Stars Behind Bars. I. The Milky Way’s Central Stellar Populations

Tobias Buck1,a, Melissa K. Ness1, Andrea V. Macciò1,2, Aura Obreja3,a, and Aaron A. Dutton2
1 Max-Planck Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany; buck@mpia.de
2 New York University Abu Dhabi, PO Box 129188, Abu Dhabi, UAE
3 Universität-Sternwarte München, Scheinerstr.1, D-81679 München, Germany
Received 2017 November 14; revised 2018 May 17; accepted 2018 May 26; published 2018 July 9

Abstract

We show for the first time that a fully cosmological hydrodynamical simulation can reproduce key properties of the innermost region of the Milky Way (MW). Our high-resolution simulation reproduces qualitatively the profile and kinematics of the MW’s boxy/peanut-shaped bulge, and hence we can use it to reconstruct and understand the bulge assembly. In particular, the age dependence of the X-shape morphology of the simulated bulge parallels the observed metallicity-dependent split in the red clump stars of the inner Galaxy. We use this feature to propose an observational metric that (after calibrated against a larger set of simulations) might allow us to quantify when the bulge formed from the disk. The metric we propose can be employed with upcoming survey data to constrain the age of the MW bar. From the split in stellar counts we estimate the formation of the 4 kpc scale bar in the simulation to have happened \( t_{\text{form}}^{\text{bar}} \sim 8.2 \) Gyr ago, in good agreement with conventional methods to measure bar formation in simulations. We test the prospects for observationally differentiating the stars that belong to the bulge/bar compared to the surrounding disk, and we find that the inner disk and bulge are practically indistinguishable in both chemistry and ages.

Key words: dark matter – galaxies: bulges – galaxies: formation – galaxies: individual (Milky Way) – galaxies: kinematics and dynamics – methods: numerical

1. Introduction

Almost 50% of all nearby galaxies show signs of a boxy- or peanut-shaped bulge (Lütücke et al. 2004), and our Galaxy, the Milky Way (MW), is observed to host a boxy/peanut-shaped bulge and a galactic bar (Okuda et al. 1977; Blitz & Spergel 1991; Weiland et al. 1994; Dwek et al. 1995). The major axis of the MW’s Galactic bar is inclined by about 27° with respect to the line of sight, and it reaches out to about 3.5 kpc (Gerhard 2002; Wegg et al. 2015), with the bar extending in the plane up to about 5 kpc (Portail et al. 2017).

The formation scenario of boxy/peanut-shaped bulges from the galactic disk is well studied in idealized simulations, and several mechanisms have been identified whereby stars of the disk become the boxy bulge. Isolated N-body simulations of galaxies have shown that boxy/peanut-shaped bulges can form in situ via disk instabilities (Bureau & Freeman 1999; Athanassoula & Martinez-Valpuesta 2009), where flat disks develop a bar after only a few revolutions. This bar then puffs up into a boxy/peanut-shaped bulge structure (Raha et al. 1991; Merritt & Sellwood 1994; Bureau & Athanassoula 2005; Debattista et al. 2006) via a vertical instability, the so-called buckling instability. The formation of boxy/peanut-shaped bulges has also been explained by orbit trapping, into a vertical Lindblad resonance during bar growth (Combes & Sanders 1981; Quillen 2002; Quillen et al. 2014) and via orbits associated with vertical resonances (Combes et al. 1990; Pfenniger & Friedli 1991). However, there is no overall agreement as to what specific orbits actually make up the boxy/peanut-shaped bulge of the Galactic bulge of the MW, and in what relative fraction (see, e.g., Portail et al. 2015a, 2015b).

The observational evidence suggests that the MW’s boxy/peanut-shaped bulge has, in large part, formed from the disk (e.g., Ness et al. 2012). However, the time of formation and the details of the subsequent evolution are uncertain. Additionally, the fraction of any underlying component that is not associated with the disk and whether this is a classical bulge or part of the inner halo are under debate. Not only is the bulge observed to be boxy in photometric images, but also the red clump stars in the center of our Galaxy are split into two components well separated along the line of sight (McWilliam & Zoccali 2010; Nataf et al. 2010). The interpretation of this phenomenon is an underlying X-shaped structure in the bulge (Saito et al. 2011; Li & Shen 2012; Ness et al. 2012), a clear signature of formation from the disk. This split shows different properties for different metallicity populations; the metal-rich populations show the strongest split, while the metal-poor stars show a weaker split, with no split seen below \([\text{Fe}/\text{H}] < -0.5\) (e.g., Ness et al. 2012; Uttenthaler et al. 2012; Rojas-Arriagada et al. 2014).

Many N-body models of bulge formation starting from a pure thin disk with evolving disk instabilities can alone explain the overall observed characteristics of the MW’s bulge (Martinez-Valpuesta & Gerhard 2013; Vásquez et al. 2013; Gardner et al. 2014; Zoccali et al. 2014). Data from the BRAVA (Howard et al. 2008), ARGOS (Freeman et al. 2013), and APOGEE surveys (Majewski et al. 2017) have revealed cylindrical rotation in the bulge of the MW (Howard et al. 2009; Ness et al. 2013b, 2016b), which is characteristic of an cigar-shaped peanut bulge. Moreover, using BRAVA kinematics (Kunder et al. 2012), Shen et al. (2010a) constrained any merger-generated component of the bulge to be less than 8%.

However, the stars in the MW’s bulge show not only different morphology as a function of metallicity (e.g., Dékány et al. 2013; Portail 2016) but also different...
Cosmological simulations are the means to link and understand the far and near universe but have typically had a hard time reproducing realistic bulges observed in spiral galaxies. Due to its inherent hierarchical nature, ΛCDM simulations of galaxy formation predict that galactic spheroids are primarily built up through hierarchical mergers (e.g., Kauffmann et al. 1993; Abadi et al. 2003; Kobayashi & Nakasato 2011; Guedes et al. 2013) that produce an old classical bulge, incompatible with a boxy/peanut-shaped bulge, as is observed in our Galaxy (Weiland et al. 1994; Dwek et al. 1995).

In this paper we use, for the first time, a fully cosmological hydrodynamical simulation of galaxy formation to study the inner region of a galaxy showing a bulge that is like that of the MW. We will establish the similarity of the simulated bulge with the observed features of the MW bulge, and—critically—we can make predictions for the properties of the bulge, the bar, and the surrounding disk in age, chemistry, and dynamics. By comparing the properties of bulge stars to properties of other components of this galaxy (thin disk, thick disk, or halo) and by tracing the stars from the inner region through time, we can understand the mass assembly of the bulge and disentangle effects of secular evolution from accretion.

This paper is organized as follows: In Section 2 we present the model galaxy and its general properties and describe the simulation code. We continue in Section 3 with a comparison of general bulge properties of our simulation and properties such as the rotation and dispersion profiles of bulge stars and the split in the line-of-sight counts of stars, which we examine in different age bins. We develop an observational metric to measure the age of the bar from the split, a critical step toward making quantifications from simulations to directly test with new generations of surveys. In Section 4 we compare properties of stars in the bar with stars in the disk, showing that neither chemistry nor ages will allow the populations to be distinguished. Finally, in Section 5 we summarize our results and conclude.

2. Simulation

The simulation analyzed in this work is a higher-resolution version of the galaxy g2.79e12 from the Numerical Investigation of a Hundred Astronomical Objects (NIHAO) project (Wang et al. 2015). The hydrodynamics, star formation recipes, and feedback schemes exploited are the same as for the original NIHAO runs, which we summarize below.

Galaxies from the NIHAO sample have been proven to match remarkably well many of the properties of observed galaxies. This includes results from abundance matching (Wang et al. 2015), the local velocity function (Macciò et al. 2016), metal distribution in the circumgalactic medium (Gutcke et al. 2016), and the properties of stellar and gaseous disks (Obreja et al. 2016; Dutton et al. 2017), or the morphological properties of high-mass galaxies at high redshift (z \sim 0.5–3; Buck et al. 2017). Therefore, this galaxy is well studied, and because it has a strong bar, it is well suited to investigate the kinematical and morphological properties of a bulge system similar to the MW’s bulge. An impression of the galaxy’s face-on and edge-on projections is given in Figure 1.
2.1. Hydrodynamics

This high-resolution simulation was run with a modified version of the smoothed particle hydrodynamics (SPH) code GASOLINE2.0 (Wadsley et al. 2017), which includes substantial updates to the hydrodynamics as described in Keller et al. (2014) to alleviate known shortcomings of the SPH method (Agertz et al. 2007). The modifications of the hydrodynamics improve multiphase mixing and remove spurious numerical surface tension (Ritchie & Thomas 2001). We adopted a metal diffusion algorithm between particles as described in Wadsley et al. (2008), and the treatment of artificial viscosity has been modified to use the signal velocity as described in Price (2008). Furthermore, the Saitoh & Makino (2009) time step limiter was implemented, and ESF-GASOLINE2 now uses the Wendland C2 smoothing kernel (Dehnen & Aly 2012) to avoid pairing instabilities.

