173. The breathing motion of spiral arms

I LOOKED AT spiral arms in essay 114, where I focussed on their structural features being revealed by Gaia. Here I will look at some remarkable and important insights that Gaia is revealing in the kinematics of the spiral features. As I will explain, Gaia is providing observational confirmation of so-called 'breathing modes' in the spiral arms which, in turn, support some of the theoretical and numerical models being developed to understand their origin and nature.

Let me first set the scene with a broad picture of what is known about spiral arms in general, and the spiral arms of our own Milky Way Galaxy in particular.

Spiral arms are common features of disk galaxies, both locally and at higher redshifts. The general consensus is that they are a manifestation of density waves, perhaps most generally arising from self-excited disk instabilities as seen in numerical simulations (e.g. recurrent 'groove modes', or 'swing amplification' of noise), although with some plausibly excited by other mechanisms such as the galaxy's central bar, or tidal encounters with other galaxies (Sellwood & Masters, 2022).

IN OUR OWN Galaxy, the disk comprises a central extended bar, beyond which are a series of spiral arms, delineated by a higher density of gas and dust, and more pronounced regions of ongoing star formation. Following the first identification of spiral structure by Morgan et al. (1952), subsequent observations and probes have been many and varied, including H I regions at 21 cm, H_2O masers with VLBA, molecular clouds in CO, H II regions probed by pulsars, red clump stars from 2MASS and Spitzer, cluster mapping by WISE, and others.

In essay 114, I described the advances being made in delineating the spiral morphology using Gaia data. Amongst these, Drimmel et al. (2023) used some 580 000 OB stars, together with 988 young open clusters, to map the spiral structure associated with star formation out to 4–5 kpc from the Sun. Further mapping of the spiral arms using Gaia DR3 combined with LAMOST and other large-scale surveys, has since been reported (e.g. Kounkel et al., 2020; Hawkins, 2023; Xu et al., 2023).

AS I CONCLUDED in essay 114, and despite our 'close-up view' of the Milky Way, many observational details of the spiral structure of our own Galaxy remain unclear. Neither is there an unambiguous excitation mechanism known to be driving them. But for the rest of this essay, we can put the morphological details to one side, and look at some fascinating kinematic aspects being revealed by Gaia, and in particular evidence for what has been termed the 'breathing mode'.

Already pre-Gaia, the existence of large-scale non-zero mean *vertical* motions with respect to the disk had been identified in various surveys, notably from SEGUE (Widrow et al., 2012; Widrow et al., 2014), LAMOST (Carlin et al., 2013), and RAVE (Williams et al., 2013).

Observationally, these vertical motions (i.e. perpendicular to the disk) fall into two distinct classes: a 'bending motion' in which stars on either side of the mid-plane move together in the same direction, and a symmetric 'breathing motion' in which stars on either side move together in opposing directions, both sides either moving towards or away from the mid-plane.

Widrow et al. (2014) suggested that both could be excited by a passing satellite or dark matter subhalo, the bending motion dominating when the perpendicular component of the impactor's velocity is small compared with that of the stars, with the breathing modes excited at larger vertical velocities of the impactor.

CERTAIN PUZZLING features of these and other observations led Faure et al. (2014) and Debattista (2014) to investigate whether these vertical velocity features could arise in the absence of such an external perturber.

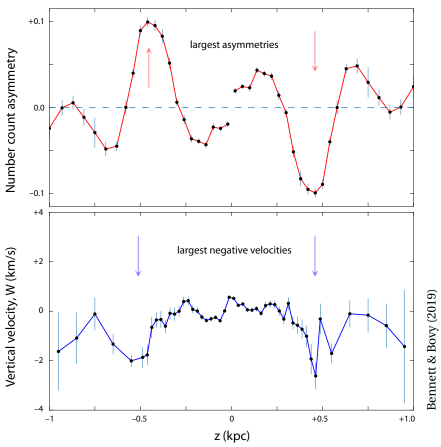
Faure et al. (2014) showed that in an equilibrium axisymmetric galactic disk, in which the mean galactocentric radial and vertical velocities might be expected to be zero everywhere, their 3D test-particle simulation showed instead that the global stellar response to a spiral perturbation induces both a radial velocity flow, and non-zero vertical motions, with a resulting mean velocity field qualitatively similar to what had been observed from SEGUE, LAMOST, and RAVE.

