Setting the scene for Gaia and LAMOST
Proceedings IAU Symposium No. 298, 2013
S. Feltzing, G. Zhao, N. A. Walton & P. A. Whitelock, eds.

doi:10.1017/S1743921313006376

Dynamical Modeling of the Milky Way Bugle

Juntai Shen

Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China
email: jshen@shao.ac.cn

Abstract. Bulges are commonly believed to form in the dynamical violence of galaxy collisions and mergers. We model the stellar kinematics of the Bulge Radial Velocity Assay (BRAVA) and find no sign that the Milky Way contains a classical bulge formed by scrambling pre-existing disks of stars in major mergers. Rather, the bulge appears to be a bar seen somewhat end-on, as hinted from its asymmetric boxy shape. We construct a simple but realistic N-body model of the Galaxy that self-consistently develops a bar. The bar immediately buckles and thickens in the vertical direction. As seen from the Sun, the result resembles the boxy bulge of our Galaxy. We use the new kinematic constraints to show that the classical bulge contribution cannot be very significant. The model fits the BRAVA stellar kinematic data covering the whole bulge strikingly well with no need for a merger-made classical bulge. Our model contains an intriguing vertical X-shaped structure that resembles the similar structure reported recently in the Galactic bulge. The existence of the vertical X-shaped structure also suggests that the formation of the Milky Way bulge is shaped mainly by internal disk dynamical instabilities.

Keywords. Galaxy: bulge – Galaxy: kinematics and dynamics – galaxies: kinematics and dynamics

---

1. Introduction

It is well known that spiral galaxies consist of three main components, an invisible dark matter halo, an embedded, flat disk, and a central bulge. The bulge of our Galaxy is >99% made of stars that are at least 5 Gyr old (Clarkson *et al.* 2008) with a wide range of metal abundances (McWilliam & Rich 1994; Zoccali *et al.* 2008). Understanding the structure of our own Galaxy is non-trivial, mostly because we are located in the disk plane. Infrared imagery shows that the Milky Way contains a boxy, parallelogram-shaped bulge (Maihara *et al.,* 1978; Weiland *et al.,* 1994). This can be explained by a tilted bar; the near end of the bar is closer to us than the far side, consequently it appears to be bigger than the other side (Blitz & Spergel 1991).

A good distance indicator for structures of the Galaxy is red clump (RC) stars because their luminosity depends weakly on the stellar mass, age and metallicity (Stanek & Garnavich 1998). Studies of the asymmetric distribution of RC in the bulge region suggested that the bar probably extends $\sim 20° - 30°$ from the Sun–Galactic center (GC) line (Stanek *et al.* 1994). The detailed properties of the Galactic bar are still under active debate (e.g., Rattenbury *et al.,* 2007; Gerhard & Martinez-Valpuesta 2012).

Recently, two groups independently reported the bimodal brightness distribution of the RC in the Galactic bulge (McWilliam & Zoccali 2010 hereafter MZ10; Nataf *et al.,* 2010). MZ10 suggested that the bimodality is hard to explain with a tilted bar since the line of sight crossing the bar can only result in stars with one distance. One possibility speculated by Nataf *et al.* (2010) is that one RC population belongs to the bar and the other to the spheroidal component of the bulge. Another puzzling fact is that distances of the bright and faint RC are roughly constant at different latitudes, which was hard to understand with a naive straight bar. They proposed that these observed evidences can be well explained with a vertical X-shaped structure in the bulge region. The existence of this particular structure is later verified by Saito *et al.* (2011). They found that the X-shaped structure exists within (at least) $|l| \leqslant 2°$, and has front-back symmetry.

Theoretical modeling of the Milky Way bulge also made progresses recently. Zhao (1996) developed the first rapidly rotating bar model that fitted this distortion. Zhao's model was based on the Schwartzschild orbit superposition technique, so it was self-consistent and in steady state, but it did not evolve into that state from plausible initial conditions. Also, little stellar kinematic data were available to constrain Zhao's steady-state model and early N-body models (e.g., Fux 1997), and subsequent radial velocity data from a survey of planetary nebulae, although compared with a range of dynamical models (Beaulieu *et al.* 2000), led to only limited conclusions because of the small numbers and uncertain population membership of the planetary nebulae.