Gas cooling is implemented via hydrogen, helium, and various metal lines as described in Shen et al. (2010b), and cooling functions are calculated using Cloudy (version 07.02; Ferland et al. 1998). Furthermore, the effects of photoheating and photoionization from the Haardt & Madau (2005) UV background and from Compton cooling in a temperature range from 10 to 10^9 K are included.

2.2. Star Formation and Feedback

The star formation recipe in the simulation follows the one described in Stinson et al. (2006). Dense and cool gas (n_neb > 10.3 cm^{-3}, T < 15,000 K) is eligible to form stars reproducing the Kennicutt–Schmidt law. The threshold number density n_neb of gas is set to the maximum density at which gravitational instabilities can be resolved in the simulation: n_neb = 50 m_{gas}/\epsilon_{gas}^3 = 10.3 \text{ cm}^{-3}, where m_{gas} denotes the gas particle mass, \epsilon_{gas} denotes the gravitational softening of the gas, and the value of 50 denotes the number of neighboring particles.

Two modes of stellar feedback are implemented as described in Stinson et al. (2013b). The first mode models the energy input from stellar winds and photoionization from luminous young stars and happens before any supernovae explode. The energy input for this mode consists of the total stellar flux, 2 \times 10^{50} \text{ erg of thermal energy per } M_{\odot} \text{ of the entire star population}, and the efficiency parameter for the coupling of the energy input is set to \epsilon_{ESF} = 13\% (Wang et al. 2015).

The second mode models the energy input from supernovae and starts 4 Myr after the formation of the star particle. It is implemented using the blast wave formalism as described in Stinson et al. (2006) and applies a delayed cooling formalism for particles inside the blast region to avoid the artificial fast energy loss of the feedback energy in the dense regions of the interstellar gas surrounding the supernova explosions due to its efficient cooling. See Stinson et al. (2013b) for further information and an extended feedback parameter search.

2.3. Galaxy Properties

This galaxy has been run using cosmological parameters from Planck Collaboration et al. (2014), namely, \Omega_{m} = 0.3175, \Omega_{\Lambda} = 0.6825, \Omega_{b} = 0.049, \mathcal{H}_{0} = 67.1 \text{ km s}^{-1} \text{ Mpc}^{-1}, and \sigma_{8} = 0.8344. The mass resolution of this simulation is m_{dark} = 5.1 \times 10^5 M_{\odot} for dark matter particles and m_{gas} = 9.4 \times 10^4 M_{\odot} for the gas particles. The initial star particle mass is set to 1/3 \times m_{gas} = 3.1 \times 10^4 M_{\odot}. The corresponding force softenings are \epsilon_{dark} = 620 \text{ pc} for the dark matter particles and \epsilon_{gas} = \epsilon_{star} = 265 \text{ pc} for the gas and star particles (see also Table 1). However, the smoothing length of the gas particles (the scale of hydrodynamical forces) can be much smaller, e.g., as low as h_{smooth} \sim 20 \text{ pc}.

The main properties of this galaxy can be found in Table 2. The total mass within the virial radius (R_{vir} \sim 300 kpc) is M_{tot} = 3.13 \times 10^{12} M_{\odot}, and the stellar mass of the galaxy (measured within 0.1 \times R_{vir}) is M_{star} = 1.59 \times 10^{11} M_{\odot}. The galaxy’s stellar disk has a scale length of R_d \sim 5 kpc and a total scale height of H_z \sim 500 pc within the innermost 5 kpc and H_z \sim 1 kpc in the outskirts at R > 10 kpc.

Table 1

| Property        | Particle Mass (10^5 M_{\odot}) | Force Soft. (pc) | Smoothing Length (median, min.) (pc) |
|-----------------|---------------------------------|------------------|-------------------------------------|
| DM              | 5.141                           | 620              | ...                                 |
| GAS             | 0.938                           | 265              | (155, 20)                           |
| STARS           | 0.313                           | 265              | ...                                 |

Figure 1. Stellar composite image of the galaxy in face-on and edge-on projections. We use r, v, and z-band fluxes to create the r, g, and b maps. The colors are based on luminosities found using Padova simple stellar populations from Girardi and Marigo (Marigo et al. 2008; Girardi et al. 2010). We did not run a radiative transfer code to account for dust attenuation.
see in the center of our MW is the bar, and this is the same as the bulge (when viewed edge-on), which appears to be boxy/peanut shaped. Therefore, throughout the rest of the paper we will use (boxy/peanut-shaped) bulge or bar for referring to the same thing. If we take all stars in the inner region, including the disk surrounding the bar, we refer to the innermost region of the MW. At redshift zero the bar in the simulation extends out to about 4 kpc from the galactic center. We characterize the bar in our simulation using the:

\[ A_2 = \sum_j \exp(i2\varphi_j)m_j, \]  

where \( m_j \) and \( \varphi_j \) are mass and azimuth angle of the stars, respectively. The sum extends over all stars in the considered region (spherical bins) of the galaxy. This \( m = 2 \) mode encodes the bar strength defined as

\[ A_2/A_0 = \frac{|A_2|}{\sum_j |m_j|}. \]

We use this quantity to estimate the formation time of the bar as a function of radius (see Figure 2). In Figure 2 we show the bar strength \( A_2/A_0 \) as a function of radius at several redshifts represented by the different colors. After an initial strong fluctuation of the bar strength due to a violent, merger-dominated phase before redshift \( z = 2 \), the bar strength grows continuously from redshift \( z \approx 2 \) onward. Before \( z = 1 \) the value of \( A_2/A_0 \) in the innermost 4 kpc is relatively low, while after that time it shows a larger value, \( A_2/A_0 \sim 0.17 \). This is the signature of a bar extending up to \( \sim 4 \) kpc. The bar in this simulation is first clearly visible in surface density images at redshift \( z = 1.3 \) or \( \sim 8 \) Gyr ago, and from then onward it grows in strength and size. At redshift \( z \approx 0.75 \) or equivalently \( \sim 6.5 \) Gyr ago, the bar buckles, forming the boxy/peanut-shaped bulge. This process causes a reduction in bar strength and an increase in vertical velocity dispersion. Thus, we conclude that the bar in our simulation formed between \( \sim 10 \) and \( 8 \) Gyr ago at a redshift of \( z \sim 2 \) as can be confirmed by visual inspection.

3. Bulge Properties: Comparison to the MW

In this section we compare the properties of the bulge region of our simulation to key observations from our own Galaxy to establish the similarity between the simulation and the MW. In the analysis that follows we place the Sun at \((x, y, z) = (8, 0, 0)\) kpc and rotate the simulation such that the bar is inclined at \(27^\circ \) with respect to the line of sight to match the position of the Sun in the MW (Wegg & Gerhard 2013). We then transform all coordinates to galactic longitude and latitude \((l, b)\).

3.1. The Age Distribution of Bulge Stars

Figure 3 shows the age distribution of the stars in our model galaxy, for stars of the disk within 25 kpc from the galactic center and at a height smaller than 6 kpc from the midplane. Three spatial bins are shown: (i) stars in the inner galaxy, <3.5 kpc from the galactic center but excluding the bar; (ii) stars in the bar selected to meet the spatial selection criteria \(-3.5 < x/\text{kpc} < 3.5\), \(-1.25 < y/\text{kpc} < 1.25\), and \(-1.0 < z/\text{kpc} < 1.0\) (for the bar aligned with the \(x\)-axis); and (iii) stars of the disk outside of the inner 3.5 kpc. Our model galaxy
shows a wide distribution of stellar ages ranging from 0 to \( \sim 14 \) Gyr with a peak around 10–11 Gyr and a tail toward lower ages with a slight peak for very young stars (<3 Gyr). The distribution of stellar ages in the outer disk and in the bar is very similar. However, the inner disk excluding the bar shows a lower (larger) proportion of young (old) stars. This points toward a preferential origin of bar stars from the outer disk, which we study in much more detail in a follow-up paper (Buck et al. 2018a). We will come back to the similarity of ages in the inner disk region and those trapped in the bulge in Section 4.3, when we discuss the origin of stars in the bar.

