A KILOPARSEC-SCALE NUCLEAR STELLAR DISK IN THE MILKY WAY AS A POSSIBLE EXPLANATION OF THE HIGH VELOCITY PEAKS IN THE GALACTIC BULGE

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Abstract

The Apache Point Observatory Galactic Evolution Experiment has measured the stellar velocities of red giant stars in the inner Milky Way. We confirm that the line of sight velocity distributions (LOSVDs) in the mid-plane exhibit a second peak at high velocities, whereas those at $|b| = 2\degree$ do not. We use a high resolution simulation of a barred galaxy, which crucially includes gas and star formation, to guide our interpretation of the LOSVDs. We show that the data are fully consistent with the presence of a thin, rapidly rotating, nuclear disk extending to $\sim 1\ kpc$. This nuclear disk is orientated perpendicular to the bar and is likely to be composed of stars on x2 orbits. The gas in the simulation is able to fall onto such orbits, leading to stars populating an orthogonal disk.

Subject headings: Galaxy: bulge — Galaxy: evolution — Galaxy: formation — Galaxy: kinematics and dynamics — Galaxy: stellar content

1. INTRODUCTION

Detections of high Galactic standard-of-rest velocity ($V_{\text{GSR}}$) peaks in the Apache Point Observatory Galactic Evolution Experiment (APOGEE) commissioning data were reported by Nidever et al. (2012) across all fields at $4\degree \leq l \leq 14\degree$ and $-2\degree \leq b \leq 2\degree$. Nidever et al. (2012) interpreted the high-$V_{\text{GSR}}$ peaks as being due to stars in the Galactic bar. However, the peaks are not statistically significant in a number of fields (Li et al. 2014) and no high-$V_{\text{GSR}}$ peaks were found at negative longitudes in the Bulge Radial Velocity Assay (BRAVA), at $b \sim -4\degree$ (Kunder et al. 2012). Additionally, no high-$V_{\text{GSR}}$ peaks can be found in pure N-body models (Li et al. 2014). Molloy et al. (2015) demonstrated that resonant (2:1 and higher order) orbits, viewed on their own, were able to generate high-$V_{\text{GSR}}$ peaks. Aumer & Schönrich (2013) proposed that such resonant orbits are populated by young stars recently trapped by the bar; they argued that the APOGEE selection function is biased toward such young stars.

Bars have been implicated in building large gas reservoirs at the centers of galaxies, fuelling high star formation rates there. As in other barred galaxies, the Milky Way (MW)‘s bar funnels gas inwards (Binney et al. 1991; Weiner & Sellwood 1999; Fox 1999). This gas gives rise to structures such as the Central Molecular Zone (CMZ), spanning $-10\degree \leq l \leq 10\degree$. The CMZ contains $5\times10^7\ M_\odot$ of molecular gas (Bally et al. 1987; Güsten 1989), driving a star formation rate of $\sim 0.14\ M_\odot\ yr^{-1}$ (Wardle & Yusef-Zadeh 2008). A molecular gas disk extends across $|l| < 6\degree$ and $|b| < 1.6\degree$ (Boye & Cohen 1994; Dame & Thaddeus 1994; Liszt & Burton 1980) and interpreted the observed molecular, atomic and ionized gas outside the CMZ to Galactic longitude $|l| \sim 10\degree$ as a (tilted) disk with semi-major axis of radius $\sim 1.4\ kpc$ with a hole at its center. In external galaxies, star formation in nuclear rings builds nuclear disks (Kormendy & Kennicutt 2004). In this Letter we demonstrate that the high-$V_{\text{GSR}}$ peaks in the line of sight velocity distributions (LOSVDs) are consistent with the presence of a nuclear disk in the MW.

2. SIMULATION

Here we use a high resolution simulation, with gas and star formation, which develops a bar, driving gas to the center and forming a stellar nuclear disk (Cole et al. 2014), to derive the kinematic signatures of such a disk. We use these to guide our interpretation of the APOGEE Data Release 12 (Alam et al. 2015) stellar velocity data for the inner MW. While the simulation was not designed to match the MW, Cole et al. (2014) showed that the nuclear disk that it forms is qualitatively similar to those in external galaxies.