We recently simulate numerically the self-consistent formation of a bar that buckles naturally into a thickened state, and we scale that model to fit new kinematic data on bulge rotation and random velocities (Shen *et al.* 2010). The radial velocity observations are provided by the Bulge Radial Velocity Assay (*BRAVA*; Rich *et al.* 2007; Howard *et al.* 2008). This is a spectroscopic survey of the stellar radial velocities of M-type giant stars whose population membership in the bulge is well established. These giants provide most of the 2 μm radiation whose box-shaped light distribution motivates bar models. *BRAVA* emphasizes measurements in two strips at latitude $b = -4°$ and $b = -8°$ and at longitude $-10° < l < +10°$. A strip along the minor axis ($l \equiv 0°$) has also been observed. We use nearly 5,000 stellar radial velocities in this work. A preliminary analysis of data found strong cylindrical rotation (Howard *et al.* 2009) consistent with an edge-on, bar-like pseudobulge (Kormendy 1993; Kormendy & Kennicutt 2004), although a precise fit of a bar model to the data was not available. This success leads us here to construct a full evolutionary N-body model that we can fit to the radial velocity data.

2. Model Setup

We use a cylindrical particle-mesh code (Shen & Sellwood 2004) to build fully self-consistent N-body galaxies. It is well suited to study the evolution of disk galaxies: we model the disk with at least 1 million particles to provide high particle resolution near the center where the density is high. We try to construct the simplest self-consistent N-body models that fit the *BRAVA* data, avoiding contrived models with too many free parameters. Initially, they contained only an unbarred disk and a dark halo. The profile of the Galactic halo is poorly constrained observationally; we adopt a rigid pseudo-isothermal halo potential $\Phi = \frac{1}{2}V_c^2 \ln(1 + \frac{r^2}{R_c^2})$. Here $V_c \sim 250$ km s^{-1} is the asymptotic circular-orbit rotation velocity at infinity, and $R_c = 15$ kpc is the core radius inside which the potential is effectively constant. This halo gives a nearly flat initial rotation curve between 5 to 20 kpc. A simple halo form allows us to run many simulations quickly; this is important for a parameter search such as the present one. A rigid halo also omits dynamical friction on the bar, but the central density of the cored halo we adopt is low enough so that friction will be very mild. More importantly, we are mainly interested in the bulge, which is embedded well interior to R_c. So the exact profile of the dark halo at large radii is not critical. We will explore more sophisticated halos in future studies.

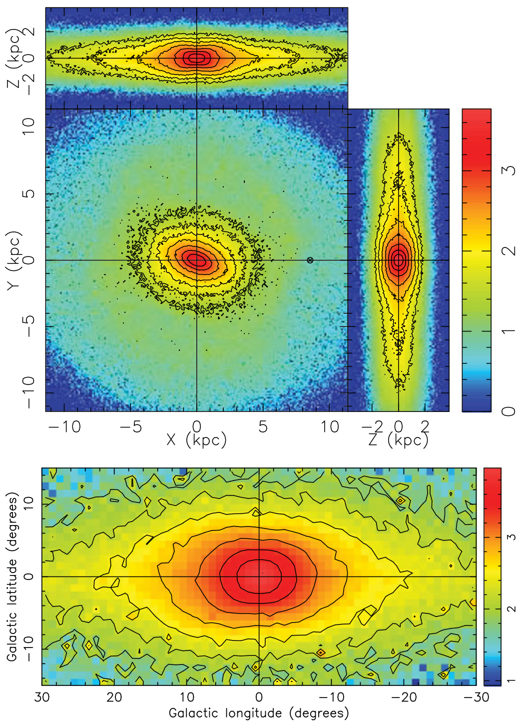

Figure 1. Upper three panels: Face-on and side-on views of the surface density of our best-fitting model as seen from far away. The Sun's position 8.5 kpc from the Galactic center is marked along the $+x$ axis. The Galaxy rotates clockwise as seen in the face-on projection. Bottom panel: Model surface brightness map in Galactic coordinates as seen from the Sun's location. Our perspective makes the box-shaped, edge-on bar look taller on its nearer side. The Galactic boxy bulge is observed to be similarly distorted.

