Absence of an X-shaped Structure in the Milky Way Bulge Using Mira Variable Stars

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Received 2016 October 25; revised 2016 December 12; accepted 2016 December 12; published 2017 February 23

Abstract

The stellar density distribution of the bulge is analyzed through one of its tracers. We use oxygen-rich Mira variables from the Catchpole et al. survey and OGLE-III survey as standard candles. The average age of these stars is around 9 Gyr. The population traced by Mira variables matches a boxy bulge prediction, not an X-shaped one, because only one peak is observed in the density along the analyzed lines of sight, whereas the prediction of an X-shape gives two clear peaks.

Key words: Galaxy: bulge – Galaxy: structure

1. Introduction

The nature of the Galactic bulge morphology has been discussed using different interpretations over the last decades. Its non-axisymmetry was quickly recognized with the arrival of the first near-infrared surveys (e.g., Weiland et al. 1994; López-Corredoira et al. 1997; Babusiaux & Gilmore 2005), but its shape has not been free from debate. A peanut shape was evident in the projection of the bulge, especially in infrared surveys covering the full sky, like COBE-DIRBE, and extinction surveys. Its non-axisymmetry was quickly recognized with the arrival of the first near-infrared surveys (e.g., Weiland et al. 1994; López-Corredoira et al. 1997; Babusiaux & Gilmore 2005), but its shape has not been free from debate. A peanut shape was evident in the projection of the bulge, especially in infrared surveys covering the full sky, like COBE-DIRBE, and extinction surveys.

2. Distribution of Mira Variables

Catchpole et al. (2016) report periods and JHKL observations for 643 oxygen-rich Mira variables found in two outer bulge fields centered at $b = -7°$ and $\ell = \pm 8°$, each approximately 25 square degrees. They also use the 6528 Mira stars from the OGLE-III Catalog of Variable Stars (Soszyński et al. 2013) in regions with lower Galactic latitudes, providing periods and photometry in $V$ and $I$, which are dominated by oxygen-rich sources (Matsumoto et al. 2005). Here we use both sets of data and we cross-correlate OGLE data with 2MASS (Skrutskie et al. 2006) within 1 arcsec to also obtain the $K$-magnitude (in a single epoch), finding 6363 common stars.

Neither Catchpole et al. (2016) nor Soszyński et al. (2013) have carried out a proper analysis to test the X-shape hypothesis, so these data can be further explored with that purpose. Figure 12 of Catchpole et al. (2016), with the intermediate-age population, is misleading since the clumpiness of the distribution is mostly due to noise: there are not enough stars to produce a map with bins of $0.15 \times 0.15$ kpc$^2$ (630 stars in $\sim 4$ kpc$^2$ gives an average of 3.5 star/bin, which is insufficient for performing a statistical analysis), and there are some incomplete counts because the entire selected region $-6° < \ell < 10°$, $-4°5 < b < -2°5$ was not totally covered. In any case, Catchpole et al. (2016) have not tested the X-shaped bulge hypothesis in this intermediate-age population. Instead, they just plotted Figure 12 in this range of absolute magnitudes with the projected counts and put their results according to some authors (Dékány et al. 2013; Pietrukowicz et al. 2015), and young ($\lesssim 5$ Gyr) populations like F0-F5V stars are not X-shaped according to different interpretations (López-Corredoira 2016), interpretations that might also have doubt cast upon. For instance, the argument for a non-X shape by López-Corredoira (2016) might also raise doubts based on the possible dispersion of absolute magnitudes, which might be much larger than assumed and thus may convolve the two peaks along the line of sight into one. If we assume that all of these results are correct, we would have the surprising result of a Galaxy with three bulges, which raises suspicions something is wrong with some of the previous analyses.

Here we want to throw further light on the question by analyzing a new population, Mira variables, which includes both young and old stars.
together with those of McWilliam & Zoccali (2010), which corresponds to $b = -8^\circ$, and observed that some stars are where they should be. The rough comparison between Figure 12 and McWilliam & Zoccali (2010) is invalid because they correspond to different latitudes.

