THE X-SHAPED BULGE OF THE MILKY WAY REVEALED BY WISE

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ABSTRACT

The Milky Way bulge has a boxy/peanut morphology and an X-shaped structure. This X-shape has been revealed by the “split in the red clump” from star counts along the line of sight toward the bulge, measured from photometric surveys. This boxy, X-shaped bulge morphology is not unique to the Milky Way and such bulges are observed in other barred spiral galaxies. N-body simulations show that boxy and X-shaped bulges are formed from the disk via dynamical instabilities. It has also been proposed that the Milky Way bulge is not X-shaped, but rather, the apparent split in the red clump stars is a consequence of different stellar populations, in an old classical spheroidal bulge. We present a Wide-Field Infrared Survey Explorer (WISE) image of the Milky Way bulge, produced by downsampling the publicly available “unWISE” coadds. The WISE image of the Milky Way bulge shows that the X-shaped nature of the Milky Way bulge is self-evident and irrefutable. The X-shape morphology of the bulge in itself and the fraction of bulge stars that comprise orbits within this structure has important implications for the formation history of the Milky Way, and, given the ubiquity of boxy X-shaped bulges, spiral galaxies in general.

Key words: Galaxy: bulge – Galaxy: structure – surveys

1. INTRODUCTION

The boxy nature of the bulge of the Milky Way was first revealed in the COBE satellite image (Dwek et al. 1995). Using photometric data from the VVV survey, Wegg & Gerhard (2013) measured the three-dimensional density of red clump stars in the bulge, earlier revealed to show two peaks along the line of sight (McWilliam & Zoccali 2010; Nataf et al. 2010), and determined their distribution to be characteristic of a strong boxy/peanut bulge within a barred galaxy. This observed split in the red clump is reported to be a property of the more metal-rich stars in the bulge, with [Fe/H] > ~0.5 (Ness et al. 2012; Uttenthaler et al. 2012); although according to Nataf et al. (2014) this metallicity dependence may be subject to biases. Portail et al. (2015b) used the VVV red clump stellar density to show that the Milky Way’s bulge has an off-centered X-structure and using orbit based characterization of the X-shape, determined that the fraction of stars in orbits that contribute to the X-shape is 40%–45% of the mass of the bulge (Portail et al. 2015a). The X-shape in the Milky Way bulge is similar to that seen in the unsharp masked images of other barred spiral galaxies (e.g., Bureau et al. 2006). Such X-shaped structures, which underlie the boxy/peanut, have been shown to form in N-body simulations, via dynamical instabilities in the disk (e.g., Athanassoula 2005; Debattista et al. 2006; Martinez-Valpuesta et al. 2006). This shape is a consequence of the $x_1v_1$ (Pfenniger 1984; Athanassoula 1992) and other orbit families (e.g., Portail et al. 2015a).

Lee et al. (2015) have questioned the existence of the X-shaped nature of the bulge, instead proposing the split in the red clump stars to be a consequence of different stellar populations in a classical bulge. Conversely, Gonzalez et al. (2015) summarize the set of observational properties of the bulge, which explain the link between the double or split red clump and the X-shape.

We present, for the first time, the WISE image of the Milky Way (Lang 2014; Meisner et al. 2016), which clearly demonstrates that the Milky Way bulge is irrefutably morphologically X-shaped. This follows expectations from the observational evidence, from dynamical models of boxy/peanut bulges like the Milky Way, and from observations of other barred galaxies that reveal such an X-shaped profile is not uncommon (Laurikainen et al. 2014). (Also see Athanassoula 2016 for a review).

2. THE UNWISE IMAGE OF THE MILKY WAY BULGE

The WISE mission (Wright et al. 2010) is a full-sky photometric survey using four bands in the mid-infrared at 3.4, 4.6, 12, and 22 μm (W1–W4). The original WISE data release was based on a co-adding approach that is optimal for detecting isolated point sources but effectively blurs the images. Lang (2014) implemented an alternative co-adding methodology that does not degrade the resolution of the imaging. These “unWISE” coadds have been publicly released.5 Recently, Meisner et al. (2016) have released updated coadds using data from before and after the reactivation of the WISE satellite. In addition to more data, these coadds reduce the impact of scattered light from the moon and other artifacts.

