Vertical density waves in the Milky Way disc induced by the Sagittarius dwarf galaxy

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Accepted 2012 October 30. Received 2012 September 14; in original form 2012 July 12

ABSTRACT
Recently, Widrow and collaborators announced the discovery of vertical density waves in the Milky Way disc. Here we investigate a scenario where these waves were induced by the Sagittarius dwarf galaxy as it plunged through the Galaxy. Using numerical simulations, we find that the Sagittarius impact produces north–south asymmetries and vertical wave-like behaviour that qualitatively agrees with what is observed. The extent to which vertical modes can radially penetrate into the disc, as well as their amplitudes, depends on the mass of the perturbing satellite. We show that the mean height of the disc is expected to vary more rapidly in the radial than in the azimuthal direction. If the observed vertical density asymmetry is indeed caused by vertical oscillations, we predict radial and azimuthal variations of the mean vertical velocity, correlating with the spatial structure. These variations can have amplitudes as large as 8 km s⁻¹.

Key words: Galaxy: disc – Galaxy: structure – galaxies: formation – galaxies: kinematics and dynamics.

1 INTRODUCTION
Minor mergers can significantly perturb the overall structure of their host galactic disc (Quinn, Hernquist & Fullagar 1993; Villalobos & Helmi 2008). As they merge, relatively small satellite galaxies can induce the formation of spiral arms and ring-like structures as well as radial migration, significantly flare or warp the disc and influence the growth of a central bar (Tutukov & Fedorova 2006; Kazantzidis et al. 2008; Villalobos & Helmi 2008; Younger et al. 2008; Minchev et al. 2009; Quillen et al. 2009; Purcell et al. 2011; Bird, Kazantzidis & Weinberg 2012; Gómez et al. 2012a).

Purcell et al. (2011, hereafter P11) presented simulations of the response of the Milky Way (MW) disc to tidal interaction with the Sagittarius dwarf galaxy (Sgr). They showed that many of the global morphological features observed in the Galactic disc can be simultaneously explained by this interaction. An example is the kinematically cold structure known as the Monoceros ring (Newberg et al. 2002; Jurić et al. 2008), which naturally emerges in these simulations, although its origin is still a matter of debate (see Conn et al. 2012; Li et al. 2012; Lopez-Corredoira et al. 2012). Gómez et al. (2012b, hereafter G12) showed that perturbations observed in the phase-space distribution of old disc stars in the solar neighbourhood (SN) can be reproduced qualitatively with these simulations. They interpreted such perturbations as signatures of radial density waves excited on the plane of the disc by Sgr. Perturbations in the vertical direction were not explored in their work. However, using a much larger photometric and spectroscopic data set, Widrow et al. (2012, hereafter W12) recently identified a north–south asymmetry in both the spatial density and the velocity distribution of SN stars. The asymmetry has the appearance of a coherent, wave-like perturbation, intrinsic to the disc. W12 speculate that this perturbation could have been excited by the passage of a satellite galaxy through the Galactic disc. In this paper, we explore the possibility of Sgr being the perturber associated with both the vertical and radial modes.

2 SIMULATIONS
In this section we briefly describe our simulations; we refer the reader to P11 and G12 for a more detailed description. Two
Simulations with different models for the Sagittarius dwarf galaxy progenitor were performed. A Light (Heavy) Sgr progenitor, with effective virial mass \( M_{\text{vir}} = 10^{10.5} M_\odot (10^{12} M_\odot) \), was initialized with a Navarro–Frenk–White (NFW) dark matter halo of scale length 4.9 kpc (6.5 kpc), self-consistently with a separate stellar component. For the stellar component, a King profile with core radius 1.5 kpc, tidal radius 4 kpc and a central velocity dispersion of 23 km s\(^{-1}\) (30 km s\(^{-1}\)) was used. The satellites were launched 80 kpc from the Galactic Centre in the plane of the MW, travelling vertically at 80 km s\(^{-1}\) towards the North Galactic Pole. The mass loss that would have occurred between virial radius infall and this ‘initial’ location is accounted for by truncating the progenitor DM halo mass profile at the instantaneous Jacobi tidal radius, \( r_t = 23.2 \) (30.6) kpc. This leaves a total bound mass that is a factor of \( \sim 3 \) smaller than the effective virial mass originally assigned. The simulations reach a present-day configuration after \( \approx 2.7 \) Gyr (2.1 Gyr) of evolution. In both cases, the host galaxy includes an NFW dark matter halo with a scale radius of 2.84 kpc and a vertical scale height of 0.43 kpc; the central bulge has a mass of 9.52 \( \times 10^9 M_\odot \) and an \( n = 1.28 \) Sérsic profile, with an effective radius of 0.56 kpc. The initial disc in both Sgr infall models is completely smooth at \( t = 0 \) Gyr. The simulations followed the evolution of 30 million particles with masses in the range 1.1–1.9 \( \times 10^5 M_\odot \).