The simulation was evolved with the N-body+smoothed particle hydrodynamics code GASOLINE (Wadsley et al. 2004). The galaxy forms out of gas cooling off a hot corona in pressure equilibrium within a dark matter halo of virial mass $M_{200} = 9 \times 10^{11}\ M_\odot$. Both the dark matter halo and the initial gas corona are represented by $5 \times 10^6$ particles. As the gas cools and reaches high density, star formation is triggered. Star particles then provide feedback via winds from massive stars, and types Ia and II supernovae (Stinson et al. 2006). Gas particles all have initial mass of $2.7 \times 10^4\ M_\odot$ and star particles are spawned from gas with 35% of this mass. This high mass resolution allows us to use a high star formation threshold of 100 cm$^{-3}$ for the gas (Governato et al. 2010). By the end of the simulation the galaxy has a stellar mass of $6.5 \times 10^{10}\ M_\odot$ in $\sim 1.1 \times 10^7$ particles. This large number of star particles provides a very fine sampling of the mass distribution at the center of the model. Further details of the simulation are provided in Cole et al. (2014).

The bar forms at around 4 Gyr. After 6 Gyr a prominent nuclear disk starts to form which, by 10 Gyr, has a semi-major axis of 1.5 kpc. The nuclear disk is perpendicular to the bar and its stellar streaming is perpendicular to the bar’s. At 10 Gyr the nuclear disk in the simulation is quite massive and is thus unlikely to match...
any nuclear disk in the MW. Therefore here we consider
the model at two earlier times: at \( t_1 = 6 \) Gyr, before
the nuclear disk forms, and at \( t_2 = 7.5 \) Gyr when a strong
nuclear disk is established. Aside from the nuclear disk
becoming more massive and the bar growing longer, the
model at 10 Gyr is not qualitatively different from at \( t_2 \).

2.1. Scaling to the MW and Viewing Perspective

In order to compare to the MW, we rescale the model
in both size and velocity. Size rescaling is accomplished by
matching the size of the bar to that of the MW. Between
\( t_1 \) and \( t_2 \) the average size of the bar in the simulation,
as measured from the radius at which the phase of the
\( m = 2 \) Fourier moment deviates from a constant by more
than 10\(^\circ\) (Aguerri et al. 2003), is 2.1 kpc. Assuming that
the MW’s bar has a semi-major axis of 3.5 kpc (Gerhard
2002), we scale all coordinates by a factor of 1.67. (Scaling
to the more up-to-date bar size of Wegg et al. 2015,
5 kpc, leads to a nuclear disk which is much too large;
because we seek a closer nuclear disk size match, we scale
to the older bar size, but this is not to imply that the
real MW bar semi-major axis is closer to 3.5 kpc than
5 kpc.) The velocity scale factor is obtained by a least-
squares fit to the line of sight velocity dispersion of the
model to Abundances and Radial velocity Galactic Ori-
gins Survey Ness et al. (2013) data for all stars within
Galactocentric radius \( R_{GC} < 3.5 \) kpc at \( b = 5^\circ, 7.5^\circ \) and
10\(^\circ\) across \( |l| < 15^\circ \). We obtain a velocity scaling factor of
0.48. While these scalings lead to a model of roughly
the right size and rotational velocity we stress that the
model still does not match the MW and we only use it
to qualitatively predict the expected trends in the MW,
not their magnitude or precise location.

We assume that the Sun is 8 kpc from the Galactic
Center, and place the observer at \( y = -8 \) kpc. We or-
ient the bar at 27\(^\circ\) to the line of sight (Wegg & Gerhard
2013). Since we compare our model with APOGEE
(Alam et al. 2015) data, which targets bright red giant
stars, we adopt a uniform selection function for star par-
ticles at 2 kpc \( \leq R_s \leq 10 \) kpc, where \( R_s \) is the distance
from the Sun (Schultheis et al. 2014; Hayden et al.
2013). Reducing the maximum \( R_s \) to 8 kpc does not sig-
nificantly alter our conclusions. We use an opening angle
of 0.5\(^\circ\) for each LOSVD, to match the size of the smallest
APOGEE bulge fields. The (off-plane) line of sight with
the least particles contains over 2800 star particles while
the best sampled (mid-plane) field has over 57,000 star
particles; thus the shapes of the model LOSVDs are well
determined. The top row of Figure 1 shows the model’s
surface density distribution.

