The stellar mass distribution of the Milky Way’s bar: an analytic model

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ABSTRACT

We present an analytic model of the stellar mass distribution of the Milky Way bar. The model is obtained by fitting a multi-component parametric density distribution to a made-to-measure N-body model of Portail et al., constructed to match a variety of density and kinematics observational data. The analytic model reproduces in detail the 3D density distribution of the N-body bar including the X-shape. The model and the gravitational potential it generates are available as part of the software package AGAMA for galactic dynamics, and can be readily used for orbit integrations, hydrodynamical simulations or other applications.

Key words: Galaxy: centre – Galaxy: bulge – Galaxy: structure – Galaxy: kinematics and dynamics – galaxies: bar

1 INTRODUCTION

At the beginning of the 1990s it became established that the Milky Way (MW) is a barred galaxy (Blitz & Spergel 1991; Binney et al. 1991; Weiland et al. 1994; Stanek et al. 1994). During the following three decades, our knowledge of the dynamical structure of the Galactic bar has vastly increased thanks to near-infrared photometric observations (Binney et al. 1997; Launhardt et al. 2002; Ness & Lang 2016), star counts (Stanek et al. 1997; Skrutskie et al. 2006; Saito et al. 2011; Cao et al. 2013; Wegg et al. 2015; Coleman et al. 2020), line-of-sight velocity (Kunder et al. 2012; Nidever et al. 2012; Ness et al. 2013; Zoccali et al. 2014; Bovy et al. 2019) and proper motion (Sanders et al. 2019a,b; Clarke et al. 2019) data, as well as stellar (Fux 1997; Shen et al. 2010; Molloy et al. 2015; Portail et al. 2017a,b) and gas dynamical (Fux 1999; Bissantz et al. 2003; Sormani et al. 2015; Li et al. 2016, 2022) modelling.

Having an easily-computable representation of the density distribution of the Galactic bar and its associated gravitational field is important for a number of applications, such as orbit integrations (Stolte et al. 2014; Habing 2016; Price-Whelan et al. 2016; Queiroz et al. 2020; Wylie et al. 2021), hydrodynamical calculations of the response of the interstellar gas to a bar potential (Armillotta et al. 2019; Tress et al. 2020; Sormani et al. 2020), and the study of the effect of the bar resonances (Dehnen 2000; Monari et al. 2019; Binney 2020; Chiba et al. 2021). However, there is a lack of a synthetic model that summarises in a concise way our current knowledge of the mass distribution of the Milky Way bar resulting from the huge body of work mentioned above.

Portail et al. (2017a) (hereafter P17) constructed dynamical models of the Milky Way bar by integrating an N-body system and slowly adjusting the masses of the particles until the time-averaged density field and other model observables converged to prescribed data, using a made-to-measure (M2M) method (Syer & Tremaine 1996; de Lorenzi et al. 2007). The P17 models are constrained to reproduce a variety of stellar density and kinematic data, and they build upon previous reconstructions of the 3D bar density from red clump giant star counts (Wegg & Gerhard 2013; Wegg et al. 2015). P17’s overall best-fitting model had a pattern speed of $\Omega_0 = 40\,\text{km}\,\text{s}^{-1}\,\text{kpc}^{-1}$. The pattern speed is one of the most important parameters of the bar since it sets the location of the resonances. More recently, there has been evidence for somewhat lower values of $\Omega_0$ (Clarke et al. 2019; Binney 2020; Chiba & Schönrich 2021; Clarke & Gerhard 2021). Here we consider the P17 model with $\Omega_0 = 37.5\,\text{km}\,\text{s}^{-1}\,\text{kpc}^{-1}$ which is a good match to the VIRAC proper motions (Clarke et al. 2019) and, with gas dynamical modelling, to the observed distribution of cold gas in the $(l, v)$-diagram (Li et al. 2022). This model can therefore be considered a state-of-the-art model that takes into account most of the available constraints on the structure of the MW bar.

In this short research note we present a detailed 3D analytic fit to the stellar mass distribution of the dynamical model of P17. The analytic model can reproduce the 3D N-body density accurately, including the X-shape. The analytic model and its associated gravitational potential are available as part of the software package AGAMA for galactic dynamics (Vasiliev 2019).