Comparing our results to observed age distributions for stars in the MW and its bulge, we find very good agreement. The total age distribution of stars in this model galaxy is very similar to the reconstructed one of the MW by Snaith et al. (2015) using spectroscopic data from Adibekyan et al. (2012). Their age distribution shows a strong peak at \( \sim 11 \) Gyr and a tail toward lower ages with indications of a secondary peak at \( \sim 3 \) Gyr well in agreement with our simulation.

Using the APOGEE data set (Majewski et al. 2017, Zhou et al. 2017) find a wide distribution of ages in the bulge region of the MW. Their high-metallicity population shows ages ranging from 2 to 14 Gyr, while their metal-poor population is slightly older, with ages between 6 and 14 Gyr. This is consistent with the findings of Bensby et al. (2013, 2017). The age–metallicity relation reconstructed from the APOGEE data is quite flat for stars in the bulge region, indicating a wide range of stellar age populations at similar metallicities. This suggests the existence of multiple stellar populations in the bulge region, ranging from young to old. This is in very good agreement with the results obtained from our simulation.

On the contrary, using ages derived from proper-motion-cleaned color–magnitude diagrams, the fraction of young stars in the bulge region of the MW is found to be less than 3.5% (Clarkson et al. 2008, 2011; Gennaro et al. 2015). This discrepancy with the results of, e.g., Bensby et al. (2013) led Haywood et al. (2016) to suggest that age–metallicity degeneracies might make a young population undetectable using color–magnitude diagrams (see recent review by Barbuy et al. 2018, for a more detailed discussion).

### 3.2. Morphology: The Visible X-shape and the Split in Stellar Counts

The MW contains a boxy/peanut-shaped bulge with a strong X-shaped structure clearly visible in photometric imaging. In Ness & Lang (2016) the X-shape of the bulge is readily seen from the WISE satellite photometry, which penetrates the dust-obscured innermost region. This X-shape and the overall boxy/peanut-shaped bulge morphology are not uncommon in extragalactic spirals (Bureau et al. 2006; Gonzalez et al. 2017).

In Figure 4 we show a K-band image of our simulation side by side with the WISE 3.4 \( \mu \)m image with data taken from Ness & Lang (2016) to show the remarkable qualitative similarity between the morphology in the simulation and that in our own Galaxy. A feature of the presence of a peanut-shaped bulge is the X-shaped structure that can often be seen if viewed side-on. In Figure 5 we show this feature for the different stellar populations of the simulation. This figure shows the surface density of stars in a thin slice of 1 kpc thickness centered around the peanut-shaped bulge midplane. Starting from the youngest stars the strength of the X-shape gets stronger with age. Only the oldest stars do not show this feature. The X-shaped morphology gets less prominent and more boxy, or thicker (stars reach larger heights above the galactic midplane), for increasingly older populations. The X-shaped morphology is strongest for the intermediate-age population (2.5 < \( t_{\text{star}}/\)Gyr < 6.0), where the stars extend in the arms of the X to the highest latitudes and trace orbits down to the lowest latitudes at the very center. The respective mass fractions in the innermost 4 kpc in the four different age bins in terms of total stellar mass of this simulated galaxy are 10%, 12%, 18%, and 18% for stellar particles in the age bins \( t_{\text{star}}/\)Gyr < 2.5, 2.5 < \( t_{\text{star}}/\)Gyr < 6.0, 6.0 < \( t_{\text{star}}/\)Gyr < 10.0, and \( t_{\text{star}}/\)Gyr > 10.0, respectively.

The bulge of our own Galaxy can only be observed from within the Galaxy. Thus, to reconstruct the structure of the bulge, one has to rely on line-of-sight counts of stars. The X-shaped structure of the bulge thus translates into a double-peaked distribution of stars as a function of distance. This feature was first observed in our own Galaxy from photometry in the star counts along the line of sight (McWilliam & Zoccali 2010; Nataf et al. 2010) and found from spectroscopy to be metallicity dependent (e.g., Ness et al. 2012; Utenthaler et al. 2012; Rojas-Arriagada et al. 2014). For the MW there have been published various studies of star counts for sight lines going through the center of the Galaxy (−2° < \( l < 2° \) at 6°5 < \( |b| < 10° \) above the Galactic plane; e.g., Ness et al. 2013a, 2013b). We use the same sight lines in our simulation, which are indicated by the dashed white lines in Figure 5. From this we see that the anisotropic distribution of stars in the X-shaped structure led to a double-peaked distribution of star counts. In Figure 6 we show the radial distribution of star counts in the bulge region of our simulation. Similarly to the observations of the MW bulge, we count the number of stars as a function of distance in the above-mentioned sight lines. We restrict ourselves to distances ranging from 5 to 11 kpc from the Sun’s assumed position (thus \( \pm 3 \) kpc from the Galactic center) and divide our stars into four different age bins.

The resulting split in the stellar line-of-sight counts of stars in the simulation looks qualitatively very similar to the observations of the ARGOS survey (Ness et al. 2013a, 2013b). Up to a stellar age of 10 Gyr we see a split in the
radial distribution of stars, and we checked that for any age bins older than 10 Gyr we do not see a split. Therefore, we conclude that this population older than 10 Gyr is not part of the boxy/peanut structure. In Figure 6 it is clearly visible that the peak separation becomes smaller for progressively older stellar populations. This is similar to what is observed for the MW—as a function of stellar metallicity—where the metal-poor population is less separated compared to the metal-rich population. This is confirmed by the surface density maps shown in Figure 5. The slight asymmetry of the line-of-sight counts for the younger stellar populations visible in Figure 6 can be explained by the inclination of the cones used to count the stars (see white dashed lines in Figure 5). On the near side the cones are close enough to the midplane to cut right through the X-shape, while on the far side the cones are too far from the midplane and the X-shape does not extend high enough above the midplane to fully intersect with the cones.

The question of the origin of such a spatial separation of different populations of stars was recently addressed by Debattista et al. (2017) using pure N-body simulations and an isolated simulation of galaxy formation. These authors find that initially cospatial stellar populations with different in-plane random motions separate when a bar forms. In their simulations the stellar population with higher radial velocity dispersion becomes a vertically thicker box, while the radially cooler population stays thinner and forms a peanut-shaped bulge.

radial distribution of stars, and we checked that for any age bins older than 10 Gyr we do not see a split. Therefore, we conclude that this population older than 10 Gyr is not part of the boxy/peanut structure. In Figure 6 it is clearly visible that the peak separation becomes smaller for progressively older stellar populations. This is similar to what is observed for the MW—as a function of stellar metallicity—where the metal-poor population is less separated compared to the metal-rich population. This is confirmed by the surface density maps shown in Figure 5. The slight asymmetry of the line-of-sight counts for the younger stellar populations visible in Figure 6 can be explained by the inclination of the cones used to count the stars (see white dashed lines in Figure 5). On the near side the cones are close enough to the midplane to cut right through the X-shape, while on the far side the cones are too far from the midplane and the X-shape does not extend high enough above the midplane to fully intersect with the cones.

The question of the origin of such a spatial separation of different populations of stars was recently addressed by Debattista et al. (2017) using pure N-body simulations and an isolated simulation of galaxy formation. These authors find that initially cospatial stellar populations with different in-plane random motions separate when a bar forms. In their simulations the stellar population with higher radial velocity dispersion becomes a vertically thicker box, while the radially cooler population stays thinner and forms a peanut-shaped bulge.

Figure 4. Left panel: MW 3.4 μm image of the WISE satellite (Ness & Lang 2016). Middle panel: K-band image of the boxy/peanut-shaped bulge of the g2.79e12 simulation in galactic coordinates. Right panel: K-band image of the bulge of the nonbarred simulation g7.08e11 (Buck et al. 2018a). The two leftmost panels show clearly the boxy/peanut shape of the bulge region with a qualitative visual similarity between the MW and the simulation analyzed here. In contrast, the rightmost panel shows one of our nonbarred galaxies clearly showing morphological differences with respect to the other two panels.