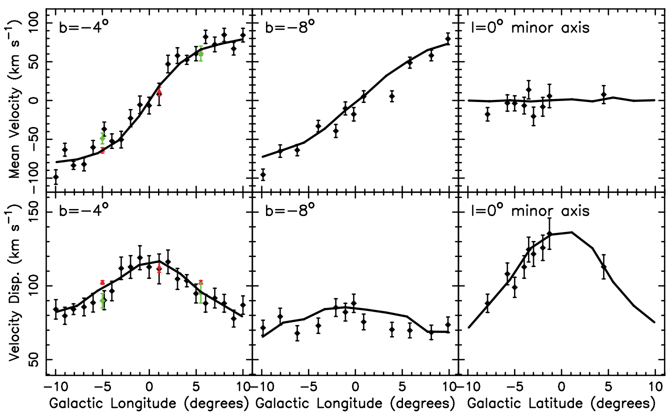

Figure 2. (top): Mean velocity and velocity dispersion profiles of the best-fitting model (black lines) compared to all available kinematic observations. The left two panels are for the Galactic latitude $b = -4°$ strip; the middle two panels are for the $b = -8°$ strip; and the right two panels are for the $l = 0°$ minor axis. The black diamonds and their error bars are the *BRAVA* data; the green diamonds are for M-type giant stars (Rangwala *et al.* 2009), and the red triangles are the data on red clump giant stars (Rangwala *et al.* 2009). This is the first time that a single dynamical model has been compared with data of such quality. The agreement is striking.

https://doi.org/10.1017/S1743921313006376 Published online by Cambridge University Press

3. Results and Discussions

In our models, a bar develops self-consistently from the initially unbarred, thin disk. Bar formation enhances the radial streaming motions of disk particles, so the radial velocity dispersion quickly grows much bigger than the vertical one. Consequently the disk buckles vertically out of the plane like a fire hose; this is the well known buckling or corrugation instability (e.g., Raha *et al.* 1991). It raises the vertical velocity dispersion and increases the bar's thickness. This happens on a short dynamical timescale and saturates in a few hundred million years. The central part of the buckled bar is elevated well above the disk mid-plane and resembles the peanut morphology of many bulges including the one in our Galaxy.

Out of a large set of N-body models, we find the one that best matches our *BRAVA* kinematic data after suitable mass scaling. The barred disk evolved from a thin exponential disk that contains $M_{\rm d} = 4.25 \times 10^{10} M_{\odot}$, about 55 % of the total mass at the truncation radius (5 scale-lengths). The scale-length and scale-height of the initial disk are $\sim$ 1.9 kpc and 0.2 kpc, respectively. The disk is rotationally supported and has a Toomre-Q of 1.2. The amplitude of the final bar is intermediate between the weakest and strongest bars observed in galaxies. The bar's minor-to-major axial ratio is about 0.5 to 0.6, and its half-length is $\sim$ 4 kpc. Figure 1 (top three panels) shows face-on and side-on views of the projected density of the best-fitting model. A distinctly peanut shaped bulge is apparent in the edge-on projection. Figure 1 (bottom panel) shows the surface brightness distribution in Galactic coordinates as seen from the Sun's vantage point. Nearby disk stars dilute the peanut shape, but the bar still looks boxy. Moreover, from close up, an asymmetry in the longitudinal direction is apparent; this means that the bar cannot be aligned with the direction from the Sun to the Galactic center. Rather, its near end is at positive Galactic longitude, so it looks taller in that quadrant, and it extends farther from the Galactic center on the near side than on the far side. Both the boxy shape and the asymmetry are in good agreement with the morphology revealed by the COBE satellite near-infrared images (Weiland *et al.* 1994).

Figure 2 compares the best-fitting model kinematics (solid lines) with the mean velocity and velocity dispersion data from the *BRAVA* and other surveys. All velocities presented here have been converted to Galactocentric values (the line-of-sight velocity that would be observed by a stationary observer at the Sun's position). Our model can simultaneously match the mean velocities and velocity dispersions along two Galactic latitudes ($-4°$ and $-8°$) and along the minor axis. Comparison with the complete *BRAVA* data release (Kunder *et al.* 2012) reaches a similar conclusion. We also tested to see whether or not a significant classical bulge is present, since it could have been spun up by the formation of a bar, flattened thereby and made hard to detect. We found that including a classical bulge with $>\sim$15 % of the disk mass considerably worsens the fit of the model to the data, even if we re-adjust the disc accordingly (Shen *et al.* 2010). Figure 3 shows the pattern speed of the bar ($\Omega_p \approx 40$ km/s/kpc) and locations of the Lindblad resonances.