### 3 Perturbations in local volumes

Fig. 1 shows an overdensity map of the Heavy (left) and Light (right) Sgr simulation discs at present-day configuration. The maps are obtained by normalizing the local stellar density to the mean axisymmetric density at the corresponding galactocentric distance. The non-axisymmetric energy kick imparted by the satellite as it merges with the host induces the formation of spiral density waves. As shown by G12, waves excited by the Heavy Sgr satellite can be detected in SN-like volumes as peaks in the local energy distribution. These density waves are mainly in the radial direction. In fact, in very small local volumes (i.e. distances \( \lesssim 0.2 \) kpc), these waves can be observed as well-defined features in the radial (\( v_r \)) and tangential (\( v_\theta \)) velocity field (see Minchev et al. 2009; G12). In the left-hand panel of Fig. 2, we show with dashed lines the normalized total energy distribution \( E = f(x, v) \) of two SN-like cylindrical volumes extracted from the Heavy Sgr simulation. The volumes have a 1 kpc radius, and are located at 8 kpc from the galactic centre. Their locations, chosen based on the G12 results, are indicated with a blue dot and a red dot in the left-hand panel of Fig. 1. Note the well-defined peaks in these distributions, which reveal the presence of density waves. As expected from disc orbits, the in-plane energy distribution \( E_z = f(x, v_z) \) (solid lines) is very similar to the total energy distribution, indicating that these peaks are associated with perturbations mainly in the plane of the disc. Nevertheless, the stellar particles in these volumes present non-symmetrical energy distributions in the vertical direction \( E_\ell = f(x, v_\ell) \), as shown in the right-hand panel of Fig. 2. Furthermore, these distributions are shifted with respect to one another.

To explore whether the asymmetries and shifts observed in the \( E_\ell \) distributions are indications of vertical density waves, we compute for both volumes the distribution of stellar particles as a function of height with respect to the mid-plane of the galactic disc: \( n(Z)_{\ell,v} \), or simply \( n(Z) \). A north–south asymmetry in this distribution could be an indication of vertical modes (see W12). To compute \( n(Z) \), we have carefully aligned the disc with the \( X-Y \) plane. This is done by iteratively computing, and aligning with the \( Z \)-direction, the total angular momentum of the disc particles located within 4 kpc radius cylinders of decreasing height. In order to identify signatures of vertical density waves, it is desirable to compare \( n(Z) \) obtained from the perturbed disc with its corresponding smooth underlying distribution. For this purpose, W12 fitted a smooth two-component model to their stellar sample’s number density. In this work we follow a different approach: we obtain a smooth distribution of stellar particles, as a function of height, by azimuthally averaging \( n(Z) \), i.e.

\[
n_{\ell,v}(Z)_{av} = (2\pi)^{-1} \int_0^{2\pi} n(Z, \theta)_{\ell,v} \, d\theta.
\]

Our assumption is that local asymmetries of this distribution are erased after averaging over all azimuthal angles. In addition, we expect \( n_{\ell,v}(Z)_{av} \) to be a better representation of the true smooth height distribution of particles than smooth analytic fits. The top panels of Fig. 3 show, with coloured dots, the \( n(Z) \) distributions obtained from the ‘blue’ and ‘red’ volumes in Fig. 1, whereas the black solid line corresponds to \( n_{\ell,v}(Z) \). Note that \( n_{\ell,v}(Z) \) was renormalized to the total number of particles in each volume. Due to finite particle numbers, we are able to reliably track \( n(Z) \) only up to \( |Z| \approx 1.4 \) kpc. These panels indicate a shift of the local with respect to the smooth.

