Formation and Evolution of Galaxy Outskirts
Proceedings IAU Symposium No. 321, 2016
A. Gil de Paz, J.H. Knapen & J.C. Lee, eds.

doi:10.1017/S1743921316011121

The Vertical Displacement of the Milky Way Disk

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Abstract. An oscillating vertical displacement of the Milky Way, with a wavelength of about 8 kpc and and amplitude of about 100 pc (increasing with distance from the Galactic center) is observed towards the Galactic anticenter. These oscillations are thought to be the result of disk perturbations from dwarf satellites of the Milky Way. They explain the Monoceros Ring and could be related to Milky Way spiral structure.

Keywords. Galaxy: disk, Galaxy: kinematics and dynamics, Galaxy: structure

1. Introduction

It has been fourteen years since Newberg *et al.* (2002) used a 2.5°-wide stripe of Sloan Digital Sky Survey (SDSS; York *et al.* 2000) data to discover that the Milky Way's stellar spheroid was not a smooth power law distribution of stars, but was instead dominated by density substructures that turned out to be tidal streams from dwarf galaxies that are in the process of being torn apart as they fall into the Milky Way's gravitational potential (Bullock & Johnston 2005). These tidal streams are still being discovered in the outskirts of the Milky Way and also in other galaxies (Martínez-Delgado *et al.* 2010).

Figure 1 of Newberg *et al.* (2002) shows the density of color-selected turnoff stars along the Celestial Equator from the SDSS, showing structure that is now known as the Sgr dwarf tidal stream, the Virgo Overdensity, and the Monoceros Ring. The Monoceros Ring has been a particularly controversial structure originally identified at $(l, b) = (223°, 20°)$ and mean apparent magnitude $g_0 = 19.4$, where the subscript "0" indicates that the magnitude has been corrected for reddening.

If one looks in detail at the substructure near the anticenter in Figure 1 of Newberg *et al.* (2002), there appears to be an oscillation in the star counts above and below the Galactic plane that was unnoticed for more than a decade. There are more stars above the plane at $g_0 = 15$, more stars below the plane at $g_0 = 17.5$, more stars above the plane at $g_0 = 19$, and more stars below the plane at $g_0 = 20$. It turns out that this oscillation is real, is not due to the larger extinction in the south Galactic cap, and is present over more than 100° of Galactic longitude near the anticenter at low latitude.

2. An Oscillating Vertical Displacement of the Milky Way Disk

In (Xu *et al.* 2015), we showed that the Galactic disk is not symmetric around the $b = 0$ plane. As one looks towards the anticenter at low Galactic latitude the sign of the asymmetry oscillates with distance from the Sun. There are more stars in the north at distances of about 2 kpc from the Sun, more stars in the south at 4-6 kpc from the Sun, more stars in the north at 8-10 kpc from the Sun, and possibly more stars in the south 12-16 kpc from the Sun. The asymmetry is observed in the Galactic longitude range $110° < l < 229°$. The Galactocentric distance to the observed structure increases slightly from the second quadrant to the third quadrant, roughly following the opening of the Milky Way spiral arms. We fit an exponential disk model with an oscillating, axisymmetric vertical displacement to the star counts within 8 kpc of the Sun looking towards the Galactic anticenter; the best fit raises the disk midplane by 70 pc, 2.5 kpc from the Sun; and lowers the disk midplane by 170 pc at 6 kpc from the Sun. The amplitude of the oscillation increases farther from the Galactic center.

These results were obtained from analysis of seven SDSS stripes that pass through the Galactic plane at constant Galactic longitude. Photometric data with $10° < |b| < 30°$ was divided up into $2.5° \times 2.5°$ bins, positioned symmetrically on each side of the Galactic plane at $b = 0°$. We created H-R diagrams for each sky patch. We then subtracted the H-R diagram from that of the symmetric sky patch on the other side of the Galactic plane. The result was an oscillating pattern of black and white main sequences. At brighter magnitudes (closer distances) there was a white main sequence, meaning there were more main sequence stars in the north. Going fainter there was a dark main sequence (more stars in the south), then another white main sequence (more in the north), and at the faintest portion of the subtractions there was possibly another darker main sequence. Note that an error in reddening correction could not cause this pattern because the reddening direction is roughly aligned with the main sequence, so reddening would just move the stars along the main sequence and would not cause the main sequences to be misaligned in magnitude from one hemisphere to the other.