2.2. Line of Sight Velocity Distributions

Viewing the model from the Solar perspective, we mea-
sure the distribution of line of sight velocities in the
Galactocentric restframe, \( V_{GSR} \). Figure 1 shows the
LOSVDs for various lines-of-sight (indicated in the top
row) in the mid-plane \((b = 0^\circ, \) second row\) and off-plane
\((b = 2^\circ, \) third row\). At \( t_1 \) each LOSVD at \( l \leq 12^\circ \) has
a single peak, both in the mid-plane and off the plane. The
LOSVDs have a shoulder to high \( V_{GSR} \), which Li et al.
(2014) showed is produced by stars at large distances
seen close to tangentially. The peak in \( V_{GSR} \) moves to
larger velocities with increasing \( l \), but remains well be-
low the Galaxy’s circular velocity. By \( t_2 \) the LOSVDs at
\( l = 8^\circ \) and \( l = 10^\circ \) have developed a second, high-\( V_{GSR} \) peak.
This peak is more prominent than the low-\( V_{GSR} \) peak,
due to the model’s very vigorous star formation in the
nuclear disk, roughly ten times higher than in the MW for
the corresponding region. This very high star
formation rate quickly leads to a relatively massive nu-
clear disk; thus the relative amplitudes of the low- and
high-\( V_{GSR} \) peaks are not predictions of the model.
Indeed if we reduce the weight of star particles younger
than 1 Gyr by a factor of 5, to compensate for the high
star formation rate of the model, then the high-\( V_{GSR} \) peaks
become smaller than the main peaks, as seen in
Figure 1. The distribution around the high-\( V_{GSR} \) peak is
narrower (i.e. cooler) than that around the main peak
and is skewed toward low \( V_{GSR} \). Interior to \( l = 8^\circ \),
the LOSVDs are broadened relative to those at \( t_1 \), but no
high-\( V_{GSR} \) peak is evident. At \( l \geq 14^\circ \) no high-\( V_{GSR} \) peak
is present in the mid-plane, indicating that the struc-
ture responsible for the feature does not extend this far.
The off-plane and mid-plane LOSVDs are not substan-
tially different at \( t_1 \), aside from the mid-plane hosting
more stars at \( V_{GSR} \geq 100 \) km s\(^{-1} \). At \( t_2 \) the high-\( V_{GSR} \) peaks,
which dominate the mid-plane, are entirely ab-
sent in the \( b = 2^\circ \) LOSVDs. Therefore the presence of a
nuclear disk is only evident in the mid-plane. As in the
MW, outside the nuclear disk, the off-plane LOSVDs at
\((l, b) = (14^\circ, 2^\circ) \) also contain a statistically significant
high-\( V_{GSR} \) peak/shoulder, but this is also present at \( t_1 \),
and is not related to the nuclear disk. Thus the kinematic
signatures of a nuclear disk are (1) a second, high-\( V_{GSR} \) peak
at roughly the circular velocity, (2) which is ab-
sent a few degrees off the mid-plane, (3) is kinemati-
cally cooler than the low-\( V_{GSR} \) peak, and (4) is skewed toward
low \( V_{GSR} \).

2.3. LOSVD Stacking

The top row of Figure 1 shows color-coded maps of
the average \( V_{GSR} \). \( \langle V_{GSR} \rangle \): the peak velocities at orbit
tangent points manifest as the characteristic “winged”
pattern of the \( \langle V_{GSR} \rangle \) fields. Although the two \( \langle V_{GSR} \rangle \)
maps show the model before and after the nuclear disk
forms, they are not very different, indicating that the
formation of the nuclear disk does not lead to a wholesale
change of the galaxy as much as populating new parts
of its phase space. At the low longitudes of the nuclear
disk, \( \langle V_{GSR} \rangle \) occurs only close to the galactic center while
at other radii \( \langle V_{GSR} \rangle \) is smaller.

Even with a survey the size of APOGEE, the number
of stars in individual fields is still relatively small, giv-
ing a low signal-to-noise ratio for any second peak in any
one field (Li et al. 2014). In order to overcome this dif-
ficulty, we note that the \( V_{GSR} \) of the second peak does
not change significantly with longitude at \( 6^\circ \leq l \leq 10^\circ \).
Therefore by stacking the LOSVDs we can enhance the
signal-to-noise ratio of the high-\( V_{GSR} \) peak. Because the
main peak is dominated by stars streaming along the
bar, \( \langle V_{GSR} \rangle \) of these changes with \( l \), the main peak
in a stacked LOSVD will be quite broad. If we include
\( l < 4^\circ \), then the exponentially higher density of disk and
bar stars near the center masks out any features at high
\( V_{GSR} \). In the bottom panels of Figure 1 we present a stack of
the model’s LOSVDs at \( l = 6^\circ, 8^\circ \) and \( 10^\circ \). As with the individual LOSVDs, a peak at high \( V_{GSR} \) is
evident at \( t_2 \) in the mid-plane but is absent at \( b = 2^\circ \).
Fig. 1.— Top row: Face-on views of the model: contours indicate the surface density while colors show $\langle V_{\text{GSR}} \rangle$. The bold dotted circles indicate the radii between which star particles are chosen (the selection function). The dashed lines show longitudes $4^\circ$-$14^\circ$ in $2^\circ$ steps, color-coded as in the next two rows. Second row: Mid-plane LOSVDs for the different longitudes. Third row: LOSVDs at $b = 2^\circ$, colored as in the rows above. Bottom row: Stacked model LOSVDs from $l = 6^\circ$, $l = 8^\circ$ and $l = 10^\circ$ in the mid-plane (black) and at $b = 2^\circ$ (red). The dashed black lines show the effect of reducing the weights of star particles younger than 1 Gyr by a factor of 5, to compensate for the very high star formation rate in the model. All LOSVDs have been normalized to unit peak. The left panels are at $t_1$ while the right ones are at $t_2$. 