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**Figure 1.** Overdensity map of the Heavy (left) and Light (right) Sgr simulations at the present time. The colours and relief indicate the ratio of the local stellar density to the mean axisymmetric disc density at the corresponding galactocentric distance. The blue and red dots indicate the location of the volumes explored.

**Figure 2.** Left-hand panel: total (dashed lines) and in-plane (solid lines) energy distributions of disc particles located within the blue and red volumes shown in Fig. 1. Right-hand panel: as in the left-hand panel, but for the vertical energy distribution.
distribution, although this occurs in different directions for the two cases. Note, however, that for large $|Z|$ (i.e. $\gtrsim 0.7$ kpc), the shift in both distributions becomes progressively smaller, exhibiting a wave-like pattern. As in W12, we plot the residual,

$$
\Delta = \frac{n(Z) - n_{av}(Z)}{n_{av}(Z)},
$$

to highlight these asymmetries. This is shown in the second row of Fig. 3 with blue and red dots. In both cases, $\Delta$ is an odd function of $Z$. The grey dots show data from fig. 1 of W12, derived from a sample of main-sequence stars in SDSS DR8, the eighth data release of the Sloan Digital Sky Survey (Aihara et al. 2011). To match the phases of the waves, on the right-hand panels we have shifted the observational data with respect to the axes $Z = 0$ and $v_z = 0$ to match the phases of the waves.

4 AZIMUTHAL AND RADIAL DEPENDENCE

We have shown that the phase-space distributions of SN-like volumes extracted from our Heavy Sgr simulation exhibit wave-like perturbations in the vertical direction. However, it is not clear from the analysis shown thus far whether these are localized perturbations or are signatures of a global mode perturbing the entire disc. From Fig. 3, we know that the $n(Z)$ distributions of the two analysed volumes are shifted with respect to one another, as well as with respect to $n_{av}(Z)$. If the observed shifts are signatures of vertical waves, we would expect to find correlations in the mean height of the disc $Z$ as a function of galactocentric radius and azimuthal angle. We explore this in Fig. 5, where we show maps of $Z$ for the Heavy and Light Sgr simulation disc out to $R \approx 20$ kpc. To obtain these maps, we grid the disc with a regular Cartesian mesh of bin size $=0.5$ kpc aligned with the $X$–$Y$ plane. On each grid node we centre a 1 kpc radius cylinder and compute $\langle Z \rangle$ by fitting a Gaussian distribution to $n(Z)$. In the top-left panel, we show the $Z$ map reflecting the initial conditions of both discs at $t = 0$ Gyr. As expected from an initially unperturbed disc, the maps are consistent with $Z = 0$ at all radii, except for small-scale departures due to finite particle resolution. The situation dramatically changes when we explore the present-day configurations. The second column of panels in Fig. 5 shows the $Z$ map of the Heavy (top) and Light (bottom) Sgr simulation discs, obtained after $t \approx 2.1$ and 2.6 Gyr, respectively. The colour coding indicates different values of $Z$ and white regions represent volumes devoid of particles. We can now clearly identify wave-like, spiral perturbations travelling across the disc. It is possible to appreciate how the mean height of the disc gradually increases (decreases) as we follow one of these patterns azimuthally. Departures of $Z$ with respect to the mid-plane can be as large as 0.3 kpc, especially for the Heavy Sgr simulation (top panels). The local volumes analysed previously are indicated with coloured dots. As expected from Fig. 3, the blue (red) volume is relatively low statistical significance. As before, grey dots indicate data extracted from the top panel of fig. 4 in W12. At large $Z$ ($\approx 1$ kpc), the ‘blue’ (‘red’) volume shows a global trend towards negative (positive) values as $Z$ decreases (increases). As explained by W12, this suggests a coherent motion of stellar particles away from the disc mid-plane.