The edge-on galaxy with a side-on bar is shown in the upper panel of Figure 4, and an X-shaped structure is discernible in the inner region of the boxy bulge. The X-shaped structure is highlighted in the bottom panel of Figure 4 (Li & Shen 2012). In the X direction, the end-to-end separation between the inner two edges of the X-shaped structure is $\sim$2 kpc. For the outer two edges, the end-to-end separation is $\sim$4 kpc. We estimate the size of the X-shaped structure in the X direction by averaging the two separations, which yields $\sim$3 kpc. This value is less than half of the full length of the bar (8 kpc). Similarly, in the Z axis, the end-to-end separation between the inner two edges of the X-shaped structure is $\sim$1.2 kpc. For the outer two edges in the Z axis, this separation is

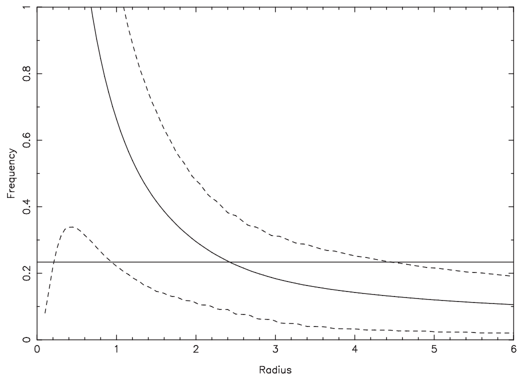

Figure 3. The horizontal line marks the pattern speed Ω_p of the quasi-steady bar in internal simulation unit with $R_{\rm d} = G = M_{\rm d} = 1$. Here $\Omega_p \approx 40$ km/s/kpc in physical units. The solid line shows the curve of the circular angular frequency Ω, and the dashed line marks $\Omega \pm \kappa/2$ at around $t = 4.8$ Gyr.

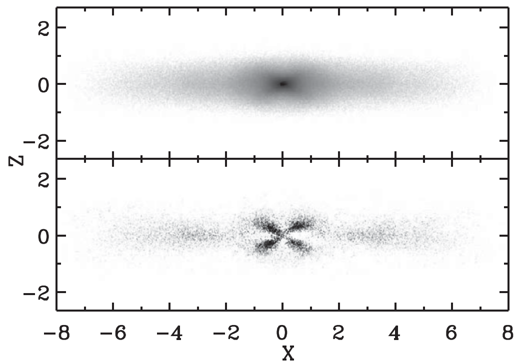

Figure 4. The upper panel shows the side-on view of the bar in our model. The lower panel shows the residual after subtracting the underlying smooth light contribution. The vertical X-shaped structure is highlighted in this residual image. The length unit is $R_{\rm d} = 1.9$ kpc.

$\sim$2.4 kpc. Therefore the size of the X-shaped structure in the Z direction is $\sim$1.8 kpc. From the image it is also apparent that the X shape is quite symmetric in the X-Z plane. By summing up the pixels with positive values in the X-shaped region, we estimate that the light fraction of this X-shaped structure relative to the whole boxy bulge region is about 7%. More detailed comparisons with observations, such as the bimodal distribution in the distance histograms, can be found in Li & Shen (2012).

This X-shaped structure does not have a straight-forward explanation in classical bulge formation scenarios (Bureau *et al.,* 2006), but it is a natural consequence of the bar buckling mechanism as we have shown here. We can qualitatively reproduce the observational signatures of the X shape, such as double peaks in distance histograms (MZ10) and number density maps (Saito *et al.* 2011). The existence of the X-shaped structure in our Milky Way implies that the Galactic bulge is shaped mainly by internal disk dynamical instabilities instead of mergers.