Figure 5. Side-on surface density plots of a thin slice of thickness 1 kpc centered on y = 0 kpc of the X-shaped bulge in our simulation. The Sun’s position is assumed to be at (x, y, z) = (8, 0, 0) kpc. The white dashed lines indicate the cones in which we do star counts along the line of sight for Figure 6. From top to bottom we show the different age populations used in Figure 6 from the youngest stars (age < 2.5 Gyr) to the oldest stars (age > 10.0 Gyr).

Figure 6. Star counts as a function of distance from the Sun in different age bins for lines of sight going through the center of the galaxy (−2°.0 < l < 2°.0) at a height of 6.5° < |b| < 10° above the galactic plane, similar to ARGOS observations of our Galaxy (Ness et al. 2013a, 2013b). The Galactic center position is indicated by the vertical dashed gray line at r = 8 kpc.
These authors termed this mechanism “kinematic fractionation.”

One important prediction of this mechanism is that even after the buckling instability of the bar the disk stars can be scattered by the bar to large heights above the disk. As explained in Debattista et al. (2017, Section 2), as long as the bar is slowing down, the disk will continue to thicken at different rates for different radial dispersion populations, allowing the separation of populations to persist in subsequent evolution. This mechanism is important in this simulation, as we see the bar forming around 8 Gyr ago. We also observe a strong X-shape in the stars with ages between 2.5 and 6 Gyr as can be seen in Figure 5. This, however, points toward further dynamical influences after bar formation acting on the redistribution and star formation in the already-barred galaxy. For example, Fragkoudi et al. (2017) have shown that thin-disk stars get trapped more easily in the bar compared to thick-disk stars, which explains the enhanced contribution of young stars to the bar compared to the inner disk seen in Figure 3.

We confirm with this fully cosmological simulation that indeed the radial velocity dispersion is higher for older stellar populations over the whole cosmic time of evolution, which agrees with the picture presented in Debattista et al. (2017). It is reassuring that the same mechanism is at work in pure $N$-body simulations and idealized, isolated simulations of galaxy formation, as well as in the fully cosmological context. These mechanisms thus also seem to shape the galaxy in an environment where there are many additional perturbations, from incoming satellites and minor mergers, as per this work.

In Figure 7 we show the evolution of the radial (left panel) and vertical (right panel) velocity dispersion of stars in the inner region ($R < 3.5$ kpc). Color coding is the same as in Figure 6. For both panels we trace back all the stars within a sphere of 3.5 kpc at radial dispersion bins aligned with the stellar disk and then average over all bins, as in Debattista et al. (2017). We see that the lowest radial dispersion is found in the youngest stars (blue line) and that the radial velocity dispersion increases with increasing stellar age. The vertical velocity dispersion of the stars is much more similar among different subpopulations as can be seen from the right panel of Figure 7. The increase in vertical velocity dispersion around $7.5$ Gyr is due to the buckling instability of the bar, and the spike in vertical velocity dispersion at $t \sim 10$ Gyr is due to a massive satellite passing through the stellar disk of our simulated galaxy, causing almost equal extra heating of the stellar populations. Interestingly, the radial velocity dispersion is less affected by the disk passage of the satellite.

As a last remark, we see gradual kinematical heating of all stellar populations in the simulation. With cosmic time the radial and vertical velocity dispersion of the stars increases, although the relative increase is stronger for the vertical velocity dispersion.

3.3. Kinematics: Rotation and Dispersion Profiles as a Function of Stellar Age

The stars in the inner MW ($R < 3.5$ kpc) show a distinct rotation and dispersion profile (Kunder et al. 2012; Ness et al. 2013a; Zasowski et al. 2016). The rotation is the mean radial velocity for stars at distances 5–11 kpc along the line of sight, as a function of galactic longitude $l$, and the dispersion profile is the velocity dispersion along the line of sight as a function of galactic longitude $l$. In Figure 8 we compare the rotation and dispersion profiles of the bulge stars in our simulation (for all stars and for our four different age populations) with observed profiles for the MW calculated from ARGOS data—for all stars, across all [$Fe/H$]; this helps to guide the eye to compare how the trends in the simulation change with age.

In the left panels of Figure 8 we compare the rotation curves (top panel) and the dispersion profiles (bottom panel) for all stars in the observational sample and all stars in the simulation. Following the observations, we calculate rotation and dispersion in $2^\circ$ sized bins in ($l$, $b$). Due to the higher mass of our model galaxy compared to estimated values of the MW, the rotation and dispersion values obtained from the simulation are slightly too high compared to the observed values. Thus, we rescale the rotation and dispersion values by a constant factor of $\sim 0.45$ to match the observed dispersion value at ($l$, $b$) = ($0^\circ$, $-5^\circ$) of the observations. This rescaling is valid since the interesting feature of the observations is not the absolute value of rotation or dispersion but the particular shape of the profiles. After the rescaling, the dispersion
profile of all stars shows excellent agreement with the observed profiles (colored shaded bands) for both latitude bins (blue dots: $b = -5^\circ$; yellow triangles: $b = -10^\circ$). Our simulation is able to recover the flat dispersion profile for large heights above the plane and the triangular peaked shape of the dispersion profile closer to the disk midplane. The rotation profile of our simulation shows the same qualitative behavior as the observations but somewhat smaller maximum values of rotation for the smallest and largest $l$-bins. The reason for this is most likely a slight mismatch in size of our simulation and the MW.

The other eight panels of Figure 8 show the rotation and dispersion profiles for stars of our simulation in the different age bins (chosen to be the same as in Figure 6), together with the profiles of all stars in the observations to guide the eye (a closer, more direct comparison between simulation and MW will be done in a follow-up paper). We do not see large differences in the rotation profiles of different age populations. Note, however, that the rotation is slowest for the oldest stars (the far right panel). This is in qualitative agreement with the observations given that metal-poor stars are generally younger than metal-rich stars. Observationally, the rotation profile shows only a very slight variation for different metallicity populations in our MW for stars with [Fe/H] > −1.0 (see, e.g., Ness et al. 2013b). However, for the most metal-poor stars observed in the bulge, that is, the 5% of stars with [Fe/H] < −1.0, which have the highest dispersions, the rotation is far slower than the more metal-rich stars (on the order of 50% of the more metal-rich population, as measured by ARGOS). The RR Lyrae population, which peaks at [Fe/H] = −1.0 in the bulge, shows no rotation at all, in the observations of Kunder et al. (2016).

We now turn to examining the dispersion profiles, which for the MW bulge stars show a strong variation for different metallicity populations (Ness et al. 2013a, 2016a; Babusiaux 2016; Zasowski et al. 2016). The simulation shows that with increasing age of the stars, the velocity dispersion increases for both $b$-bins. This is in qualitative agreement with what is seen in the ARGOS survey for stars of decreasing [Fe/H], down to [Fe/H] > −0.5 (see, e.g., Ness et al. 2013b, Figure 6). Observations show that the most metal-rich stars ([Fe/H] > 0) are, overall, the kinematically coolest and show a triangularly peaked dispersion profile at low latitudes ($b = 5^\circ$) and a flatter dispersion profile at high latitudes ($b = 10^\circ$), across longitude (see, e.g., Figure 8).

Furthermore, the shape of the dispersion profile for the low-latitude value $|b| = 5^\circ$ changes in the simulation. The dispersion profile for the lowest age bin shows a flatter dispersion profile at $b = 5^\circ$ than the older stars, and at $b = 10^\circ$ it shows structure in the dispersion profile as a function of longitude. From a visual inspection, we find that this structure at $b = 10^\circ$ is due to the line-of-sight selection of stars that are crossing the arms of the X and comprises the stars confined to the X-shape orbits. Lower dispersion is indicative of stars that most strongly trace out the X, which are on coherent orbits. The triangular shape that is seen in the simulation at low latitudes of $b = 5^\circ$ is due to an intermediate-age and old stellar population (this peaked morphology is not present for the youngest stars in the second panel from the left).

