171. The Small Magellanic Cloud

THE MAGELLANIC CLOUDS are two 'nearby' irregular dwarf galaxies, visible to the unaided eye in the dark skies of the southern hemisphere.

The Large Magellanic Cloud (LMC) has a diameter of 4.3 kpc, compared with about 30 kpc for the Milky Way. It lies at a distance of 50 kpc, corresponding to a parallax of 20 micro-arcsec. The Small Magellanic Cloud (SMC) has a diameter of 2 kpc, and lies about 60 kpc away (de Grijs & Bono, 2015). The two are separated by 20° on the sky, 23 kpc apart. Only the smaller Sagittarius dwarf elliptical (discovered in 1994), and the Canis Major dwarf galaxy (discovered in 2003) are closer neighbours.

Both LMC and SMC probably have large dark matter halos. The LMC is believed to be the fourth most massive of over 50 galaxies comprising the 'Local Group'. Observations and theory suggest that both have both been distorted by tidal interaction with the Milky Way. Their gravity has, in turn, affected our own Galaxy, distorting the outer parts of our Milky Way's disk.

Whether the LMC and SMC are bound as orbital companions to our Milky Way remains uncertain. If they are, their orbital period is at least 4 Gyr. The other possibility is that they are on a first (or even second) approach, and we are witnessing the start of a merger that may overlap with the Milky Way's expected merger with the Andromeda galaxy sometime in the future.

I DESCRIBED some of Gaia's first insights into the Magellanic Clouds in essay 38, based largely on an analysis of the Gaia EDR3 data release by Luri et al. (2021). Using the positions, parallaxes, and proper motions, they identified ~11 million Gaia sources in the LMC, and some 1.7 million in the SMC. Further division according to star colour allows the stars to be grouped according to age and evolutionary phase.

Smoothed maps of the proper motion field showed a clear ordered rotation of the LMC, while the SMC is more chaotic. And one of the most prominent features in their outskirts is the existence of a bridge between them, attributed to tidal forces that strip gas and stars from the least to the most massive galaxy.

THE LINE-OF-SIGHT structure of the SMC is complex and, collectively, the data have been difficult to interpret (e.g. Murray et al., 2023). Substantial advances in the past 5–10 years, both observational and modelling, have benefitted from a wide range of observations, including from HST, the VISTA–VMC survey, and APOGEE.

Today, Gaia's proper motions, radial velocities, and parallaxes (for foreground suppression), are proving to be of great importance in understanding its structure. And amongst the most recent work, Murray et al. (2023) suggest a radically new picture: that the SMC is composed of two distinct structures, with its interstellar medium arranged in two, superimposed, star-forming regions separated by ~5 kpc along the line-of-sight.

TO APPRECIATE the complexities and set the scene, I will first summarise some of the most recent work. Much of this exploits the Gaia data, which I have indicated here (as superscript) according to data release.

The oldest stellar populations are reasonably spherical within a radius of ~10 kpc, with suggestions of rotation in the central region (Helmi et al., 2018^{DR2}; Niederhofer et al., 2018; Zivick et al., 2018; Niederhofer et al., 2021^{DR2}). But stars with estimable distances (red clump stars, Cepheids, and RR Lyrae) extend some 20–30 kpc along the line-of-sight (Scowcroft et al., 2016; Ripepi et al., 2017; Zivick et al., 2021^{DR2}).

In contrast, stars of the young main sequence and red giant branch display a radial velocity gradient indicating rotation (El Youssoufi et al., 2023^{EDR3}), along with distinct substructures along the line-of-sight, both morphological (e.g. Subramanian et al., 2017; Martínez-Delgado et al., 2019^{DR2}; Tatton et al., 2021; Omkumar et al., 2021^{DR2}; Cullinane et al., 2023^{EDR3}; Almeida et al., 2023^{DR3}), as well as chemical (Hasselquist et al., 2021; Massana et al., 2022; Mucciarelli et al., 2023).