2 THE MODEL

The analytic model is composed by four components: three barred components, and an axisymmetric disc. The total density is:

$$\rho(x, y, z) = \rho_{\text{bar,1}} + \rho_{\text{bar,2}} + \rho_{\text{bar,3}} + \rho_{\text{disc}}.$$  \hspace{1cm} (1)

The first two components together represent the bulge/bar (hereafter simply “bar”), i.e. the X-shaped boxy component in the centre. The third component represents the long bar, i.e. a vertically flat extension
of the bar which contribute to the “ears”, or bright enhancements at the ends, also known as “ansae” in the literature of external galaxies (e.g. Buta 2013). Note however that this decomposition is to some degree arbitrary and so these components only approximately correspond to the components with the same name in P17 and Wegg et al. (2015) (see also Sect. 4).

The first term on the right-hand side of Equation (1) is a modification of equation 9 of Coleman et al. (2020), which in turn is a generalisation of equation 10 of Freudenreich (1998):

$$\rho_{\text{bar},i}(x, y, z) = \rho_1 \sech(a m) \left[ 1 + \alpha \left( e^{-\alpha R_n} + e^{-\alpha z_n} \right) \right] e^{-\left( \frac{\rho}{\rho_{\text{cut}}} \right)^2},$$

where

$$a = \left[ \left( \frac{|R|}{R_c} \right)^{c_{z,i}} + \left( \frac{|y|}{y_c} \right)^{c_{y,i}} + \left( \frac{|z|}{z_c} \right)^{c_{z,i}} \right]^{\frac{1}{c_{z,i}}},$$

$$a_{\pm} = \left[ \left( \frac{x \pm c_{x,i}}{x_c} \right)^2 + \left( \frac{y}{y_c} \right)^2 \right]^{\frac{1}{2}},$$

$$r = \left( x^2 + y^2 + z^2 \right)^{\frac{1}{2}}.$$  \tag{5}

The parameter $\alpha$ quantifies the strength of the X-shape, while the parameter $c$ quantifies its slope in the $(x, z)$ plane.

The second and third terms on the right-hand side of Equation (1) have the same functional form, which is a modification of equation 9 of Wegg et al. (2015):

$$\rho_{\text{bar},i}(x, y, z) = \rho_i e^{-a_{R,i}^{n_i}} \sech^2 \left( \frac{R}{R_{\text{cut},i}} \right) e^{-\left( \frac{R_{\text{cut},i}}{R_{\text{cut},i}} \right)^{n_{\text{cut},i}}} e^{-\left( \frac{R_{\text{cut},i}}{R_{\text{cut},i}} \right)^{n_{\text{cut},i}}},$$

where $i = \{2, 3\}$ and

$$a_i = \left[ \left( \frac{|R|}{R_c} \right)^{c_{z,i}} + \left( \frac{|y|}{y_c} \right)^{c_{y,i}} \right]^{\frac{1}{c_{z,i}}},$$

$$R = \left( x^2 + y^2 \right)^{\frac{1}{2}}.$$  \tag{8}

The disc is an axisymmetric component that covers the region outside the bar. We take its density distribution to be:

$$\rho_{\text{disc}}(R, z) = \frac{\rho_0}{4\pi_d} R^{n_d} e^{-\frac{R}{R_{\text{cut},d}}} e^{-\frac{R_{\text{cut},d}}{R_{\text{cut},d}}} \sech \left( \frac{|z|}{z_{d}} \right)^{m_d}. \tag{9}$$

where $R$ is the cylindrical radius given by Equation (8).

We fit the multi-component density distribution given by (1) to the time-averaged stellar density of the P17 M2M N-body model. The model of P17 originally has $10^6$ stellar particles; its time-averaged density was computed on the fly during the fitting run on a 3D grid with spacing $\Delta x = \Delta y = 0.3$ kpc and $\Delta z = 0.1$ kpc. In this way the effective particle number is increased $\sim 100\times$, allowing for a much smoother density distribution. We then minimise the quantity $\chi^2 = \sum_i (\rho_{\text{analytic},i} - \rho_{\text{N-body},i})^2$ using a standard Nelder-Mead algorithm, where $\rho_{\text{analytic},i}$ is the density of the analytic model, $\rho_{\text{N-body},i}$ is the time-averaged density of the P17 N-body model, and the sum is extended over all points $i$ of the 3D grid.