It is important to realize that the phase-space distribution of the blue SN-like volume qualitatively reproduces not only the observed vertical structure (W12), as we just demonstrated, but also features seen in the plane of the local Galactic disc. As shown by G12, local samples of old disc stars present a total energy distribution that is in good agreement with the distribution shown in the left-hand panel of Fig. 2 (blue lines).
located in a region lying slightly below (above) the mid-plane. In this simulation, the inner 7 kpc of the disc has not been strongly vertically perturbed by the satellite galaxy. Although the Light Sgr simulation (bottom panels) also exhibits wave-like perturbations, they generally have smaller amplitudes. Note that strong perturbations are observed only at $R > 10$ kpc. In both cases, such boundary is located near corotation, where density waves are reflected backwards to the outer disc. This can be more clearly appreciated in panels (A) and (B) of Fig. 6, where we show the $\langle Z \rangle$ maps in polar coordinates. The black dashed lines, at $R = 8$ kpc and $\theta = 1.06$ rad (measured with respect to the positive X semi-axis), cross at the location of the blue volume. For comparison, this location is indicated in both discs. Note that the inner regions of the Light Sgr disc present a value of $\langle Z \rangle \approx 0$ for a larger radial extent. Panel (C) in Fig. 6 shows $\langle Z \rangle$, as a function of $\theta$, at $R = 8$ kpc for both discs. Significant vertical perturbations at this galactocentric radius can be observed only in the Heavy Sgr simulation. A dependence of $\langle Z \rangle$ with azimuthal angle $\theta$ is present. Panel (D) shows $\langle Z \rangle$, as a function of $R$, at $\theta = 1.06$ rad. In both discs, a well-defined wave-like pattern can be observed, with an amplitude increasing as a function of $R$. Note that $\langle Z \rangle$ exhibits a stronger dependence with galactocentric radius than with azimuthal angle; a result that could be contrasted against currently available stellar samples. In the third column of Fig. 5, we explore the relationship between these vertical patterns and the radial modes shown in Fig. 1. Here, the different colours indicate different values of $\langle Z \rangle$, whereas the relief traces overdense regions. Overdense features can be found both above and below the mid-plane. Furthermore, we can appreciate how the mean height of a given spiral arm changes as a function of the azimuthal angle.

If the observed patterns are indeed signatures of vertical density waves, then a correlation between $\langle Z \rangle$ and the mean vertical velocity $\langle v_z \rangle$ is expected. We explore this in panel (E) of Fig. 6, where we plot, for the Light Sgr disc, $\langle Z \rangle$ and $\langle v_z \rangle$ as a function of $R$, at a fixed azimuthal angle. A wave-like pattern is also observed in $\langle v_z \rangle$. At galactocentric radii where $\langle Z \rangle$ takes an extrema, $\langle v_z \rangle \approx 0$. On the other hand, at galactocentric radii where $\langle v_z \rangle$ takes a maximum or a minimum value, $\langle Z \rangle \approx 0$. This is exactly what is expected from oscillatory behaviour. In the last column of Fig. 5 we show, with different colours, the local $\langle v_z \rangle$ for both galactic discs. The relief in these panels traces the corresponding overdensity maps. Note again the wave-like structure of these patterns. In the Heavy Sgr simulation (top panel), $\langle v_z \rangle$ can depart from 0 km s$^{-1}$ by more than 8 km s$^{-1}$. Similarly to what is observed for $\langle Z \rangle$, the $\langle v_z \rangle$ of a given spiral arm varies as a function of the azimuthal angle, changing from positive to negative departures with respect to $\langle v_z \rangle = 0$ km s$^{-1}$.

5 THE MAGELLANIC CLOUDS AS OTHER POSSIBLE CULPRIT

We have focused our attention on perturbations induced by the Sgr dwarf galaxy. However, the Large Magellanic Cloud (LMC) has been considered in the past by several authors as a plausible perturber behind the warp observed in the MW disc’s H I layer (Kalberla & Kerp 2009). Given its traditional mass (~2 per cent of the MW mass) and location (~50 kpc) estimates, the LMC tidal field is not sufficiently strong to induce the observed vertical perturbation (e.g. Hunter & Toomre 1969; Besla et al. 2007, hereafter B07). None the less, the addition of the force from the dark matter halo wake excited
Panels (A) and (B): maps of the simulated galactic discs, ∼−simulation. The black dashed lines cross ⟨SgrR|simulation. must by some agent external to the disc. Although we have simulation, respectively. Panel (E): comparison on 30 July 2018 by guest