In more detailed models, Debattista (2014) used three-dimensional N-body simulations to confirm that spiral structures indeed induce bulk vertical velocities, as large as 10–20 km s^{-1}. He found that the vertical motions are compressive (pointing towards the mid-plane) as stars enter the spiral, and are expanding (away from the mid-plane) as they leave it. As he explains: *'Since stars enter the spiral on the leading side outside the corotation radius, and on the trailing side within corotation, the relative phase of the expanding and compressive motions switches sides at corotation. Furthermore, because stars always enter the spiral on the shallow density gradient side and exit on the steeper side, the expanding motions are larger than the compressing motions'.*

Analytical models (Monari et al., 2016a), further N-body simulations (Monari et al., 2016b), and even large-scale cosmological simulations (Grand et al., 2016) have confirmed these bending and breathing modes. More recently, Ghosh et al. (2022) made high-resolution simulations of a system with prominent spiral structure, including effects of star formation. They identified two further *predicted* features: that the breathing motions induced by spiral structure have an increasing amplitude with mid-plane distance. And at any given height, the breathing motion amplitude decreases with age.

Can any of these detailed predictions be investigated with the Gaia data? Gaia has certainly revealed a rich and complex variety of kinematic substructure in the phase-space distribution (i.e. of positions and velocities) of the solar neighbourhood, amongst them imprints of the Hercules stream (essay 115), the Arcturus and HR 1614 streams (essay 116), and the Gaia 'phase-space spiral' (Antoja et al., 2018; essay 117).

Such bending and breathing modes in the solar neighbourhood were soon identified: in the RAVE–TGAS data (Carrillo et al., 2018), in a 3.2 million DR2 giant star sample (Katz et al., 2022), and in the number counts (2 million stars) and velocity distributions (865 000 stars) in DR2 by Bennett & Bovy (2019), as shown here.



In an analysis of 3.1 million Gaia DR2 stars within 10 kpc (with distances, and importantly ages, as given by Sanders & Das, 2018), Ghosh et al. (2022) demonstrated that, at the location with the largest breathing motion ($x = 7.6 - 8.1$ kpc, $y = 0.9 - 1.4$ kpc) the amplitude increases monotonically with distance from the mid-plane, and decreases with age, i.e. the breathing motion is strongest for the youngest stellar populations.

With both these observational signatures consistent with their numerical simulations, they concluded that the observed breathing motions are indeed driven by spiral density waves, while the bending motions are not.

These findings became even more convincing with the improved accuracies of Gaia DR3, along with more robust estimates of the complex selection effects entering number density estimates (notably the satellite scanning law, the presence of open star clusters, and the effects of reddening and extinction).

Widmark et al. (2022) used several million DR3 stars to distinguish three distinct structures: the presence of the 'Gaia phase–space spiral', a large-scale bending mode seen in both number density and vertical velocity, and an elongated over-density in star counts with a corresponding breathing-mode compression in vertical velocity at the location of the Local Spiral Arm.

Asano et al. (2024) worked with a sample of 26 million DR3 stars to confirm a number of features of the now well-established breathing motion. They found a clear alignment of the compressing breathing motion with the Local Arm, similar to that seen in the growth phase of spiral arms in numerical simulations. They concluded that the Local Arm's compressing breathing motion can be explained by it being in the growth phase of a transient and dynamic spiral arm.

They also found tentative signatures of the expanding breathing motion associated with the Perseus arm, and a compressing breathing motion coinciding with the Outer arm, implying that the Perseus and Outer arms are in the disruption and growth phases respectively.

In their face-on map of number counts (left), the spiral arms are not evident due to the various selection biases; the locations shown are those of massive star-forming regions from Reid et al. (2019). But the alignment between the Local Spiral Arm and the compression mode in the Gaia data (right) is particularly striking. More insights will come from future Gaia data releases.