We should also point out that this simulation does not reproduce two of the MW properties: (1) the almost latitude-independent dispersion of old stars as seen in the MW for stars with −0.5 > [Fe/H] > −1.0, and (2) the presence of a very dynamically hot population with [Fe/H] < −1.0 (Ness et al. 2013b). That the model does not reproduce the kinematics of the most metal-poor stars indicates that there is some population missing from the model (similar to Debattista et al. 2017). We conclude that our model galaxy is able to qualitatively well reproduce the overall rotation and dispersion profiles seen for the MW, but again there might be a population that is missing in this division by age that matches the kinematics of the most metal-poor stars. In the ARGOS survey

![Figure 8](image-url)

**Figure 8.** Rotation (top) and dispersion (bottom) profiles for stars of different ages for two different latitudes $|b| = 5^\circ$ (blue) and $|b| = 10^\circ$ (yellow). Rotation is the mean radial velocity for stars at distances 5–11 kpc along the line of sight, as a function of galactic longitude $l$. The dispersion profile is the velocity dispersion along the line of sight as a function of galactic longitude $l$. Lines show the measurements from ARGOS (Ness et al. 2013a, 2013b) for the whole sample of MW stars, and dots/triangles show the result obtained for our simulation. From left to right, the panels show the profiles for all stars, young stars (age < 2.5 Gyr), stars with ages 2.5 < age/Gyr < 6, stars with ages 6 < age/Gyr < 10, and the oldest stars with age > 10 Gyr. The numbers in each panel indicate the number of stellar particles in each sample, the first for sight lines with $|b| = 5^\circ$, the second for $|b| = 10^\circ$. The Astrophysical Journal, 861:88 (16pp), 2018 July 10
these show a latitude-independent hot dispersion, and the RR Lyrae stars in the MW show negligible rotation and significantly hotter dispersion than the more metal-rich stars. We will further elaborate on the different components building up these profiles and the differences from the observed profiles in a follow-up investigation.

3.4. Rotation and Dispersion Maps

Observational surveys, particularly those that target distant stars in the bulge (e.g., APOGEE, Majewski et al. 2017; ARGOS, Freeman et al. 2013; Gaia-ESO, Gilmore et al. 2012; GIBS, Zoccali et al. 2014) typically adopt a pencil-beam survey approach as completeness in coverage is expensive. In Figure 9 we complement the rotation and dispersion measurements of Figure 8 done in only 18 bins in $(l, b)$ by all-sky maps in $(l, b)$ of the same measurements. The left column shows the surface density maps, the middle column shows the mass-weighted rotation maps, and the right panel shows the mass-weighted dispersion maps for all stars within $R = 25$ kpc from the center of our simulated galaxy. Again we divide our simulation into different age bins. The top row shows the maps for all stars, the second row shows stars younger than 2.5 Gyr, the third row shows stars in the age range from 2.5 to 6 Gyr, the fourth row shows stars in the age range from 6 to 10 Gyr, and the bottom row shows stars older than 10 Gyr.

From the surface density plots in the left column we see that the scale height of the disk increases for increasingly older populations while the scale length decreases (see, e.g., Haywood et al. 2013; Stinson et al. 2013a; Marinacci et al. 2014; Bovy et al. 2016;
Ma et al. 2017). In the surface density map of all stars we see the peanut-shaped (X-shaped) structure of the bulge, and by comparing the surface density maps of different age populations, we see that this structure is most prominent in the two intermediate-age bins. The youngest stars are too concentrated to the midplane to exhibit the strong features high above the plane, while the oldest population is too spherically symmetric.

In the rotation maps we see that the highest values of rotation are found close to the galaxy midplane and in the \(l\)-range of \(\sim 5^\circ < |l| < 25^\circ\). Furthermore, we see that with decreasing age of the stars the rotation velocity increases across all \((l, b)\). The old stars show a more spherically symmetric, slowly rotating configuration at all \((l, b)\), from the bulge into the disk.

The dispersion maps are most interesting and show different structures as a function of stellar age. For all populations (including for the oldest stars) we see the lowest dispersion values in the disk midplane and far away from the galactic center \((-10^\circ < l < 10^\circ)\), while there is a peak in velocity dispersion in the galactic center. For the younger stars (see second panel from top in Figure 8) the velocity dispersion peak in the center itself shows an X-shaped substructure, while for the older stars it is more spherically symmetric. In agreement with the findings from the rotation maps, we see that the dispersion maps show the lowest dispersion values for the young stars and increasingly higher values for older stars.

### 4. Key Predictions for Observables

Having established the overall agreement of our simulation with observations of the MW bulge, we will now use this simulation to understand the formation scenario of the bar/bulge in the simulation—and make predictions for upcoming surveys. We will focus in the next subsections on the age of the bar structure and the differences between stars in the bar and the surrounding disk, and in Section 4 we will investigate the formation of the bulge in detail.

#### 4.1. Age of the Bar and X-structure as Measured from the Split in Stellar Counts

In Figure 2 we have seen that the bar in our simulation forms around 8 Gyr ago at redshift \(z \sim 1\). This corresponds well with our results from Figure 6, where we found that the split in the stellar counts is visible only for the stellar populations younger than 10 Gyr. Combining this with previous findings, that the complex dynamics of stars under the influence of the bar causes the X-shaped structure (see, e.g., Di Matteo 2016; Debattista et al. 2017; Fragkoudi et al. 2017), we propose that the split in the stellar counts might be used to determine the formation time of the bar of the MW. We do this by linking the X-shape distribution as a function of stellar age to the time of formation in the simulation. The underlying assumption of this method is that (a) the effect of an evolving bar on disk stars is different for stellar populations of different (radial) velocity dispersion and (b) there is significant evolution of the (radial) stellar velocity dispersion with cosmic time and thus with stellar age. We present here a first idea of how such a measurement could be performed. We caution, however, that more simulations of barred disk galaxies and more detailed studies on the dependence of the X-shaped structure on time of formation and the specific mechanisms at play are needed to result in a robust age estimate of the bar. However, this is outside the scope of this paper, and we proceed by laying out the principals of our idea: We have seen that the peak heights and peak separation of the double-peaked distribution of stars decrease with increasing stellar ages until the double-peaked feature finally disappears for the oldest stellar bins, and we are left with a single-peaked distribution. Kinematic fractionation, as described in Debattista et al. (2017), has differentiating effects on different stellar populations. Given
this, and that we know the formation of the bar precisely, we might be able to calibrate the time of formation to the distribution of stars as a function of their age and apply it to galaxies like the MW.

In the simulation the procedure is as follows: We divide the stars in the simulation into different age bins separated by 500 Myr and fit a double Gaussian to the two peaks in the stellar counts as a function of distance. From this we first determine, for every age bin, the height $C_1(t)$ and $C_2(t)$ of the two Gaussians and average them to a mean peak height $C_{\text{peak}}(t)$. We define the dip height $C_{\text{dip}}$ as the value of the double Gaussian in the center at $R=8$ kpc. From the ratio of the central dip height to the average peak height $C_{\text{dip}}/C_{\text{peak}}$, we can determine the time when the double-peaked distribution transits into a single-peaked distribution. A similar measure can be obtained from the ratio of the peak separation $\delta_R$ to the sum of the widths of the two Gaussians $\sigma_1 + \sigma_2$. The former ratio as a function of time is shown in the middle panel of Figure 10, while the latter ratio is shown in the bottom panel of Figure 10. If we compare the evolution of these two curves to the evolution of the bar strength, we see that either a value of $C_{\text{dip}}/C_{\text{peak}} \sim 0.5$ or a value of $\delta_R/(\sigma_1 + \sigma_2) \sim 2$ marks the formation of the bar in our simulation (indicated by gray dashed lines in Figure 10). This agrees well with the expectation that a value of $C_{\text{dip}}/C_{\text{peak}} \sim 0.5$ would correspond to a clear visual separation of two equal Gaussians with roughly a separation of 3.33$\sigma$ (full width at a quarter of a maximum). And a value of $\delta_R/(\sigma_1 + \sigma_2) \sim 2$ corresponds well with the fact that for a separation of 2.355$\sigma$ (FWHM) two equal Gaussians can well be distinguished from a single peak distribution (in this case $C_{\text{dip}}/C_{\text{peak}} \sim 1$). Clearly, the agreement between the two different ways of measuring the separation of the two Gaussians is not perfect. But this is due to the fact that we do not deal with two identical Gaussians, but with asymmetric Gaussians where the Gaussian peak on the near side of the bulge is higher than the one on the far side. Needless to say that the assumption of Gaussian peaks is already a simplification. We therefore indicate in the figure the extreme case of $C_{\text{dip}}/C_{\text{peak}} \sim 1$ and correspondingly $\delta_R/(\sigma_1 + \sigma_2) \sim 2.355$ with thin dotted lines. Taking these into account and given the fact that the bar forms around $t_{\text{form}} \sim 8^{12}$ Gyr ago, we are able to calibrate the values of $C_{\text{dip}}/C_{\text{peak}}$ and/or $\delta_R/(\sigma_1 + \sigma_2)$ to $\sim 0.5$ and/or $\sim 2$. However, we caution that this method is used on only a single galaxy here. Calibration against more simulations of barred spiral galaxies would be needed in order to account for possible degeneracies between actual formation time of the bar and its effects on the stellar populations of the underlying disk. Further calibrations would also enable a more robust determination of the values of $C_{\text{dip}}/C_{\text{peak}}$ and $\delta_R/(\sigma_1 + \sigma_2)$, which correspond to the formation of the bar. As we detailed above, we expect the bar to influence all stars present in the inner disk. Thus, the formation of the bar does not coincide with the transition from a single peak to a double-peaked distribution, and stars of all ages can be found in the bar. We do not investigate the role of diffusion over time of the stars in the bulge, where the bulge stars lose the dynamical information linked to their interaction with the bar. However, the observations that show a strong correlation between the morphology of stars in the bulge and their kinematics as a function of [Fe/H] (and in the simulation as a function of their age) are a strong indicator that this information is preserved. This holds promise for the use of a metric as we propose to age-date the bar’s formation. Further testing and calibrating this method on a larger set of simulations should be carried out to make a better-informed estimate of the formation time of the bar in the MW.