Using the period–luminosity relationship (Whitelock et al. 2008; Catchpole et al. 2016, Equation (2)),

$$M_K = (-3.51 \pm 0.20) \lambda - (7.25 \pm 0.07),$$

$$\lambda = \log_{10}[P(\text{days})] - 2.38,$$

and the $K$-band extinction $A_K = 0.11 A_V$ (Fitzpatrick 1999). The extinction $A_V$ is calculated by Catchpole et al. (2016) for their data and by us using the Schlegel et al. (1998) maps for OGLE data; we can use this extinction to obtain the distance of each Mira star.

For the OGLE data, the $K$-magnitude is derived for a single epoch from 2MASS; it is not the average $K$-magnitude. This can generate a large dispersion in distances, due to the variability of the sources (Matsunaga et al. 2005). We wonder why Catchpole et al. (2016) did not make any attempt to correct this dispersion of magnitudes, which introduces noise in the density maps. Here, in order to avoid this error in distance (although with average zero, which should be compensated for when large numbers of stars are used) due to the difference between the average magnitude of Mira stars and the magnitude in a single epoch, we calibrate the average relationship between the color $I$(OGLE)–$K$(2MASS) (corrected for extinction) and the period in the OGLE sample of 1235 stars with $|b| \geq 4^\circ$ (to avoid high-extinction regions), and we use this relationship to calculate the “average” $K$-band magnitude in the OGLE stars used here. This relationship is

$$I - K = 3.96 + 3.69 \lambda + 10.33 \lambda^2 + 10.98 \lambda^3.$$  (2)

The dispersion of 2MASS single-epoch $K$-magnitudes with respect to this law gives an average rms $= 0.85$ mag (see Figure 1), which is on the order of magnitude of the expected value due to variability (Matsunaga et al. 2005), with higher dispersion toward higher periods. Given that we have used 1235 stars, the error of $I - K$ given in the above expression is 0.024 mag. If we choose stars with $\log_{10}[P(\text{days})] < 2.6$, the rms is reduced to 0.62 mag. We will use this constraint in OGLE stars to avoid the highest deviations from the color–period relationship.

Then, for the OGLE data, rather than using the single epoch 2MASS magnitude, we use the $I$-magnitudes for each of the stars and this color to calculate the average $K$-magnitude, i.e.,

$$m_K = m_I - (I - K),$$

where $(I - K)$ is calculated from the period in Equation (2).

In Figure 2, we see the distribution of Catchpole et al. (2016) along different lines of sight and for some interesting regions of OGLE data. For our analysis, since X-shape features are observable mainly at $4^\circ \lesssim |b| \lesssim 10^\circ$ (Nataf et al. 2010; Wegg & Gerhard 2013), we study the region with the lowest negative longitude and highest abs (latitude): $-7^\circ < \ell < -3^\circ$, $-6.5^\circ < b < -4.5^\circ$. The density and star counts are related through $\rho[r(m_K)] = \frac{5}{\ln 10} A(m_K)$, where $r(m_K) = 10^{m_K - M_\text{K,0}}$. The $K$-band magnitude and the differential star counts are $A(m_K) = \frac{dN(m_K)}{dm_K}$. There may be some incompleteness of sources due to the patchiness of extinction, especially in regions with lower $|b|$, but this does not affect the shape of the density along the line of sight, although its amplitude is affected. In the same plot, we do a linear fit in the regions with 4.5 kpc < $r$ < 5 kpc and 11 kpc < $r$ < 14.5 kpc, which represents approximately the disk counts along those lines of sight, and the excess over this linear fit is the bulge density. The analysis of the disk counts is not the matter here, but note that this may be composed of both thick and thin disks, and the inner flare of the disk (López-Corredoira et al. 2004) leads to a sizable amount of disk stars even ~1 kpc from the plane. For the bulge density, we can observe that there is only one peak in all lines of sight.

