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Galactoseismology in the Age of Gaia

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Abstract. Recent observations from SEGUE, RAVE, and LAMOST have revealed tantalizing evidence that the local stellar disk of the Milky Way is in a state of disequilibrium. In particular, the disk appears to exhibit bending and breathing waves normal to its midplane within 2 kiloparsecs of our position within the disk. There also appear to be bending waves or corrugations at larger Galactocentric radii. These waves may be linked to other time-dependent disk phenomena such as the bar, spiral structure, and warp, or they may be the result of a passing dark matter subhalo or dwarf galaxy. Here, we discuss the observational evidence for these waves, the theory of bending and breathing waves in (simulated) stellar disks, and implications of disequilibrium for attempts to determine the local vertical force and dark matter density (the Oort problem). We also discuss the types of analyses that one might do with the *Gaia* database.

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

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1. Observational Overview

When viewed face on, disk galaxies display richly varied structures in the form of bars, rings, and spiral arms. These features can arise in isolated galaxies through dynamical instabilities and feedback mechanisms such as swing amplification. Alternatively, they can result from the interactions of a disk with its dark halo or with another galaxy. Bars and spiral structure are dynamic in nature, changing in strength and morphology over the lifetime of a galaxy.

Galactic disks also exhibit dynamic features in the vertical direction, that is, the direction perpendicular to their respective midplanes. The most prominent examples are the HI warps seen in edge-on galaxies (see Binney 1992 and references therein). Some warps have a grand design, as with the integral-sign warps. These can be understood as long-lived $m = 1$ bending waves, where m is the azimuthal mode number. Others are more irregular with no obvious symmetry properties. Indeed, the outer HI disk of the Milky Way shows complex bending and flaring perpendicular to the midplane (Levine *et al.* 2006).

Though warps are mainly studied in HI, they are also found in the stellar disks of both external galaxies (see Reshetnikov *et al.* 2016 and references therein) and the Milky Way (Reylé *et al.* 2009). In the latter, an analysis of stars from the 2MASS survey shows that the stellar warp reaches an amplitude of ~ 1 kpc at a Galactocentric radius of 20 kpc. In addition to the warp, there is evidence in both M31 and the Milky Way for a population of stars that have been "kicked up" from the disk to the high galactic latitudes normally associated with the stellar halo (Dorman *et al.* 2013, Sheffield *et al.* 2016).

As one moves inward toward the centre of the Galaxy, the amplitude of vertical bending and breathing motions descreases. One example is the corrugation or wavelike pattern reported by Xu *et al.* (2015). This feature, which was uncovered by analyzing SDSS star counts on both sides of the Galactic midplane, has a wavelength of ~ 6 kpc and an amplitude of 100 pc, or about an order of magnitude smaller than that of the warp. The corrugations may in fact include the Monoceros Ring, which was originally thought to be the tidal debris of a disrupted satellite (Newberg *et al.* 2002 and Yanny *et al.* 2003). In the Solar Neighbourhood, Widrow *et al.* (2012), Williams *et al.* (2013), and Carlin *et al.* (2013) found evidence for vertical bulk motions on the order of $5 - 10\,\mathrm{km\,s^{-1}}$. These motions may be thought of as a combination of bending and breathing of the disk perpendicular to the Galactic midplane. In addition, there appear to be North-South asymmetries in the number counts of stars in both the SEGUE and LAMOST surveys (Widrow *et al.* 2012; Yanny & Gardner 2013; Wang *et al.* 2017).

To summarize, the Galactic disk exhibits a wide range of vertical features, from the breathing-like motions of Solar Neighbourhood stars, to a corrugation pattern of bending waves at Galactocentric radii from $10 - 20$ kpc, to the warp and kicked-up stars in the outer disk. The term Galactoseismology refers to the idea that by studying these motions, one can learn about the structure of the Milky Way's disk and the environment in which it lives.

