Part II Astrophysics Essay 2021

Gaia's living and breathing Galaxy

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ESA space observatory Gaia continuously monitors positions and fluxes of 1.5 billion stars in our Galaxy. These astrometric and photometric data are send to Earth and used to reconstruct a map of the current state of the density distribution of the Milky Way and to place constraints on its formation history. Before embarking on such a reconstruction, a few key assumptions need to be verified. One of them is that of equilibrium, in other words, the conjecture that the state of the Galaxy does not change appreciably with time. Before Gaia Data Release 2, the steady state of our Galaxy's stellar disk was only postulated. After the release, it could be quantified. For example, Antoja et al (2018) have recently demonstrated that the phase–space density distribution of the disk stars is highly structured. When the azimuthal component of velocity is plotted against the galacto-centric radius, many discontinuities become immediately apparent, visible as sharp diagonal ridges (see also Kawata et al 2018). Even more striking is the spiral-like pattern clearly discernible in the behaviour of the vertical stellar velocity as a function of height above the disk. The exact processes producing these inhomogeneities have yet to be fully understood, but Antoja et al (2018) provide a rather convincing hypothesis: the apparent fluctuations in the coarse-grained density are a telltale sign of a system out of equilibrium. More precisely, the striation in the radial dependence of the azimuthal velocity could be caused by the interactions with the Galactic bar or the spiral arms, whereas the vertical velocity spiral is likely the consequence of a perturbation caused by a dwarf galaxy satellite punching through the Milky Way's disk. Antoja et al (2018) suggest that by analysing the properties of the spiral, the details of the interaction can be deciphered. They make an estimate of the time of the fly-by and arrive at a number in agreement with the epoch of the disk crossing of the Sagittarius dwarf galaxy. Sagittarius is the third largest satellite of the Milky Way and has long been suspected to wreak havoc in our Galaxy's disk.

Such interactions between our Galaxy and its satellites were much more common and frighteningly more dramatic in the past. The memory of these events is preserved in the orbital structure of the Milky Way's stellar halo and can today be read off Gaia's measurements. One particular record stands out most clearly, that of the spectacular head-on collision between the young Milky Way and a massive dwarf galaxy some 8–11 billion years ago (Belokurov et al 2018; Helmi et al 2018). As the two objects smashed into each other, the dwarf's debris sprayed over our Galaxy, populating the halo with stars on highly eccentric orbits. The exact shape of these orbits could not have been identified without Gaia's data. This is because for an eccentric orbit observed near the Sun, most of the velocity is in the line-of-sight component, yielding a minuscule proper motion on the sky, smaller than the typical astrometric uncertainty in the pre-Gaia era. The merger rearranged the Milky Way into the Galaxy we observe today. The most fragile Galactic component, the disk, suffered the most: it was likely truncated, puffed up and scattered. But at the same time, the intruder probably brought with it a fresh supply of gas, which, once accreted, may have been used later to rebuild the Milky Way's disk. We are only beginning to comprehend the implications of this violent encounter. One of the first illuminating insights is the discovery of a large number of globular clusters likely deposited into the Milky Way by the dwarf galaxy in the last throws of disruption (Myeong et al 2018).

Questions to discuss: Why and how did our perception of the Galaxy evolve from a neat superposition of well-defined (and autonomous) components to an evolving "organism" where all parts are constantly interacting? Is our Galaxy in equilibrium? What have we learnt from the Gaia data about the formation of the Milky Way (its thin and thick disc, its bar and its halo)?

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