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Moreover this second peak is still cooler than the low-
$V_{\text{GSR}}$ peak, and remains skewed toward it. Thus stacking
LOSVDs preserves the kinematic signatures of a nuclear
disk, and provides a reliable method for searching for a
nuclear disk in the APOGEE data.

3. APOGEE DATA

3.1. Data Selection

We select APOGEE survey stars in the fields of in-
terest, excluding stars with the STAR BAD flag (cor-
responding to poor stellar parameter fits) and those flagged
as flux and telluric standards. Stars with a velocity scat-
ter between different visits of more than 5 km s$^{-1}$ are also
removed. (The same analysis including also stars flagged
as STAR BAD, which leads to 763 in the plane and 1401
off-plane stacks.)

The small numbers of stars in the APOGEE commis-
sioning data resulted in peaks with low signal-to-noise
ratio. We increase the statistical significance of a high-
$V_{\text{GSR}}$ peak by stacking the APOGEE DR12 data in the
longitude range $6^\circ \leq l \leq 8^\circ$ for fields in the mid-plane
and off-plane at $|b| = 2^\circ$ (totalling 617 and 1114 stars,
respectively). Table 1 lists the fields stacked together
and the number of stars used from each field.

Figure 2 plots these two stacked APOGEE LOSVDs.
The mid-plane stack has a clear second peak at $V_{\text{GSR}} \sim
220$ km s$^{-1}$, corresponding to roughly the circular
velocity of the MW in the bulge region (Sofue et al. 2009). No
comparable second peak is visible in the off-plane stacked
LOSVD, which is non-Gaussian and skewed toward high
$V_{\text{GSR}}$, i.e. it has a shoulder to high $V_{\text{GSR}}$ (Li et al. 2014).
A Kolmogorov-Smirnov test shows that the null hypoth-
esis that the mid-plane and off-plane LOSVDs are drawn
from the same distribution has a relatively low $p$-value
of 0.04.

We fit two Gaussians to the mid-plane stacked LOSVD
in the range $-300 \text{ km s}^{-1} \leq V_{\text{GSR}} \leq 300 \text{ km s}^{-1}$,
constrained such that the smaller Gaussian contains
less than 25% of the stars (to avoid fitting just the
skewed low-$V_{\text{GSR}}$ distribution with two Gaussians). We
obtain a low-$V_{\text{GSR}}$ component having mean velocity
($V_{\text{GSR}}$) = 24 km s$^{-1}$ and standard deviation $\sigma_{\text{GSR}}$
= 57 km s$^{-1}$, while the high-$V_{\text{GSR}}$ component has ($V_{\text{GSR}}$)
= 217 km s$^{-1}$ and $\sigma_{\text{GSR}} = 44$ km s$^{-1}$, making it cooler
than the low-$V_{\text{GSR}}$ component. These two Gaussians
are also shown in Figure 2. The velocity distribution at
$V_{\text{GSR}} \geq 200$ km s$^{-1}$ hints at a skewness opposite to that
of the main distribution, but the signal-to-noise ratio is
still too low for a robust measurement.

The high-$V_{\text{GSR}}$ Gaussian has a significant number of
stars associated with it, and is significantly separated
from the low-$V_{\text{GSR}}$ Gaussian. In order to test the like-
lihood of such a second peak arising purely from Pois-
son noise, we perform Monte-Carlo tests drawing 617
stars from the off-plane stacked LOSVD. Fitting two
Gaussians as before to the resulting LOSVD, we label as
$G_l$ and $G_h$ the low- and high-$V_{\text{GSR}}$ components,
respectively. We repeat this procedure 100,000 times, and
for each we compute $N_h/N_{\text{tot}}$, the ratio of stars in the
high-$V_{\text{GSR}}$ component to the total number of stars, and
the overlap of the two components, defined as