Although the X-shaped structure in our simple model is qualitatively similar to the observed one, it still cannot match all details of observations. Nevertheless, it is encouraging that our simple model matches observations in many aspects, and may help to guide future analyses. Further improvements on this model are clearly desired to completely understand the Galactic bulge structure, its dynamical and chemical histories.

https://doi.org/10.1017/S1743921313006376 Published online by Cambridge University Press

Acknowledgements

The research presented here is partially supported by the National Natural Science Foundation of China under grant No. 11073037, by 973 Program of China under grant No. 2009CB824800, and by the CAS Bairen Grant.

References

Beaulieu, S. F., Freeman, K. C., Kalnajs, A. J., Saha, P., & Zhao, H. 2000, *AJ*, 120, 855
Bissantz, N., Debattista, V. P., & Gerhard, O. 2004, *ApJL*, 601, L155
Blitz, L. & Spergel, D. N. 1991, *ApJ*, 379, 631
Bureau, M., Aronica, G., Athanassoula, E., *et al.*2006, *MNRAS*, 370, 753
Clarkson, W., *et al.* 2008, *ApJ*, 684, 1110
Fux, R. 1997, *A&A*, 327, 983
Gerhard, O., & Martinez-Valpuesta, I. 2012, *ApJL*, 744, L8
Howard, C. D., *et al.* 2009, *ApJL*, 702, L153
Howard, C. D., Rich, R. M., Reitzel, D. B., Koch, A., De Propris, R., & Zhao, H. 2008, *ApJ*, 688, 1060
Kormendy, J. 1993, in IAU Symposium, Vol. 153, Galactic Bulges, ed. H. Dejonghe & H. J. Habing (Dordrecht: Kluwer), 209
Kormendy, J., & Kennicutt, R. C. 2004, *ARAA*, 42, 603
Kunder, A., Koch, A., Rich, R. M., *et al.*2012, *AJ*, 143, 57
Li, Z.-Y. & Shen, J. 2012, *ApJL*, 757, L7
Maihara, T., Oda, N., Sugiyama, T., & Okuda, H. 1978, *PASJ*, 30, 1
McWilliam, A. & Rich, R. M. 1994, *ApJS*, 91, 749
McWilliam, A. & Zoccali, M. 2010, *ApJ*, 724, 1491 (MZ10)
Nataf, D. M., Udalski, A., Gould, A., Fouqué, P., & Stanek, K. Z. 2010, *ApJL*, 721, L28
Raha, N., Sellwood, J. A., James, R. A., & Kahn, F. D. 1991, *Nature*, 352, 411
Rangwala, N., Williams, T. B., & Stanek, K. Z. 2009, *ApJ*, 691, 1387
Rattenbury, N. J., Mao, S., Sumi, T., & Smith, M. C. 2007, *MNRAS*, 378, 1064
Rich, R. M., Reitzel, D. B., Howard, C. D., & Zhao, H. 2007, *ApJL*, 658, L29
Saito, R. K., Zoccali, M., McWilliam, A., *et al.*2011, *AJ*, 142, 76
Shen, J. & Sellwood, J. A. 2004, *ApJ*, 604, 614
Shen, J., Rich, R. M., Kormendy, J., *et al.*2010, *ApJL*, 720, L72
Stanek, K. Z., Mateo, M., Udalski, A., *et al.*1994, *ApJL*, 429, L73
Stanek, K. Z., & Garnavich, P. M. 1998, *ApJL*, 503, L131
Weiland, J. L., *et al.* 1994, *ApJL*, 425, L81
Zhao, H. S. 1996, *MNRAS*, 283, 149
Zoccali, M., Hill, V., Lecureur, A., Barbuy, B., Renzini, A., Minniti, D., Gómez, A., & Ortolani, S. 2008, *A&A*, 486, 177

Discussion

Noriyuki Matsunaga: Is there any chance that the dark matter halo or some streams disturbed the Galactic bulge and they changed the kinematic imprints?

Juntai Shen: I think it is unlikely, because the bulge is massive and tightly bound in the central region of the Galaxy. The dark matter streams are not massive and close enough to affect the kinematics of the bulge significantly, in my opinion.

Alice Quillen: Have you looked for evidence of banana shaped orbits by computing the vertical oscillation frequency?

Juntai Shen: Yes, my student, Yu-jing Qin, is working on the problem, and he will be able to tell you more on this offline.