A prediction of the bulge densities of two models, X-shaped and boxy, is given in Figure 3. They were derived from the analytical expressions given in López-Corredoira (2016, Section 4.1) for the boxy and X-shaped bulges observed by López-Corredoira et al. (2005) and Wegg & Gerhard (2013), respectively:

$$\rho_{\text{boxy}}(x, y, z) = \rho_0 \exp \left( -\left( \frac{x^4 + \left( \frac{y}{0.5} \right)^4 + \left( \frac{z}{0.4} \right)^4}{740 \text{ pc}} \right)^{1/4} \right)$$

$$\rho_{\text{x-shape}}(x, y, z) = \rho_0 \exp \left( -\left( \frac{s_1}{700 \text{ pc}} \right) \exp \left( -\left( \frac{|z|}{322 \text{ pc}} \right) \right) \right) \times \left[ 1 + 3 \exp \left( -\left( \frac{s_2}{1000 \text{ pc}} \right)^2 \right) \right]$$

$$+ 3 \exp \left( -\left( \frac{s_3}{1000 \text{ pc}} \right)^2 \right).$$  (4)

$$s_1 = \text{Max} \left[ 2100 \text{ pc}, \sqrt{x^2 + \left( \frac{y}{0.7} \right)^2} \right].$$

$$s_2 = \sqrt{(x - 1.5z)^2 + y^2}.$$  

$$s_3 = \sqrt{(x + 1.5z)^2 + y^2}.$$
For the positive longitude $\ell = +8^\circ$ there is not much distinction in the functional shape of the density between the two models. However, for the negative longitude $\ell = -8^\circ$ line of sight and for the three selected OGLE regions, the two predictions are very different, with a double peak for the X-shaped bulge and a single peak for the boxy bulge.

Figure 4 shows a plot that helps us understand the origin of this double peak along $\ell = -8^\circ$, $b = -7^\circ$. This line of sight crosses two maxima in a constant $z$ slice, first in the left-hand bump, at around $r = 7$ kpc, followed by a constant or slight decrease of the density in the hollow created by the peanut shape (the line remains in the region between the blue and violet colors), and when we take into account the increase of $|z|$ at higher values of $r$, this becomes a decrease of density. Then there is a second big peak at around 9.5 kpc associated with the right-hand bump; this second peak is indeed not as high in amplitude in Figure 3 because we must add the effect of the increase of $|z|$ with distance, which makes the amplitude of the second peak similar to the first peak. One may wonder why Figure 6 of Wegg & Gerhard (2013) and Figure 3 of Saito et al. (2011) do not explicitly show the double peaks. Indeed, these images show double bumps, but the lowest contours do not reach the longitude $-8^\circ$. It is a question of contrast, as it is not enough for the lowest contours to be seen in these figures. However, in Figure 3/top-right panel of McWilliam & Zoccali (2010) for $(\ell = -6^\circ$, $b = -8^\circ)$, a double peak is clearly observed; see also their Figure 6, which shows the effect of double peaks between $\ell = -9^\circ$ and $\ell = +3^\circ$. For lower values of $|\ell|$, it is even more evident that the X-shape should provide double peaks at negative longitudes. In any case, if there is no double peak for the red clumps, it would remove the question regarding the X-shape at least for this region, although not for the other regions.

Clearly, the boxy bulge resembles the results of Figure 2, whereas the X-shaped bulge does not. For the OGLE data, the covered areas are lower, and that is the reason it produces a noisier density. A $\chi^2$ analysis in the comparison of the models with data in the range $5 \text{ kpc} < r < 11 \text{ kpc}$ (once subtracted the disk) gives

1. for the line of sight $\ell = -8^\circ$, $b = -7^\circ$: $\chi^2_{\text{reduced}} \equiv \frac{\chi^2}{N-i}$

$(N = 8 \text{ values of } r)$ equal to 2.81 and 1.09, respectively, for the X-shaped and boxy bulges, corresponding to probabilities of $6.4 \times 10^{-3}$ and 0.37, i.e., the X-bulge is
excluded within 99.36% C.L. (2.7σ) whereas the boxy bulge matches the data; and
2. for the line of sight at \( \ell = -5°, b = -5.5° \): \( \chi^2_{\text{Reduced}} \) equal to 2.30 and 1.40 respectively for the X-shaped and boxy bulges, corresponding to probabilities 0.024 and 0.20, i.e., X-bulge is excluded within 97.6% C.L. (2.3σ) and boxy bulge fit is not good but it is only excluded within 80% C.L. (1.3σ), which is much likely than the X-shaped bulge.

