related to the bulge metallicity components identified by Ness et al. (2013a) in the ARGOS sample.

The connection between the Milky Way’s peanut bulge and planar bar is much less explored, primarily because this region is observationally less accessible. Hammersley et al. (2000); Benjamin et al. (2005); Cabrera-Lavers et al. (2007) found evidence from starcounts for a ‘long bar’ at an angle of ~ 45°, apparently tilted relative to and therefore distinct from the barred bulge. Martinez-Valpuesta & Gerhard (2011) used an N-body model to argue that the long bar may nonetheless be the planar part of the same Galactic bar that contains the peanut bulge (see also Romero-Gómez et al. 2011). In their model, the outer parts of the bar oscillate from trailing to leading, coupling with nearby spiral arms which rotate at lower pattern speed (Tagger et al. 1987). Future APOGEE kinematic observations in this region (e.g. Nidever et al. 2012) will test the model predictions and shed more light on the dynamical transition between bulge, two-dimensional bar, and inner disk.

3. Bulges in cosmological disk galaxy simulations

Galaxies in the hierarchical universe grow continuously by accretion of matter, and they are subjected to a variety of external perturbations, for example, from merging satellites. Therefore, eventually the idealized disk simulations will need to be superseded by more realistic disk galaxy formation simulations embedded in a cosmological setting. It has only become possible recently to follow realistic high-resolution, fully cosmological simulations from high redshift to now. These models are already stimulating our understanding of bulge formation, but they still have considerable uncertainties in how the star formation and feedback processes are modelled.

As a reference point, I start with a brief discussion of the dissipative collapse model by Samland & Gerhard (2003). This may be viewed as a modern version of the dissipative collapse envisaged by Eggen et al. (1962). The model considered the formation of a large disk galaxy in a $2 \times 10^{12} \, M_\odot$, spinning ($\lambda = 0.05$) halo, with accretion history taken from cosmological simulations. Star formation and feedback were modelled by a 2-phase fluid/cloud fluid model calibrated on observed star formation rates, and the enrichment of Fe and α-elements was tracked separately. Axisymmetric collapse was followed excluding all minor mergers.

In this dissipative collapse, the galaxy formed from inside out. The star formation history closely followed the gas accretion history. The disk grew from initially small, thick and dynamically hot to a large, thin and cold disk at redshift $z = 0$. The final bulge consisted of at least two stellar populations. One was formed in the early rapid collapse phase, the second was formed later in the disk which grew bar unstable. They differed by their [$\alpha$/Fe]-ratios; the final bulge contained [$\alpha$/Fe]-enhanced stars for a range of [$Fe/H$], and also some super-solar stars made from gas channeled inwards by the bar. This illustrates the chemodynamical signatures which can be used to understand the origin of the Milky Way bulge from the new data.

Obreja et al. (2013) compared the properties of bulges made in some of the recent cosmological simulations, from Brook et al. (2012); Doménech-Moral et al. (2012). Generally, these simulations employ strong feedback to prevent overproduction of stars at early times. As in the dissipative collapse model, the star formation rate (SFR) in these simulations closely follows the mass accretion rate, and the formation history can be divided into an early starburst-collapse phase and a later phase with lower SFR
driven by disk instabilities and minor mergers. The stellar populations show corresponding age and metallicity distributions, with the old population being more metal poor and \(\alpha\)-enhanced. Most of the old population found in the final bulge formed in disjoint places along filaments at high redshift (as opposed to in the early collapsing halo in the dissipative collapse model).

One can associate the rapid phase with a classical bulge, and the late phase with a box/peanut or disky bulge. Such a classical bulge is clearly different from a bulge formed by a late major merger. In all of the five simulations analyzed by Obreja et al. (2013), both components were present, with different mass ratio. Guedes et al. (2013) and Okamoto (2013) followed the evolution of such ‘pseudo-bulges’ in very high resolution simulations. The structure of these bulges is characterized by a Sersic index around \(n = 1 \pm 0.5\), possibly depending on the feedback model. One important result from these simulations is that, because of the inside-out formation, the inner bulge region can form early and consist of predominantly very old stars, whereas the disk further out has a much more uniform star formation history. In the Eris simulation of Guedes et al, the bulge is built from the early, low-angular momentum part of the disk. This model does not have a final box/peanut bulge like in the Milky Way, but it illustrates how the bulge stars could be very old as is observed in Baade’s window in the Galactic bulge.

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