Spectra of the stars in the brighter two main sequences are as expected for disk stars in kinematics, metallicity, and density distribution. They show the familiar asymmetric drift in the velocity distribution that is fit exactly, with no free parameters, by the formulae in Schönrich (2012). We did not have spectra for the stars in the outer two structures at the positions of the Monoceros Ring and Triangulum-Andromeda Cloud, but presumably these are also part of the Milky Way stellar disk and not separate tidal streams. This is supported by recent claims that Tri-And stars are disk-like (Price-Whelan *et al.* 2015).

The details of the analysis and results can be found in the Xu *et al.* (2015) paper.

3. Implications

Our result implies that the disk of the Milky Way extends out to 25 kpc from the Galactic center, and has oscillating vertical displacements. We suspect that previous studies showing the stellar disk density falling off abruptly at 15 kpc from the Galactic center were compromised by the unexpected shift in stars from one side of the Galactic plane to the other. In our new picture of the disk, the Monoceros Ring and Triangulum-Andromeda Clouds are part of the stellar disk, and *not* dwarf galaxy tidal streams. These structures are now presumed to be at peak displacements (one to the north and one to the south) of the disk midplane.

At present, there is only one mechanism known to cause vertical displacements in the disk midplane, and that is the disk response to a dwarf galaxy (or dark subhalo) falling into the Milky Way. A Sagittarius dwarf-sized galaxy falling into the Milky Way produces qualitatively similar vertical displacements, though the results have not yet been matched in detail (Gómez *et al.* 2013). This same mechanism could also explain the observed oscillation of the stellar density perpendicular to the plane (Yanny & Gardner

2013), and the coherent substructure in the velocities of disk stars that has been found in the SDSS (Widrow *et al.* 2012), RAVE (Williams *et al.* 2013), and LAMOST (Carlin *et al.* 2013) surveys. Again, the observations have not been matched in detail with a particular model but qualitatively they look similar.

Of particular interest is the relationship between wavelike oscillations observed in the Milky Way stellar disk and those observed in the gas. Hydrodynamic simulations have been matched with the observed gas oscillations to predict the approximate mass and orbit of a dwarf galaxy that is presumed to have produced the disturbance (Chakrabarti *et al.* 2011). It is possible that the gas and stars are exhibiting wave motions from different satellites, since the physics of wave propogation and damping are different in these two Galactic components. However, this relationship remains to be fully tested.

Another open question is the relationship between the vertical displacement of the disk and spiral structure. N-body simulations of satellites passing near the Milky Way disk produce spiral structure. However, spiral arms are very low scale height structures that are populated by bright, young stars and star-forming regions that are thought to be the result of compression of the gas in spiral density waves. Spiral arms are not simply density variations in the typical disk star population. On the other hand, it is tempting to think that an infalling dwarf galaxy could be the energy source that maintains spiral density structure over a large portion of the age of the Universe. Satellites could perturb the disk on each orbital passage, explaining why most spiral galaxies are not grand design spirals with easily traced spiral arms.

Vertical oscillations in the gas have been observed in galaxies outside of the Milky Way (Matthews & Uson 2008), but oscillations in the stellar disks have not. It is harder to observe oscillations in the stellar disk because the stars have a scale height that is larger than the observed amplitude of the oscillations. They can only be seen in edge-on galaxies, and the oscillations will be blurred along our line-of-sight through the galaxy. However, we expect that if people look for vertical oscillations of the stars in external galaxies that they will find them.

For more than a decade, there has been a controversy over the identity of the Monoceros Ring. Half of the community (including me) thought that the Monoceros Ring was tidal debris from an infalling dwarf galaxy. Half of the community thought that the Monoceros Ring was a warping or flaring of the stars in the disk. Our result suggests that the Monoceros Ring is neither; it is a wavelike perturbation of the disk caused by a satellite (dwarf galaxy or dark subhalo) of the Milky Way.

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