### 3 RESULTS

The best-fitting parameters are reported in Table 1. The statistical uncertainties on the parameters are negligibly small and not very meaningful, since those stemming from the chosen functional form of the density profiles are likely much larger. The total masses of the three barred components and of the disc are $M_{\text{bar},1} = 1.28 \times 10^{10}$ M$_\odot$, $M_{\text{bar},2} = 0.33 \times 10^{10}$ M$_\odot$, $M_{\text{bar},3} = 0.22 \times 10^{10}$ M$_\odot$ and $M_{\text{disc}} = 3.19 \times 10^{10}$ M$_\odot$ respectively. Figure 1 shows that the surface density of the analytic model provides an excellent fit to the surface density of the P17 N-body model. Figures 2 and 3 shows that the analytic fit reproduces in detail the 3D structure of the N-body model, includ-
Figure 3. \((x, z)\) density slices at fixed values of \(y\) of the analytic model (full black lines) compared to the P17 model (dashed red lines).

Figure 2. \((x, y)\) density slices at fixed values of \(z\) of the analytic model (full black lines) compared to the P17 model (dashed red lines).

We have presented an analytic model of the stellar mass distribution of the Milky Way bar, obtained by fitting a made-to-measure N-body model of P17. The analytic model reproduces the 3D density distribution of the N-body model in detail, including the X-shape.

We have also checked that the potential is very well approximated outside the plane \(z = 0\). Finally, Fig. 5 compares the surface density along the \(x\), \(y\) and \(z\) axes, while Fig. 6 dissects the surface density of the analytical model into its separate components.

4 DISCUSSION AND CONCLUSION

We have presented an analytic model of the stellar mass distribution of the Milky Way bar, obtained by fitting a made-to-measure N-body model of P17. The analytic model reproduces the 3D density distribution of the N-body model in detail, including the X-shape.
The model and the gravitational potential it generates are available as part of the software package Agama for galactic dynamics, and can be used for a number of applications, such as orbit integrations or hydrodynamical calculations of the response of the interstellar gas to a bar potential.

The distinction between “bar” and “long bar” in our fitting does not have an immediate physical meaning (e.g. in the sense that the two components correspond to two distinct orbital families, Skokos et al. 2002; Harsoula & Kalapotharakos 2009; Wylie et al. 2021), but it should be clearly seen as a convenient way of parametrising the density distribution. The bar + long bar components together can be considered as a meaningful component.

The P17 model was mainly fitted to data of the inner Galaxy and not to data of the outer disc. As such, the axisymmetric disc component might not represent the disc of the MW as accurately as other models available (e.g. McMillan 2017). Indeed, the disc of the P17 model produces a circular velocity that is slightly too low at the solar radius (Li et al. 2022). In some applications where a model of the gravitational potential of the Milky Way is needed, it might be convenient to replace the axisymmetric disc with a different model while keeping the bar + long bar components as presented here.