4.2. Where Do the Stars in the Bar Come From?

The bar (and the boxy/peanut-shaped bulge) of the simulated galaxy formed around $8 \, \text{Gyr}$ ago, and as such two questions arise naturally: (1) what triggers the bar formation, and (2) where do the stars that currently belong to the bar come from? We have checked visually that no merger is responsible for triggering the bar instability in this simulation. However, at redshift $z = 1$ when a strong bar forms, we can identify two close encounters between satellites and the main galaxy after which the bar is established (see Figure 14 in the Appendix). This might just be a coincidence, but investigating the connection between close encounters and bar formation is outside the scope of this paper and is left for future work (see Zana et al. 2017, for a detailed discussion).

To address the second question, we trace backward in time the stellar particles of the $z = 0$ bar via their unique particle IDs and analyze their spatial distributions at each time step. The procedure is as follows: We select stars at redshift $z = 0$ in the center of the galaxy in a bar-like structure. First, we rotate the simulation such that the stellar disk of our simulation lies in the $x$–$y$-plane and the long axis of the bar coincides with the $x$-axis. We then select all the stars in the region $-3.5 < x < 3.5$, $-1.25 < y < 1.25$, and $-1.0 < z < 1.0$. These spatial cuts agree well with a visual identification of the bar in surface density images and also agree with the assumptions of Portail et al. (2015b) for the bulge region of the MW.

Having selected these stars, we plot in Figure 11 the histograms of their radial distributions (left panel) and their vertical distance from the midplane of the stellar disk (middle panel) for increasingly earlier times (only for those stars already born at that given time). We see that most of the stars that are at present day in the bar (black line) were born at small galactocentric radii (the sharp cut in the black histogram at $R \sim 3.5$ kpc marks our selection of the bar at $z = 0$). The histograms of the radial distribution stay peaked around $R \sim 1$ kpc for all previous times shown. Only a few stars migrated inward. As a sanity check, we tracked the position of stars that have been in the bar already at redshift $z = 1$ down to redshift $z = 0$ and find similar results. Almost all stars already in the bar at $z = 1$ stay there, with only a few migrating outward. These findings suggest that stars in the bar region at the present day have a pure disk origin as already suggested by Di Matteo (2016) and Fragkoudi et al. (2017). In the left panel of Figure 11 we can see that there is a contribution of stars from outside 4 kpc to the present-day bar. This, in combination with the findings from Figure 3, suggests that there exists a mechanism that preferentially adds younger stars (thin-disk stars) to the bar but less so the inner disk (see also Fragkoudi et al. 2017).

The same result is found for the vertical height of stars above the stellar midplane. Stars at earlier times in the simulation show the same height distribution as stars at redshift $z = 0$. The height distribution for the whole sample stays almost unaffected. These findings might indicate that the fractionation of the early disk into the boxy/peanut-shaped bulge was not purely kinematical but also depends on the initial structure of the thick disk as suggested by Di Matteo (2016) and Fragkoudi et al. (2017). The scale height is slowly decreasing with cosmic
time. About 3 Gyr after the big bang we find scale heights of almost 1 kpc. This reduces to a scale height of about 470 pc at redshift $z = 0.25$, or about 11 Gyr after the big bang. These scale heights are almost twice as large as the gravitational softenings of the stellar and gaseous particles ($\sim 260$ pc) in this simulation, and thus the disk is at all times well resolved. Observations of stellar disks at higher redshifts $z \gtrsim 1$ (e.g., Elmegreen & Elmegreen 2006; Elmegreen et al. 2017) show that scale heights at these redshifts are of the order of $\sim 1$ kpc. This is in good agreement with the scale heights we find for our simulation (see also Buck et al. 2018b for a resolution study of stellar scale heights). We have seen in Figure 9 that younger stars show a thinner configuration and are found closer to the stellar midplane. This behavior is analyzed in more detail in the right panel of Figure 11, where we examine the age distribution of stars as a function of height above the stellar midplane at redshift $z = 0$. For simplicity we have selected all stars with galactocentric radius $r < 3.5$ kpc and grouped them into four different bins in height $|z|/kpc < 0.5, 0.5 < |z|/kpc < 1.0, 1.0 < |z|/kpc < 1.5$, and $1.5 < |z|/kpc < 2.0$. We then plot the distribution of stellar ages for every slice of height above the midplane. In general, we see a double-peaked distribution with one old peak around stellar ages of $\sim 9$–10 Gyr and a younger peak with stellar ages around $\sim 2$ Gyr. Comparing the younger peak with the older peak, we see that there is a slight overabundance of young stars close to the disk midplane (blue line), while older stars are more abundant at larger heights from the disk (red and black lines). This is in concordance with the results from Figure 9, where we have seen that young stars are concentrated close to the disk midplane while older stars can also be found at larger heights from the disk. These findings are also consistent with the results from Ness et al. (2014), who studied the bulge region in an isolated simulation of galaxy formation, and the results from Di Matteo et al. (2014), who studied in detail the formation of boxy/peanut-shaped bulges by means of idealized $N$-body simulation. These authors find that all stellar populations within the outer Lindblad resonance of the bar get mapped into this structure, which points toward a pure disk origin of the MW bulge. A consequence of this is that the bulge and disk populations show very similar properties.

Putting together the results from Figures 11 and 9, we conclude that the bar/bulge region in this simulation is formed in situ from the disk, with stars belonging to this region being locked up there. For the whole population we do not see considerable evolution in the thickness or in the radial component. However, we do see that there are different subcomponents present in the bar/bulge region showing different spatial distributions, with younger stars being found closer to the disk midplane, in agreement with observational findings from Bensby et al. (2013) and theoretical results from Ness et al. (2014).

### 4.3. Differentiating Stars in the Bar from Stars in the Surrounding Disk

Given our finding that most stars in the bar were locked up in this structure since they were born, or at least shortly after their birth, we now try to answer the question whether bar membership comes with a distinct imprint on this stellar

---

**Figure 11.** Evolution of the radial and vertical distribution of stars in the bar at redshift $z = 0$. For this figure we select stars in the redshift $z = 0$ snapshot that belong to the bar and meet the following spatial selection criteria: $-3.5 < x/kpc < 3.5, -1.25 < y/kpc < 1.25$, and $-1.0 < z/kpc < 1.0$. Left panel: radial distribution of stars in the bar at redshift $z = 0$ (black line) and for different snapshots at earlier times in the simulation. Middle panel: vertical distribution of the same selection of stars for the same selection of snapshots. Right panel: age distribution of stars in the innermost 3.5 kpc from the galaxy center for different heights above the stellar midplane. The blue histogram shows the age distribution for stars with $|z| < 0.5$ kpc from the midplane, the orange histogram shows stars with $0.5 < |z| < 1.0$ kpc, the red histogram shows stars with $1.0 < |z|/kpc < 1.5$, and the black histogram shows stars with $1.5 < |z|/kpc < 2.0$ kpc.