Figure 1 presents the bulge region of the Milky Way, resampled to Galactic coordinates from the unWISE images, across ($|l|, |b|$) < (60, 30) in WISE bands W1 and W2. This presents the overall Milky Way structures in exquisite detail. No additional unsharp masking or equivalent techniques have been used to enhance these data. The bulge in the central region of this figure shows a clear X-shaped morphology. Note that the arms of the X-shape are asymmetrical around the minor axis and appear larger to the left than to the right. This is a real projection

5 Available at http://unwise.me. Browseable at http://legacysurvey.org/viewer.
effect and reflects that the bulge is oriented at about $27^\circ$ with respect to the line of sight (Wegg & Gerhard 2013), with the nearest side at positive longitudes. The X-shape is also visible, though with more artifacts, in the official AllWISE data release imaging. The W3 and W4 bands largely trace dust rather than stellar light and therefore do not reveal the X-shaped profile.

3. THE CONTRAST ENHANCED UNWISE IMAGE OF THE BULGE

Figure 2 presents a contrast enhanced and zoomed-in version of Figure 1. This better reveals the X-shape light profile of the bulge and its extent across $(\ell, b)$ in the WISE image. This figure was produced with a median subtraction across each row to suppress the contribution from the disk. The arms in the image extend to longitudes of $|\ell| \approx 10^\circ$ and latitudes of $|b| \lesssim 10^\circ$; (though note again that the arms on the near side are larger than those on the far side due to projection). This extent on the sky corresponds to a length of about 2.4 kpc for each arm, for a distance to the bulge center of 8.3 kpc from the Sun and a bar angle of $27^\circ$.

4. THE RESIDUALS OF THE UNWISE IMAGE OF THE BULGE

Finally, we fit and subtract a simple exponential disk model to make the bulge structure more clear. We zoom in to the central region of the galaxy, compute the W1–W2 color of each pixel, and mask the top and bottom 5% in order to suppress the influence of the most dusty regions on the fit. We then fit a simple exponential disk model, where the ellipse shape parameters are shared between the W1 and W2 bands, and each pixel is given equal weight. The model fit parameters we get are a half-light radius on the major axis of about 1.9 kpc and an axis ratio of 0.38, yielding a vertical half-light radius of about 720 pc. Figure 3 shows these results. The projection effect is again clear in these residual maps, which reflects that the bulge is oriented with respect to the line of sight, with the nearest side at positive longitudes.

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6 Explanatory Supplement to the AllWISE Data Release Products, http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/
5. CONCLUSION

Using the publicly available “unWISE” coadds, we have presented new images of the bulge of the Milky Way in the W1 and W2 bands. These directly reveal its X-shaped nature in the integrated light, even without any special image processing or enhancement. Our contrast enhancement and residual maps further highlight the extent of the X-shape that underlies the boxy structure. Critical to understanding the bulge is a further and detailed characterization of the stars that are in the arms of the X-shape, the spatial extent of which is clearly demonstrated in our figures. The image we have presented in galactic coordinates will therefore provide a useful guide for current and future spectroscopic surveys such as APOGEE (Majewski et al. 2015), 4-MOST (de Jong et al. 2014), and bulge programs associated with the GALAH survey (De Silva et al. 2015). These data can be used to guide stellar target selection, where examining the spectroscopic ages (e.g., Ness et al. 2015; Martig et al. 2016) and metallicities of stars in the arms of the X-shape as a function of ($\ell$, $b$) will be necessary to understand the formation of the bulge and constrain the formation processes relevant in the Milky Way.

High-resolution versions of the ($\ell$, $b$) coordinate frame images for W1 and W2 in this paper are available at unwise.me. The repository containing the paper, the script to reproduce the figures in the paper, and the data files are available on github: https://github.com/mkness/Xbulge.

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Figure 3. WISE W1 and W2 image fit by a simple exponential disk model, making the X-shaped structure more apparent. Top-left: data. Top-middle: data, masking out the top and bottom 5% of pixels based on W1–W2 color, as well as pixels with negative flux. Top-right: exponential disk model fit. Bottom-left: residuals (data minus model). Bottom-middle: masked residuals. Bottom-right: 50 pixel (~1.7”) median filter of masked residuals (median of unmasked pixels).
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