2. Theoretical Framework

In this section, we outline a theoretical framework for studying vertical motions in galactic disks. Our analysis begins with the stellar phase space distribution function (DF)

$$f\left(\mathbf{x},\,\mathbf{v},\,t\right) = \frac{d^6 M\left(\mathbf{x},\,\mathbf{v},\,t\right)}{d\mathbf{x}\,d\mathbf{v}}\,, \tag{2.1}$$

where $M\left(\mathbf{x},\,\mathbf{v},\,t\right)$ is the mass distribution of the disk. From this, we construct moments of the DF across the face of the disk:

$$\Sigma_*\left(x,\,y\right) = \langle\ldots\rangle \int dz \int d^3v f\langle\ldots\rangle\,, \tag{2.2}$$

where Σ_*, the stellar surface density, is essentially the "zeroth" moment. Thus $\langle z\rangle = \Sigma_*^{-1}\int dz\int d^3v\,z\,f$ describes the midplane displacement, $\langle v_z\rangle$ the vertical motion of the disk, $\langle z^2\rangle$ the disk thickness, etc. These moments can be related to the stellar warp of the outer disk, disk flaring, the corrugations further in, and so forth.

Starting with the collisionless Boltzmann equation, one can derive the dynamical equations for the moments. For example, the equations for $\langle z\rangle$ and $\langle v_z\rangle$ can be combined to yield a single, second order PDE of the form

$$\left(\frac{\partial}{\partial t} + \Omega(R)\frac{\partial}{\partial\phi}\right)^2 \langle z\rangle = F_z \tag{2.3}$$

where $(R,\,\phi, z)$ are cylindrical Galactocentric coordinates and $F_z = F_z\left(R, \phi, \langle z\rangle\right)$ is the vertical force on an element of the disk at position $(R\,\phi)$ that has been displaced by $\langle z\rangle$. This equation is the starting point for the linear eigenmode analyses of Hunter & Toomre (1969) and Sparke & Casertano (1988) in their study of warp-like modes in self-gravitating disks and disk-halo systems. These authors focus on the $m = 1$ modes and find the following: For a disk embedded in a spherically symmetric halo, there is a discrete zero-frequency mode that corresponds to a (trivial) tilt of the disk. If the halo is flattened, spherical symmetry is broken and the tilt mode is modified in such a way that it has characteristics of integral-sign warps.

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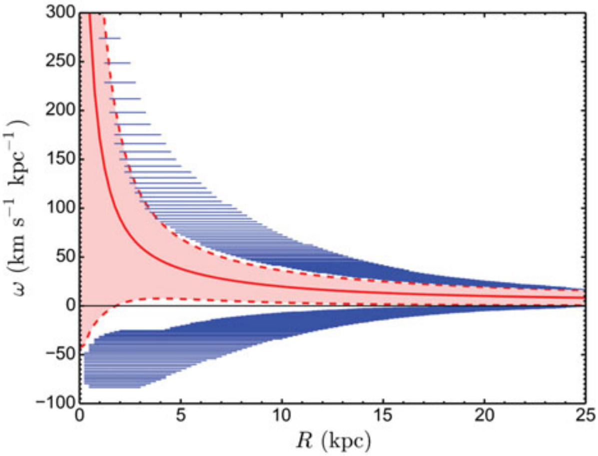

Figure 1. Continuum of linear modes for $m = 1$. The horizontal line segments show the extent of the bending mode in galactocentric radius R as a function of angular frequency ω. Modes lie just outside the forbidden region (shaded grey), which is defined by the vertical resonance curves (dashed curves). The solid curve in the middle of the shaded region shows corotation.

In addition to the discrete modified tilt mode, linear theory also predicts the existence of a continuum of bending modes. In Fig. 1, we show the modes in the frequency-R plane. Modes lie just outside the forbidden region between the two vertical resonance curves.

In passing, we note that an equation similar to Eq. 2.3 can be constructed for breathing modes. This third order partial differential equation can then be solved using techniques similar to those found in Hunter & Toomre (1969) and Sparke & Castertano (1988).

3. Numerical Simulations

In order to test these ideas, we simulated two isolated disk-bulge-halo models for a Milky Way-like galaxy (Chequers & Widrow 2017). The first model, taken from Widrow *et al.* (2008), forms a bar after several Gyr. For the second model, we reduce the mass of the disk and increase the masses of the halo and bulge so as to effectively shut off the bar instability. The simulations were evolved for 10 Gyr using GADGET Springel 2005springel2005 with live particles used to represent all three components.