**Figure 12.** Properties of bar (orange histogram) and "disk" stars (black histogram). The left panel shows the age distribution function for bar and disk stars. The middle panel shows the metallicity distribution function, and the right panel shows the oxygen abundance $[O/Fe]$ as a proxy for $\alpha$-elements vs. metallicity. The thin lines show the $1\sigma$ scatter in $[O/Fe]$. For the other two panels the scatter is much smaller than the line thickness.
population, thus enabling disk and bar to be distinguished.\(^5\) To
test this, we select two samples of stars: (A) The bar sample, for
which we select all the stars of the bar that have a distance from
the galaxy center in the range \(2 < R / \text{kpc} < 3.5\) and that
intersect with our previous bar selection of \(-3.5 < x / \text{kpc} <
3.5, -1.25 < y / \text{kpc} < 1.25,\) and \(-1.0 < z / \text{kpc} < 1.0\) for
the bar lying in the \(x-y\)-plane and being aligned with the
\(x\)-axis. (B) The disk sample, for which we select stars in the
stellar disk with the same radial distance from the galaxy
center, but instead of being located in the barred structure, we
select them to belong to a barred structure \(90°\) offset from the
bar. For these two samples of stars, we plot in Figure 12 the
distribution of stellar ages (left panel), the distribution of stellar
metallicities \([\text{Fe/H}]\) (middle panel), and the mean value of
\([\text{O/Fe}]\) for every metallicity bin (right panel).

The age distribution of bar stars and disk stars looks almost
the same, except for a slight shift to younger ages for the bar
population, maybe indicating ongoing star formation at the tips
of the bar. Similar results are found for the metallicity
distribution of bar and disk stars shown in the middle panel of
Figure 12. Bar stars and disk stars show very similar
distributions, with the bar stars offset to slightly higher
metalicities. In the \([\text{O/Fe}]\) versus \([\text{Fe/H}]\) plot we do not see
any differences between bar and disk stars at all. The only
subtle differences between bar and disk stars fit in the picture of
an in situ formation of the bar/bulge region from the disk, as
laid out previously. The slight distinctions can be explained by
the different densities of stars in the bar and the surrounding
disk, which differ for each population, e.g., the oldest stars do
not show a barred structure but a more spherically symmetric
distribution, while for increasingly younger stars the bar is
more and more pronounced. Thus, one finds in the same
volume slightly more young stars in the bar region than outside it.
This explains the similarity, but also the very slight
differences in age and metallicity. We find in our simulation
that there is continued star formation in the center and maybe
even in the bar such that new, young stars are continuously
added to the bar. The near-identical properties of the disk and
bar populations that we find in our simulation are aligned with
observational results (e.g., Alves-Brito et al. 2010; Bensby
et al. 2017). That the inner disk and bulge are practically
indistinguishable is not an unexpected result given that the bar
formed from the disk at early times. In the simulation, the
differences in the overall distributions are simply a conse-
quence of the different spatial profiles of these structures.

5. Summary and Conclusion

In this study we presented a high-resolution cosmological
hydrodynamical simulation of a galaxy, whose bulge properties
are in remarkably good agreement with MW observations. We
used this simulation to study in detail the different stellar
constituents of the bulge and bar region, their kinematical and
chemical properties, and their origin and to make predictions
for upcoming spectroscopic surveys like MOONS (Cirasuolo
et al. 2012), 4-MOST (de Jong & Consortium 2015),
APOGEE-2 (Zasowski et al. 2017), and Sloan V (Kollmeier
et al. 2017). Our main results can be summarized as follows:

1. We compare stellar counts in our simulation to the key
observations of a double-peaked distribution in the line-
of-sight star counts toward the Galactic center and find an
excellent qualitative agreement between the two. All stars
younger than 10 Gyr in our simulation show a split in the
line-of-sight counts with increasing peak separation for
younger stars (see Figure 6).

2. We find that in our simulation the bar leads to a fractionation
of the boxy/peanut-shaped bulge. By tracing the different
stellar populations of the bulge region back in time, we find
that the kinematic properties of the stars are in agreement
with the idea of kinematical fractionation (Debattista et al.
2017). We also find a significant contribution from young
stars to the bar, which implies further dynamical effects
present in the already-barred galaxy.

3. The secular evolution under the influence of the bar
separates initially cospatial populations of stars into
different orbit families, thus resulting in a different
strength of the X-shaped structure for different stellar
populations (see also Di Matteo 2016; Fragkoudi et al.
2017, for the dependence of fractionation in the boxy/
peanut-shaped bulge on the initial structure of the early
thick disk).

4. In Figure 8 we compare the kinematics of the stars in the
bulge region of our simulation with observed kinematics
of the MW bulge stars taken from ARGOS, and we find
an excellent qualitative agreement. The shapes of the
rotation and dispersion profiles agree very well, although
the rescaled (absolute) values for rotation and dispersion
of this simulation are lower (higher) than those observed
for the MW owing to a higher stellar mass of the
simulated galaxy. In the same figure we show the rotation
and dispersion profiles for different age populations of
stars in our simulation, predicting what one would see if
ages were available for MW stars.

5. The peak separation in the split of star counts along the
line of sight and the age of the stellar population are
correlated (Figure 6). Younger stars show larger peak
separation. Furthermore, we find, in agreement with
results from Debattista et al. (2017), that the split is due to
the bar separating different stellar populations. We
propose that this might be used to measure the age of
the bar in the MW. Using a Fourier analysis of our
simulation (see Figure 2), we find an age of \(\sim 8\) Gyr
for the bar, and we calibrate a measurement involving stellar
line-of-sight counts of stars in the bulge.

6. Most of the bar stars at \(z = 0\) were born at small radii
(Figure 10). Furthermore, our simulation suggests that
once stars are in the bar they are locked up there.

7. We compare the properties of stars in the bar (with radii
between 2 and 3.5 kpc) and the inner disk (same radii but
90° offset from the bar). We find almost indistinguishable
age, metallicity, and oxygen abundance distributions
(compare Figure 12). We conclude that simple cuts in
age, metallicity, or oxygen abundance are not sufficient to
discriminate stars that reside in the disk from those in
the bar.

The authors would like to thank Hans-Walter Rix for very
fruitful discussions and exceedingly useful and inspiring
comments on this work. T.B. and M.K.N. are grateful to
Victor Debattista for valuable suggestions and supporting

---

\(^5\) That is, other than via their orbits, which are not a direct observable. (Even
with \textit{Gaia}, observing the bulge is problematic owing to both reddening and
crowding, and the precision of proper motions for stars that are observed at the
distance of the bulge is too low over the 5 yr baseline of the mission to
determine orbits for stars in much of the bulge region).
discussions during the Piercing the Galactic Darkness conference. T.B. would like to further thank Ortwin Gerhard for his very useful comments on this topic and Dustin Lang for providing the WISE data needed to create Figure 4 and for support in handling the data. T.B. acknowledges support from the Sonderforschungsbereich SFB 881 The Milky Way System (subproject A2) of the German Research Foundation (DFG). M.N. acknowledges funding from the European Research Council under the European Union’s Seventh Framework Programme (FP 7) ERC Advanced Grant Agreement No. [321035]. A.O. is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—MO 2979/1-1. Simulations have been performed on the THEO cluster of the Max-Planck-Institut für Astronomie at the Rechenzentrum in Garching and the HYDRA and DRACO clusters at the Rechenzentrum in Garching. Further computations used the high-performance computing resources at New York University Abu Dhabi. We greatly appreciate the contributions of all these computing allocations. This research made further use of the PYNBODY package Pontzen et al. (2013) to analyze the simulations and used the PYTHON package MATPLOTLIB (Hunter 2007) to display all figures in this work. Data analysis for this work made intensive use of the PYTHON library SCIPY (Jones et al. 2001), in particular NUMPY and IPYTHON (Pérez & Granger 2007; Walt et al. 2011).