The combination of the two lines of sight gives, respectively, for the X-shaped and boxy bulges a probability of \( 1.1 \times 10^{-3} \) and 0.23, i.e., the X-bulge is excluded within 99.89% C.L. (3.3σ) whereas the boxy bulge is only excluded within 77% C.L. (1.2σ), which can be considered as a likely fit.

The average relative error of the distance of these Mira stars using Equation (1) is 3.6% (Catchpole et al. 2016), which is too low to produce a smoothing of the two peaks into one. The error in Equation (2) is also low, as mentioned, around 0.024 mag. The error in the extinction is around 10% (Schlegel et al. 1998), with the average extinction \( A_K \approx 0.2 \) mag for OGLE regions with \( |b| \geq 4° \). This produces another error of \( \Delta A_K \approx 0.02 \) mag and \( \Delta A_I \approx 0.1 \) mag, which is again too low to produce any confusion of the two peaks. The effect of metallicity dispersion is also negligible: first because the variations of the metallicity in the bulge along a line of sight are very low because even large variations of metallicity along a line of sight are very low

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The \( \log_{10} P \) (days) is related to the age of the star. Roughly, the ages of 1.0, 1.8, 3.0, 5.0, 7.0 Gyr correspond to \( \log_{10} P \) (days) = 2.83, 2.70, 2.65, 2.60, 2.50 (Feast 2009; Catchpole et al. 2016) so an approximate relationship can be given by a second-order polynomial fit of these numbers:

\[
\text{age(Gyr)} \sim 12 - 44\lambda + 43\lambda^2.
\]

The average \( \log_{10} P \) of the Mira variables in Figure 2 is 2.46 at the \( (\ell = -8°, b = -7°) \) line of sight and 2.45 for the combination of the three OGLE lines of sight, which represents, according to Equation (5), average ages of 8.8 and 9.1 Gyr, respectively. In Figure 5, we represent the density along \( (\ell = -8°, b = -7°) \) for three bins with approximately the same number of stars and \( \log_{10} P \) ranges of <2.39, 2.39–2.53, and >2.53, which correspond, using Equation (5), to ages of \( \gtrsim 11.6 \) Gyr, 6.4–11.6 Gyr, and \( \lesssim 6.4 \) Gyr. The C.L.s at which the X-shapes are excluded in a \( \chi^2 \) analysis are 2.1σ, 1.2σ, and 1.1σ, respectively, for these ages; for the boxy bulge, it is excluded at 1.3σ, 0.8σ, and 0.5σ, respectively. The only significant exclusion here is for the oldest Miras to be X-shaped. For the OGLE line of sight, the star counts are much lower, so these data are even more inconclusive. We
would need a higher number of Mira stars to be able to distinguish the shapes of the bulge at different ages.

3. Conclusions

The bulge with an X-shaped morphology traced by the average population of Mira variables is excluded at the 3.3σ level, whereas a boxy bulge density distribution matches the data. The significance is reduced to 2.3σ if we exclude the region of \( \ell = -8^\circ, b = -7^\circ \). Apparently, there is no agreement regarding the structure of red clumps for this line of sight of \( \ell = -8^\circ, b = -7^\circ \); some authors obtained a double peak there (e.g., McWilliam & Zoccali 2010), others do not see it there (e.g., Saito et al. 2011), others see it but relatively noisy (e.g., Nataf et al. 2010), and some authors obtained a double peak along the line of sight, not in \( \ell = -8^\circ, b = -7^\circ \) nor in \( \ell = -5^\circ, b = -5.5^\circ \).

This population has an average age of 9 Gyr. At present, using Mira variable stars, we cannot distinguish the morphology of stars with different ages. This casts some doubt on the validity of red clump analyses claiming the existence of an X-shaped bulge, even though some authors have obtained a double peak from the analysis of Mira stars, we cannot distinguish the shapes of the bulge at different ages. Even if we cannot be 100% sure, at the very least, doubts regarding the very existence of the X-shaped bulge should be established from the present work.

Thanks are given to the anonymous referee for the critical comments that motivated new calculations that reinforced the robustness of the analysis to be carried out. This work has been supported by the grant AYA2015-66506-P from the Spanish Ministry of Economy and Competitiveness (MINECO).

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