Surface density maps for the two models are shown in Fig. 2. In order to enhance time-dependent features, we show the surface density relative to the initial surface density. The bar and associated ring are clearly evident in Model 1. By contrast, Model 2 is shows only flocculent spiral structure.

Fig. 3 shows a map of $\langle z \rangle$ as a function of position in the plane of the disk. For brevity, this is done only for the 4 Gyr snapshot of the bar-forming model. The disk develops a pattern of bending waves with amplitudes of order $100-200$ pc. The waves are strongest in the outer regions of the disk. Also shown in this figure are the first three terms of an azimuthal Fourier decomposition, which indicates that the strongest components are for $m = 0$ and $m = 1$. As discussed in Chequers & Widrow (2017), the waves are actually stronger in our second model, which doesn't form a bar. In addition, we find that power in the $m = 1$ bending waves tends to move outward during the course of the simulation, eventually reaching the edge of the disk in the form of a warp.

This latter point is illustrated in Fig. 4 where we show a spectral analysis for the bar-forming disk. The figure is essentially the bending wave version of the figure often

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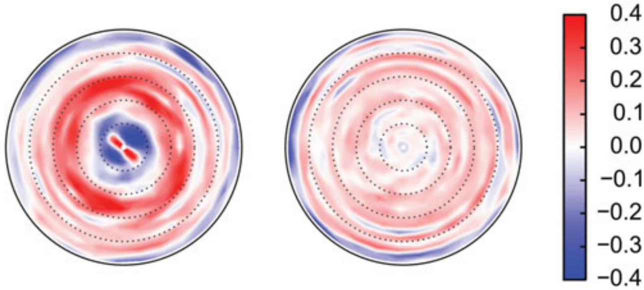

Figure 2. Surface density enhancement maps for the bar forming (left) and no-bar (right) models at 4 Gyr. We've divided through by the initial exponential surface density and took the base 10 logarithm in order to highlight changes in the disk.

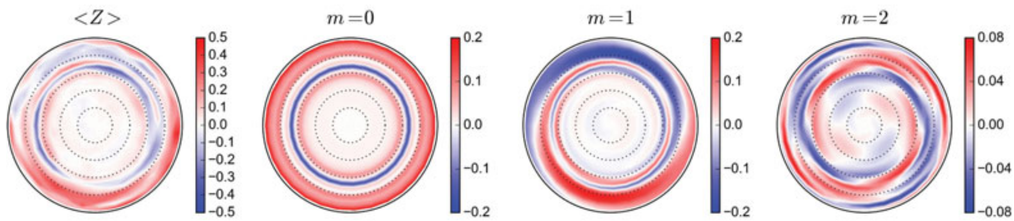

Figure 3. Bending waves across the face of the disk. In left-most panel, we show $\langle z \rangle$ at 4 Gyr for the bar-forming model. The following panels show the $m = 0$, 1, and 2 azimuthal components of $\langle z \rangle$, as indicated.

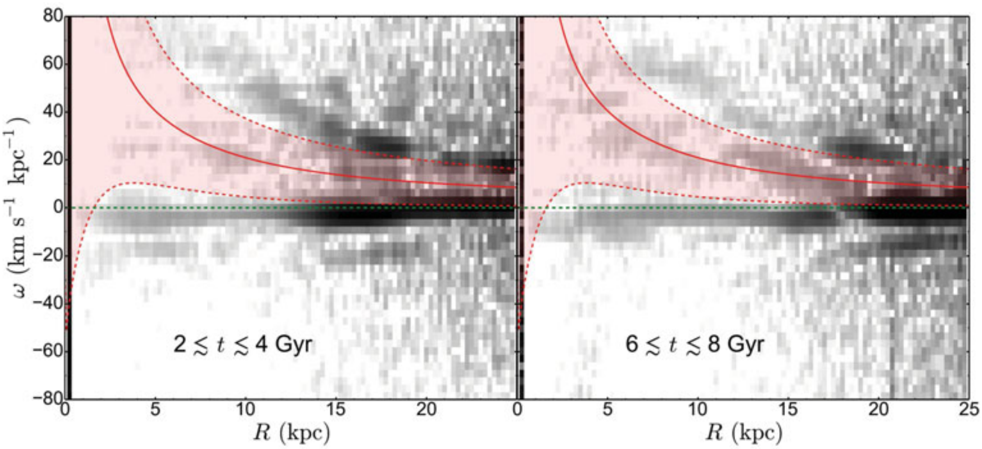

Figure 4. Spectral analysis of our bar-forming galaxy as described in the text for ~ 2 Gyr intervals as indicated. Corotation (solid red), vertical resonances (dashed red), and the WKB forbidden region (shaded red) corresponding to the initial conditions are also shown.