**Appendix**

**SFR for Different Metallicity Bins**

In Figure 13, we show the SFH of the model galaxy for all stellar particles (black histogram) and for stellar particles in different metallicity bins. This figure shows that metallicity is not a good discrimination to separate stellar particles born at different times.

Figure 14 shows an RGB image of the model galaxy at redshift $z = 1$ that highlights the close encounter of two satellites with the main galaxy. After this time a strong bar is clearly visible in the galaxy.

![Figure 13. Star formation history for stars in different metallicity bins. The black line shows the galaxy’s total star formation history, and colored lines shows the star formation history for stellar populations of different metallicity. Note the extended period of star formation for stars in the metallicity bin $0.0 < [\text{Fe/H}] < 0.5$.](image-url)
The rendering technique used is the same as for Figure 1 in the main text.

Figure 14. RGB image of the galaxy at redshift $z = 1$ in face-on (left panel) and edge-on (right panel) view. This figure shows the snapshot onward from which a strong bar is visible in the simulation. Interestingly, this is also the point in time at which we can observe a close encounter of two satellites with the main galaxy. The rendering technique used is the same as for Figure 1 in the main text.

ORCID iDs
Tobias Buck @ https://orcid.org/0000-0003-2027-399X
Aura Obreja @ https://orcid.org/0000-0003-4196-8555

References
Abadi, M. G., Navarro, J. F., Steinmetz, M., & Eke, V. R. 2003, ApJ, 591, 499
Adibekyan, V. Z., Sousa, S. G., Santos, N. C., et al. 2012, A&A, 545, A32
Agertz, O., Moore, B., Stadel, J., et al. 2007, MNRAS, 380, 963
Alves-Brito, A., Meléndez, J., Asplund, M., Ramírez, I., & Yong, D. 2010, A&A, 513, A35
Athanassoula, E., & Martinez-Valpuesta, I. 2009, ASP, 8, 77
Athanassoula, E., Rodionov, S. A., & Prantzos, N. 2017, MNRAS, 467, L46
Bagbaxia, C. 2016, PASA, 33, e026
Babary, B., Chiappini, C., & Gerhard, O. 2018, ARA&A, in press (arXiv:1805.01142)
Bensby, T., Feltzing, S., Gould, A., et al. 2017, A&A, 605, A89
Bensby, T., Yee, J. C., Feltzing, S., et al. 2013, A&A, 549, A147
Blitz, L., & Spergel, D. N. 1991, ApJ, 379, 631
Bovy, J., Rix, H.-W., Schlaufy, E. F., et al. 2016, ApJ, 823, 30
Buck, T., Macciò, A. V., Dutton, A. A., Obreja, A., & Frings, J. 2018a, MNRAS, submitted (arXiv:1804.04667)
Buck, T., Macciò, A. V., Obreja, A., et al. 2017, MNRAS, 468, 3628
Buck, T., Ness, M. K., Macciò, A. V., Obreja, A., & Dutton, A. A. 2018b, ApJ, in press (arXiv:1711.04765)
Bureau, M., Aronica, G., Athanassoula, E., et al. 2006, MNRAS, 370, 753
Bureau, M., & Athanassoula, E. 2005, ApJ, 626, 159
Bureau, M., & Freeman, K. C. 1999, AJ, 118, 126
Cirasuolo, M., Afonso, J., Bender, R., et al. 2012, Proc. SPIE, 8446, 84460S
Clarkson, W., Sahu, K., Anderson, J., et al. 2008, ApJ, 684, 1110
Clarkson, W., Sahu, K. C., Anderson, J., et al. 2011, ApJ, 735, 37
Combes, F., Debiasch, F., Friedli, D., & Pfenniger, D. 1990, A&A, 233, 82
Combes, F., & Sanders, R. H. 1981, A&A, 96, 164
Debattista, V. P., Mayer, L., Carollo, C. M., et al. 2006, ApJ, 645, 209
Debattista, V. P., Ness, M., Gonzalez, O. A., et al. 2017, MNRAS, 469, 1587
Dehnen, W., & Aly, H. 2012, MNRAS, 425, 1068
de Jong, R. S. & Consortium 2015, IAU, A22, 2255843
Dékány, I., Minniti, D., Catelan, M., et al. 2013, ApJL, 776, L19
Di Matteo, P. 2016, PASA, 33, e027
Di Matteo, P., Gómez, A., Haywood, M., et al. 2015, A&A, 577, A1
Di Matteo, P., Haywood, M., Gómez, A., et al. 2014, A&A, 567, A122
Dutton, A. A., Obreja, A., Wang, L., et al. 2017, MNRAS, 467, 4937
Dwek, E., Arendt, R. G., Hauser, M. G., et al. 1995, ApJ, 455, 716
Elmegreen, B. G., & Elmegreen, D. M. 2006, ApJ, 650, 644
Elmegreen, B. G., Elmegreen, D. M., Tompkins, B., & Jenks, L. G. 2017, ApJ, 847, 14
Ferland, G. J., Korista, K. T., Verner, D. A., et al. 1998, PASP, 110, 761
Fragkoudi, F., Di Matteo, P., Haywood, M., et al. 2017, A&A, 606, A47
Freeman, K., Ness, M., Wylie-de-Boer, E., et al. 2013, MNRAS, 428, 3660
Gardner, E., Debattista, V. P., Robin, A. C., Vásquez, S., & Zoccali, M. 2014, MNRAS, 438, 3275
Gennaro, M., Chernyshyov, K., Brown, T. M., & Gordon, K. D. 2015, ApJ, 808, 45
Gerhard, O. 2002, in ASP Conf. Ser. 273, The Dynamics, Structure &History of Galaxies: A Workshop in Honour of Professor Ken Freeman, ed. G. S. Da Costa, E. M. Sadler, & H. Jerjen (San Francisco, CA: ASP), 73
Gilmore, G., Randich, S., Asplund, M., et al. 2012, Msrnr, 147, 25
Girardi, L., Williams, B. F., Gilbert, K. M., et al. 2010, ApJ, 724, 1030
Gonzalez, O. A., Debattista, V. P., Ness, M., Erwin, P., & Gadotti, D. A. 2017, MNRAS, 466, L93
Gonzalez, O. A., Rejkuba, M., Zoccali, M., et al. 2011, A&A, 530, A54
Guedes, J., Mayer, L., Carollo, M., & Madau, P. 2013, ApJ, 772, 36
Gutcke, T. A., Stinson, G. S., Macciò, A. V., Wang, L., & Dutton, A. A. 2016, MNRAS, 464, 2796
Haardt, F., & Madau, P. 2005, ApJ, 618, 20
Haywood, M., Di Matteo, P., Lehnernt, M. D., Katz, D., & Gómez, A. 2013, A&A, 560, A109
Haywood, M., Di Matteo, P., Snaith, O., & Calamida, A. 2016, A&A, 593, A82
Hill, V., Leccreure, A., Gómez, A., et al. 2011, A&A, 534, A80
Howard, C. D., Rich, R. M., Clarkson, W., et al. 2009, ApJL, 702, L153
Howard, C. D., Rich, R. M., Reitzel, D. B., et al. 2008, ApJL, 688, 1060
Hunter, J. D. 2007, CSE, 9, 90
Jones, E., Oliphant, T., Peterson, P., et al. 2001, SciPy: Open Source Scientific Tools for Python. http://www.scipy.org/
Kauffmann, G., White, S. D. M., & Guiderdoni, B. 1993, MNRAS, 264, 201
Keller, B. W., Wadsley, J., Benincasa, S. M., & Couchman, H. M. P. 2014, MNRAS, 442, 3013
Kobayashi, C., & Nakasato, N. 2011, ApJ, 729, 16
Kollmeier, J. A., Zasowski, G., Rix, H-W., et al. 2017, arXiv:1711.03234
Kunder, A., Koch, A., Rich, R. M., et al. 2012, AJ, 143, 57
Kunder, A., Rich, R. M., Koch, A., et al. 2016, ApJL, 821, L25
Li, Z.-Y., & Shen, J. 2012, ApJL, 757, L7
Lüttinger, R., Pohlen, M., & Dettmar, R.-J. 2004, A&A, 417, 527
Ma, X., Hopkins, P. F., Wetzel, A. R., et al. 2017, MNRAS, 467, 2430
Macciò, A. V., Udrescu, S. M., Dutton, A. A., et al. 2016, MNRAS, 463, L69