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REFERENCES

Armillotta L., Krumholz M. R., Di Teodoro E. M., McClure-Griffiths N. M., 2019, MNRAS, 490, 4401
Binney J., 2020, MNRAS, 495, 895
Binney J., Gerhard O. E., Stark A. A., Bally J., Uchida K. I., 1991, MNRAS, 252, 210
Binney J., Gerhard O., Spergel D., 1997, MNRAS, 288, 365
Bissantz N., Englmaier P., Gerhard O., 2003, MNRAS, 340, 949
Blitz L., Spergel D. N., 1991, ApJ, 379, 631
Bovy J., Leung H. W., Hunt J. A. S., Mackereth J. T., García-Hernández D. A., Roman-Lopes A., 2019, MNRAS, 490, 4740
Buta R. J., 2013, Galaxy Morphology. p. 1, doi:10.1007/978-94-007-5609-0_1
Cao L., Mao S., Natal D., Rattenbury N. J., Gould A., 2013, MNRAS, 434, 595
Chiba R., Schönrich R., 2021, MNRAS, 505, 2412
Chiba R., Friske J. K. S., Schönrich R., 2021, MNRAS, 500, 4710
Clarke J., Gerhard O., 2021, arXiv e-prints, p. arXiv:2107.10875
Clarke J. F., Wegg C., Gerhard O., Smith L. C., Lucas P. W., Wylie S. M., 2019, MNRAS, 489, 3519
Coleman B., Paterson D., Gordon C., Macias O., Ploege H., 2020, MNRAS, 495, 3350
Dehnen W., 2000, AJ, 119, 800
Freudenreich H. T., 1998, ApJ, 492, 495
Fux R., 1997, A&A, 327, 983
Fux R., 1999, A&A, 345, 787
Habing H. J., 2016, A&A, 587, A140
Harsoula M., Kalapotharakos C., 2009, MNRAS, 394, 1605
Kunder A., et al., 2012, AJ, 143, 57
Launhardt R., Zylka R., Mezger P. G., 2002, A&A, 384, 112
Li Z., Gerhard O., Shen J., Portail M., Wegg C., 2016, ApJ, 824, 13
Li Z., Shen J., Gerhard O., Clarke J. P., 2022, ApJ, 925, 71
McMillan P. J., 2017, MNRAS, 465, 76
Molloy M., Smith M. C., Evans N. W., Shen J., 2015, ApJ, 812, 146
Monari G., Famaey B., Siebert A., Wegg C., Gerhard O., 2019, A&A, 626, A41
Ness M., Lang D., 2016, AJ, 152, 14
Ness M., et al., 2013, MNRAS, 432, 2092
Nidever D. L., et al., 2012, ApJ, 755, L25
Portail M., Gerhard O., Wegg C., Ness M., 2017a, MNRAS, 465, 1621
Portail M., Wegg C., Gerhard O., Ness M., 2017b, MNRAS, 470, 1233
Price-Whelan A. M., Sesar B., Johnston K. V., Rix H.-W., 2016, ApJ, 824, 104
Querzoli A. B. A., et al., 2020, arXiv e-prints, p. arXiv:2007.12915
Saito R. K., Zoccali M., McWilliam A., Minniti D., Gonzalez O. A., Hill V., 2011, AJ, 142, 76
Sanders J. L., Smith L., Evans N. W., Lucas P., 2019a, MNRAS, 487, 5188
Sanders J. L., Smith L., Evans N. W., 2019b, MNRAS, 488, 4552
Shen J., Rich R. M., Kormendy J., Howard C. D., De Propris R., Kunder A., 2010, ApJ, 720, L72
Skokos C., Patsis P. A., Athanassoula E., 2002, MNRAS, 333, 847
Skrutskie M. F., Cutri R. M., Stiening R., Weinberg M. D., et al. 2006, AJ, 131, 1163
Sormani M. C., Binney J., Magorrian J., 2015, MNRAS, 454, 1818
Sormani M. C., Tress R. G., Glover S. C. O., Kleess R. S., Battersby C. D., Clark P. C., Hatchfield H. P., Smith R. J., 2020, MNRAS, 497, 5024
Sormani M. C., et al., 2012, MNRAS, 512, 1857
Stanek K. Z., Mateo M., Udalski A., Szymanski M., Kaluzny J., Kubiak M., 1994, ApJ, 429, L73

The analytic fit and the associated gravitational potential are publicly available through the software package Agama (https://github.com/GalacticDynamics-Oxford/Agama).

DATA AVAILABILITY

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Figure 5. Surface density along the $x$, $y$ or $z$ axis of the analytic model (black full line) compared to the P17 made-to-measure N-body model (red dashed line). The left and middle panels correspond to the $x$ and $y$ axes in the $(x, y)$ map in Fig. 1, while the right panel correspond to the $z$ axis in the $(x, z)$ map.

Figure 6. Surface density of the separate components of the analytical model.

Stanek K. Z., Udalski A., Szymański M., Kalużyń J., Kubiak Z. M., Mateo M., Krzeminski W., 1997, ApJ, 477, 163
Stolte A., et al., 2014, ApJ, 789, 115
Syer D., Tremaine S., 1996, MNRAS, 282, 223
Tress R. G., Sormani M. C., Glover S. C. O., Klessen R. S., Battersby C. D., Clark P. C., Hatchfield H. P., Smith R. J., 2020, MNRAS, 499, 4455
Vasiliev E., 2019, MNRAS, 482, 1525
Wegg C., Gerhard O., 2013, MNRAS, 435, 1874
Wegg C., Gerhard O., Portail M., 2015, MNRAS, 450, 4050
Weiland J. L., et al., 1994, ApJ, 425, L81
Wylie S. M., Clarke J. P., Gerhard O. E., 2021, arXiv e-prints, p. arXiv:2110.03658
Zoccali M., et al., 2014, A&A, 562, A66
de Lorenzi F., Debattista V. P., Gerhard O., Sambhus N., 2007, MNRAS, 376, 71

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