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The well-defined structure of boxy bulges

Implications for the Milky Way bulge formation

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Abstract. Some results of idealized, dissipationless, N-body simulations which follow the formation and subsequent buckling of a stellar bar are presented in this contribution, and compared to the properties of the stellar populations in the Milky Way bulge. We find that: (i) the redistribution of stars in the disk initiated at the epoch of bar formation implies that it is the whole stellar disk that contributes to the boxy/peanut shaped structure; (ii) the contribution of stars to the local bulge density depends on their birth radius: stars born in the innermost disk tend to dominate the innermost regions of the boxy bulge, while outer stars become dominant in the external part of the boxy/peanut structure. As detailed in Di Matteo et al. (2014), stellar birth radii are imprinted in the bulge kinematics, that is the higher the birth radius of stars ending up in the bulge, the larger their rotational support and their line-of-sight velocity dispersions. On the basis of their chemical and kinematic characteristics, we suggest that the populations A, B and C, as defined by the ARGOS survey, can be associated, respectively, to the inner thin disk, to the young thick and to the old thick disk, following the nomenclature recently suggested for solar neighborhood stars by Haywood et al. (2013).

Key words. THESE STARSMethods: numerical – Galaxy: bulge – Galaxy: evolution– Galaxy: kinematics and dynamics – Galaxy: abundances – Galaxies: structure

1. Introduction

Boxy and peanut shaped bulges are present in about half of edge-on disk galaxies (Lütticke et al. 2000). The closest example of a boxy bulge can be found in our Galaxy, as revealed by infrared studies. A number of numerical works (Combes & Sanders 1981; Pfenniger et Friedli 1991; Athanassoula 2005; Martinez-Valpuesta et al. 2006) have shown that boxy bulges can be the manifestation of secular processes in disk galaxies, being thick stellar bars seen edge on. During their evolution, stellar bars can indeed go through one (or multiple) buckling phases, consequences of vertical instabilities, and depending on the bar viewing angle, the resulting thick structure can appear boxy, if seen mostly along the bar major axis, or peanut-shaped, if seen mostly along the bar minor axis.

Observations suggest that boxy bulges do not represent a homogeneous class of objects. Extragalactic boxy bulges display a range of rotational and stellar population properties (Williams et al. 2011). Also the boxy, peanut-shaped structure at the center of our Galaxy shows very complex kinematic and chemical properties, with the possible concomitance of different stellar populations (McWilliam & Rich 1994; Zoccali et al. 2006; Lecureur et al. 2007; Babusiaux et al. 2010; Bensby et al. 2013), but no consensus has been reached yet on the interpretation of these data.

The recent ARGOS survey (Freeman et al. 2013), in particular, is mapping the Galactic bulge over a large extent of latitudes and longitudes, contributing to our understanding of how the bulge populations differ in their spatial redistribution, chemical properties and kinematics (Ness et al. 2012, 2013a,b). The results of this survey suggest the existence of at least three main components in the Milky Way bulge. Two components (defined respectively as component A and B in their paper), with [Fe/H]>-0.5 dex, are part of the boxy/peanut shaped bulge, with component B ([Fe/H]~-0.25 dex) being kinematically hotter than component A ([Fe/H]~0.1 dex), rotating 20% faster than A, and being more prominent at high latitudes; component C ([Fe/H]<-0.5 dex) has the highest radial velocity dispersions in the analyzed fields, nearly constant both in latitude and longitude, and has been explained by Ness and collaborators as part of the inner thick disk. In this contribution, I will present some recent results (see Di Matteo et al. 2014, for details) showing that at least part of the characteristics observed among the stellar populations of the Galactic bulge can be explained as the simple result of the mapping of a stellar disk into a boxy/peanut shaped structure. It is the *whole stellar disk* that is involved in the formation of a boxy/peanut structure, as a result of the radial migration initiated before the buckling instability by the bar formation. Since the whole stellar disk is mapped into a boxy bulge, the stellar populations observed in the Milky Way bulge should reflect the kinematic and chemical characteristics of the entire disk at the epoch of the bar formation.