$$O = \int G_l G_h dV_{\text{GSR}}.$$  

The results are presented in Figure 3; the observed
mid-plane stacked LOSVD has $N_h/N_{\text{tot}} = 0.12$ and
$O = 4.3$. Only 0.025% of the Monte-Carlo samples
have $N_h/N_{\text{tot}} \leq 0.12$, while none of them have over-
lap $O \leq 8$, showing that the observed double-peaked
mid-plane stacked LOSVD is highly unlikely to result
from Poisson noise. The APOGEE data therefore show
a statistically significant double-Gaussian LOSVD in the
mid-plane, the properties of which agree with 3 of the 4
kinematic signatures of a nuclear disk from the simul-
ation. While the signal-to-noise is too low to be sure if
the high-$V_{\text{GSR}}$ peak is skewed to low $V_{\text{GSR}}$, the data are
suggestive that it is. Therefore a kiloparsec-scale nuclear
disk can explain the high-$V_{\text{GSR}}$ peaks in the APOGEE
data.

A simple estimate for the nuclear disk mass can be ob-
tained from the fraction of stars in the high-$V_{\text{GSR}}$
component of the double-Gaussian fit to the mid-plane
LOSVD. If we conservatively assume that the nuclear disk
mass contained within $|z| \leq 150$ pc and $4 ^\circ \leq |l| \leq 8 ^\circ$ is
12% of the total mass of the Besançon Galaxy model
(Robin et al. 2012) within this volume we obtain a lower
limit to the mass of the nuclear disk $\sim 5.8 \times 10^7 M_\odot$.

4. DISCUSSION

Attempts to explain the high-$V_{\text{GSR}}$ peak directly via
collisionless bar simulations fail (Nidever et al. 2012).

\begin{table}[h]
\begin{tabular}{|c|c|c|c|}
\hline
Field & $l$ [\degr] & $b$ [\degr] & $N_\ast$ \tabularnewline
\hline
4336 & 6.0 & 0.0 & 471 mid-plane \tabularnewline
4355 & 8.0 & 0.0 & 146 mid-plane \tabularnewline
4365 & 5.7 & 2.0 & 387 off-plane \tabularnewline
4366 & 5.7 & -2.0 & 424 off-plane \tabularnewline
4373 & 7.8 & -2.0 & 154 off-plane \tabularnewline
4377 & 7.7 & 2.0 & 149 off-plane \tabularnewline
\hline
\end{tabular}
\caption{Fields stacked together and number of stars used for each field.}
\end{table}
main 2:1 resonant orbit family of bars, the x2 family, is orientated perpendicular to the bar. This family is generally very poorly populated in the absence of gas (Sparke & Sellwood 1987; Pfenniger & Friedli 1991), but when gas is present it is driven inwards by the bar and settles into x2 orbits (Binney et al. 1991). The gas can then form stars and produce nuclear rings and disks. We propose that the high-$V_{\text{GSR}}$ peak corresponds to a kiloparsec-scale disk composed of stars on x2 orbits. These orbits are stable and therefore our model does not require that the stars in the high-$V_{\text{GSR}}$ peak are young.

Nuclear disks are known in many external galaxies (Scorza & van den Bosch 1998; Zasov & Moiseev 1999; Pizzella et al. 2002; Emsellem et al. 2004; Krajnović et al. 2008; Ledo et al. 2010); the presence of one in the MW is therefore not unusual. Nor is the kiloparsec scale unusual as a fraction of the bar size. For instance in NGC 3945 the ratio of semi-major axes of the nuclear disk to bar is $\sim 0.15 - 0.18$ (Erwin & Sparke 1999; Cole et al. 2014), whereas for the MW this ratio is $\sim 0.2$, if we adopt Wegg et al. (2013)'s 5 kpc bar. The gas ring in the simulation is $\sim 5\times$ larger than the MW’s CMZ, which is coincident with a stellar disk (Launhardt et al. 2002; Schönrich et al. 2013). The large size of the gas ring in the model is a consequence of the still low resolution (50 pc) of our simulation (Li et al. 2013; Sormani et al. 2015). This difference implies that the nuclear disk in the MW is not currently forming stars across its full extent.

We anticipate that this proposal will inspire further detailed mapping of the central mid-plane of the MW. We will provide predictions from our model of a kiloparsec-scale nuclear disk elsewhere.

**REFERENCES**

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Li et al. 2014. However Molloy et al. (2015) demonstrated that resonant, bar-supporting 2:1 x1 (with some mixture of higher order resonance) orbits by themselves can produce second peaks. Subsequently Aumer & Schönrich (2015) argued that the selection function of APOGEE favors young stars recently trapped into resonant orbits. Their interpretation requires that the stars in the high-$V_{\text{GSR}}$ peaks are younger. The other
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