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used in the analysis of bar and spiral structure formation and evolution (see Sellwood & Athanassoula 1986). To construct this figure, we divide the disk into concentric rings and calculate the $m = 1$ Fourier coefficients as a function of radius. We then Fourier transform these coefficients in time and calculate the R-dependent frequency power spectrum. The procedure is carried out for ~ 2 Gyr intervals over the simulation. We see that power tends to concentrate just outside the vertical resonance curves as predicted by the linear eigenmode and WKB analysis used to construct Fig. 1. The striking agreement between linear theory and simulation lends credence to the view that the perturbations in our simulated disks are indeed self-gravitating waves since the linear theory calculations also include self-gravity.

4. Vertical Waves from Satellite Interactions

The interaction of a satellite galaxy with a stellar disk has been implicated in the formation of warps, spiral structure, bars, and vertical heating of the disk. For example, Purcell *et al.* (2011) suggested that the passage of the Sagittarius dwarf galaxy through the Galactic disk might be responsible for the Milky Way's spiral structure and bar. Earlier work by Gauthier *et al.* (2006) found that interaction between halo substructure and the disk could excite the formation of a bar, even in a disk that is nominally stable against bar formation when embedded in a smooth halo.

Dark matter subhalos and satellite galaxies can also excite both bending and breathing modes in galaxies, as illustrated in the toy-model calculations and simulations by Widrow *et al.* (2014) and Gómez *et al.* (2013), and in the cosmological simulations by Gómez *et al.* (2016), Gómez *et al.* (2017). One can think of satellite-disk interactions as proceeding in the following phases:

• Energy transfer from satellite to disk stars: The process by which a passing satellite or globular cluster transfers energy to disk stars was considered by Toth & Ostriker (1992) and Sellwood *et al.* (1998). As discussed in Widrow *et al.* (2014), this process can be thought of in terms of the excitation of bending and breathing modes with the relative importance of the two being determined by the vertical speed of the satellite as compared with the speed of vertical epicyclic motions for the disk stars.

• Shearing and phase mixing of the perturbation: Differential rotation of the disk will tend to shear out the initial disturbance of the disk. During this stage, the motions of the stars may be well-described by kinematic phase mixing, as discussed in de la Vega *et al.* (2015).

• Vertical bending waves: Once the perturbation has been sheared out into circular arcs, it will behave as a self-gravitating wave, which can be reasonably well described by linear theory. This is the stage explored in Fig. 4.

• Vertical heating: Eventually, the energy in the vertical waves will be dispersed into the disk leading to an overall heating and thickening of the disk.

5. Oort Problem and Vertical Motions

In his seminal paper on vertical motions of stars in the Solar Neighbourhood, Oort (1932) outlined a method to determine the force perpendicular to the midplane of the Galaxy and thus derive an estimate for the total amount of mass near the Sun. Since then, numerous groups have attempted to follow Oort's prescription in order to infer the local density of dark matter. For example, Bovy & Rix (2013) (see also Trick, Bovy, & Rix 2016) describe a method in which stars of a given survey are divided into mono-abundant populations (MAPs), each of which can be treated as a quasi-isotherman distribution in

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an Oort-type analysis. This approach is particularly attractive as we enter the age of Gaia, where there will be six-dimensional phase space information for $10^8 - 10^9$ Milky Way stars.

In general, Oort-type analyses assume that the disk and tracer populations are in equilibrium. In addition, even though the MAPs will have very different kinematic and structural properties (think thin versus thick disks), they all probe the same potential. As discussed in Banik *et al.* (2017) if the tracer population is not in equilibrium then there will be systematic errors in the inferred vertical force. Moreover, the systematics will differ from one MAP to another. Thus, if the MAPs from a Bovy & Rix-type analysis lead to different results for the gravitational potential, then this may be an indication of disequilibrium in the stellar disk.

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