2. The simulations

All the simulations analyzed for this work have been already presented in Di Matteo et al. (2013). They consist of an isolated disk, with a varying bulge-to-disk ratio (B/D=0., 0.1 and 0.25, respectively), and containing no gas. The dark halo and the optional bulge are modeled as a Plummer sphere. The galaxy is represented by $N_{\mathrm{tot}} = 30720000$ particles redistributed among dark matter ($N_{\mathrm{H}} = 10240000$) and stars ($N_{\mathrm{stars}} = 20480000$). The evolution of these isolated disks is followed for 4 Gyr, by means of a Tree-SPH code (Semelin & Combes 2002). A Plummer potential is used to soften gravity at scales smaller than $\epsilon = 50$ pc.

3. Mapping a stellar disk into a boxy bulge

As a consequence of the angular momentum redistribution initiated by the bar and spiral arms, stars tend to diffuse in the disk as soon as stellar asymmetries start to develop. However, while stars inside the inner Lindblad resonance stay mostly confined in the inner bar regions (see also Martinez-Valpuesta & Gerhard 2013; Pfenniger et Friedli 1991), outer disk stars, in particular those at and beyond corotation, migrate both outward and inward, reaching both the edges and the center of the disk. In few rotational periods at the epoch of formation of the stellar asymmetries, outer disk stars are able to reach the inner disk, contributing to populate the bar: their distribution shows indeed a clear $m = 2$ asymmetry elongated with the bar major axis and tends to accumulate in two stellar overdensities at the edges of this structure (see Fig. 1, face on views). At the onset of the bar vertical instability, those stars that are close to the vertical inner Lindblad resonance (VILR), which is at about 6 kpc from the center in our models, are scattered to larger heights becoming part of the boxy/peanut-shaped structure. Since, as we have shown, stars from a large range of initial birth radii are able to reach the bar region before its vertical buckling, the resulting bulge is populated by a mixture of populations, from stars born in situ (i.e. in the inner disk) to stars coming from all the outer radii, from those just outside the bar to the outermost disk.

These stars of different provenance are not redistributed randomly in the bulge, but they appear to form a well defined structure (see Fig. 2): stars born in the innermost disk tend

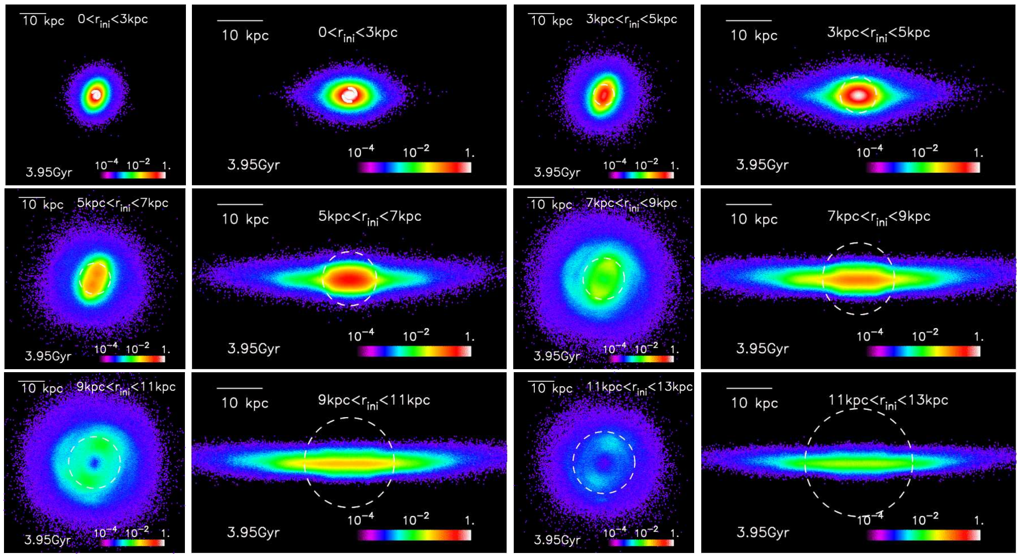

Fig. 1. Face-on and edge-on distribution of stars born at different radii. The average initial radius is indicated by a dashed white circle and the bar is inclined by 20 degrees with respect to the observer line-of-sight. See Di Matteo et al 2014, for details.