Figure 6. Panels (A) and (B): maps of the simulated galactic discs, ⟨Z⟩, at present-day configuration obtained from the Heavy (left) and Light (right) Sgr simulations in polar coordinates (in kpc). The black dashed lines cross at the location of the blue volume shown in Fig. 1. Panels (C) and (D) show the variation of the mean height of the disc as we move across the black dashed lines shown in the top panels. Blue and red lines are associated with the Heavy and Light Sgr simulation, respectively. Panel (E): comparison of the mean height (red) and vertical velocity (green), as a function of galactocentric radius obtained from the Light Sgr simulation.

by the clouds (Weinberg 1998) could be enough to account for the observed warp (Weinberg & Blitz 2006). The previous results, based on linear perturbation theory, were tested with fully self-consistent simulations by Tsuchiya (2002). Assuming a decaying orbit for the LMC, this analysis showed that the observed warp could be reproduced over a 6-Gyr time-scale, involving approximately four full orbital periods (see also García-Ruiz, Kuijken & Dubinski 2002, for a different opinion). This orbital configuration is at odds with the recent findings by B07, which suggested that the MCs are approaching the MW for the very first time on a parabolic orbit travelling at ∼400 km s⁻¹. However, Vesperini & Weinberg (2000) showed that the perturbation excited by a low-velocity (∼200 km s⁻¹) flyby encounter with a slightly more massive satellite (>5 per cent of the MW mass) can be efficiently transmitted to the inner regions of the dark matter halo, where it can affect the structure of an embedded stellar disc. More recent estimates of the total LMC mass, based on abundance matching techniques, suggested values as large as 10 per cent of the MW mass (Boylan-Kolchin, Besla & Hernquist 2011). Moreover, the orbits of the MCs are currently being revised (Kallivayalil et al., in preparation). New dynamical models, including both updated orbital parameters and total mass estimates, are required to assess whether such a mechanism would have sufficient time to operate. We defer this analysis to future work.

6 DISCUSSION

In this work, we have explored a scenario in which Sgr is the perturber behind the north–south asymmetry recently observed in the number density and mean vertical velocity of SN stars (W12). For this purpose, we have searched for both local and global signatures of vertical density waves in two simulations modelling the response of the MW to the infall of Sgr. Distributions of stellar particles as a function of height in SN-like volumes extracted from our more massive Sgr’s progenitor simulation present clear indications of a perturbation in the vertical direction of the disc. This asymmetry becomes more evident when comparing with a model of the underlying smooth vertical distribution of particles. Within the |Z| range allowed by our finite mass resolution, the phase-space distribution of certain SN-like volumes can qualitatively reproduce the north–south asymmetry observed by W12. Remarkably, the same phase-space distributions can simultaneously reproduce the signatures of radial density waves observed by G12.

By creating maps of the mean height of the disc within R ≤ 20 kpc, we have shown that the vertical perturbations observed in local volumes are signatures of a global mode perturbing the entire disc. As in the case of the radial density modes (G12), the amplitude and the extent to which vertical modes can radially penetrate into the disc depend on the mass of the perturbing satellite. Interestingly, we have shown that the mean height of the disc is expected to vary much more rapidly in the radial than in the azimuthal direction. Furthermore, the mean height of overdense spiral features varies azimuthally, moving from below to above the mid-plane of the disc. Signatures of vertical modes should also be observable in maps of the Galactic disc’s mean vertical velocity since, not surprisingly, they present a clear oscillatory behaviour.

In contrast to radial modes that can be excited by a number of different external and internal mechanisms, vertical modes must be excited by some agent external to the disc. Although we have shown that perturbations induced by Sgr could be enough to account for several features observed in the SN, it is likely that MCs are playing a role in shaping the vertical structure of the MW disc. We plan to characterize the coupling of these two perturbations in a follow-up study. Contrasting the results presented in this work against currently available samples of Galactic disc stars could help us to understand the origin of the observed vertical and in-plane perturbations.

ACKNOWLEDGMENTS

We would like to thank the anonymous referee for the useful comments and suggestions which helped improve this paper. The authors wish to thank Gurtina Besla for insightful discussions. FAG was supported through the NSF Office of Cyberinfrastructure by grant PHY-0941373, and by the Michigan State University Institute
for Cyber-Enabled Research. BWO was supported in part by the Department of Energy through the Los Alamos National Laboratory Institute for Geophysics and Planetary Physics. TCB acknowledges partial support from grant PHY 08-22648: Physics Frontiers Center/Joint Institute for Nuclear Astrophysics (JINA), awarded by the US National Science Foundation.

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