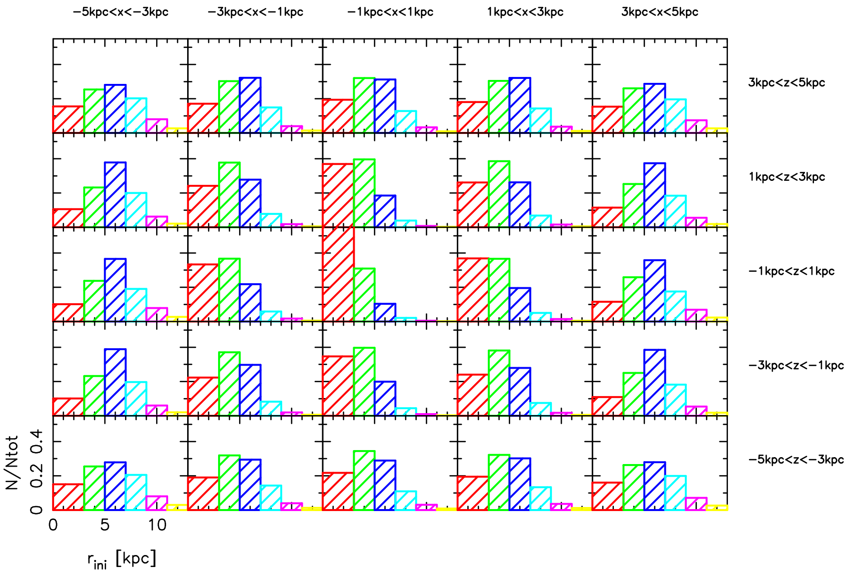

Fig. 2. Histograms of the birth radii of stars which populate the boxy bulge at time t = 3.95 Gyr, for the galaxy with B/D=0. In each panel, stars have been divided accordingly to their initial birth radius: $r_{ini} \leq$ 3 kpc (red); 3 kpc $\leq r_{ini} \leq$ 5 kpc (green); 5 kpc $\leq r_{ini} \leq$ 7 kpc (blue); 7 kpc $\leq r_{ini} \leq$ 9 kpc (cyan); 9 kpc $\leq r_{ini} \leq$ 11 kpc (purple); 11 kpc $\leq r_{ini} \leq$ 13 kpc (yellow). Each panel corresponds to an element of the grid shown on the top-right of the figure. For each of those elements, the contribution of stars of a given provenance in the disk has been normalized to the total number of stars which populate that element.

to dominate the innermost regions of the boxy bulge, while outer stars become dominant in the external part of the boxy/peanut structure. Stellar birth radii are also imprinted in the bulge kinematics, the higher the birth radius of stars ending up in the bulge, the larger their rotational support and their line-of-sight velocity dispersions (but note that this last trend depends on the bar viewing angle).

4. On the origin of the populations in the Milky Way bulge

As shown by Ness et al. (2013a), the three main components found in the bulge – A, B and C – form a sequence in chemical characteristics, from population A (mean [Fe/H] and [α/Fe]$\sim$ 0.1 dex), to population B (mean [Fe/H]$\sim$ -0.25 dex and [α/Fe]$\sim$ 0.2 dex), to population C, the most metal-poor (mean [Fe/H]$\sim$ -0.7 dex) and $\alpha-$enriched ($\sim$ 0.3 dex). This sequence is reminiscent of that found at the solar vicinity and may thus imply, for stars in the bulge, the existence of an age sequence similar to that found at the solar vicinity by Haywood et al. (2013). In this scheme, component B would be associated to the young thick disk, and thus would be kinematically colder than its more metal-poor counterpart, the old thick disk, that is component C.

Moreover, following Ness et al. (2013b), the weight of component A decreases with latitude, and its rotational support and velocity dispersions are lower than those of component B. According to our models, these trends can be explained if component A formed, on average, closer to the Galaxy center than component B. In our interpretation, component A is dominated by the metal rich thin disk, which represents only a modest contribution to the metallicity distribution at the solar vicinity, but seems to become more dominant in the inner disk, at least for 4 kpc $\leq$ R $\leq$ 7 kpc (see Anders et al. 2013).

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