Further complicating the observed morphological structure is the evidence of tidal disruption by the LMC (Niederhofer et al., 2018; Zivick et al., 2019^{DR2}; De Leo et al., 2020^{DR2}; Zivick et al., 2021^{DR2}; Niederhofer et al., 2021^{DR2}; Cullinane et al., 2023^{EDR3}).

The SMC is also important as a laboratory for studies of the interstellar medium and star formation at low metallicity (~20% solar; Russell & Dopita, 1992). And it too presents various complexities that remain poorly understood. Indeed, starting 70 years ago, studies indicated multi-peaked H I velocity profiles, suggesting the presence of sub-systems at different distances (Kerr et al., 1954; Johnson, 1961; Hindman, 1964).

It has remained unclear whether this structure has originated from gravitational interactions with the LMC (Murai & Fujimoto, 1980; Mathewson & Ford, 1984; Ma et al., 2023), or as a series of expanding gas shells (Hindman, 1967; Staveley-Smith et al., 1997). And whether the integrated H I velocity field is consistent with a rotating disk (Stanimirović et al., 2004; Di Teodoro et al., 2019), or with the motions of its young stars (Evans & Howarth, 2008; Dobbie et al., 2014; Murray et al., 2019).

Some of this complexity has been attributed to tidal interaction with the LMC, either on its first infall (Besla et al., 2007; Zivick et al., 2018), or second (Massana et al., 2022; Vasiliev, 2024$^{\rm EDR3}$), or indicative of a close impact (Zivick et al., 2021$^{\rm DR2}$; Choi et al., 2022$^{\rm DR2}$). There is stellar debris in the outer regions of both (Pieres et al., 2017; Choi et al., 2018; Martínez-Delgado et al., 2019$^{\rm DR2}$), including the gaseous features of the Leading Arm, Bridge and Stream (For et al., 2014; For et al., 2016).

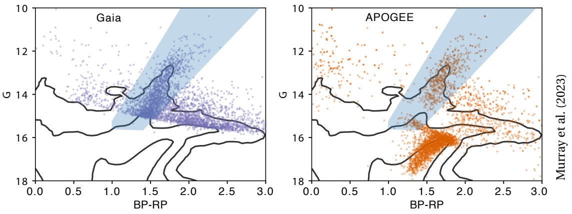
Models of the structure and dynamical history of the LMC–SMC–Milky Way system must evidently account for interactions between the LMC and the Milky Way (Besla et al., 2012; Pardy et al., 2018; Lucchini et al., 2021), but also for interactions with the SMC (Patel et al., 2020$^{\rm DR2}$), a challenge compounded by the uncertain morphology and dynamics of the SMC itself.

Across these studies, the Gaia data have been used to identify the systematic space motion of the SMC, providing evidence for a moderate rotation, some expansion, tidal stripping, and bursts of star formation.

But there has been a recurrent theme that its morphology, kinematics, and chemistry is not well replicated by a single population. For example, from a Gaia sample of red giant stars, Zivick et al. (2021) concluded with the need *'…to treat the SMC as a series of different populations with distinct kinematics'*.

A major move in this direction has been suggested by Murray et al. (2023). They compared the structure of the interstellar medium of the Small Magellanic Cloud with the kinematics of young massive stars matched to the gaseous structures in which they probably formed.

In their study, the interstellar medium was traced by high-resolution observations of H I (neutral atomic hydrogen) from the Galactic Australian Square Kilometer Array Pathfinder survey (GASKAP–HI). The relevant stars were identified on the basis of their precise radial velocities, from both the APOGEE and Gaia surveys.



Murray et al. (2023)

While the 21-cm H I emission map does not provide information on the line-of-sight distances, relative distances can be probed by means of the total dust extinction in the direction of individual stars, based on their infrared colours. Then if the average extinction towards stars with lower radial velocities is *less than* towards those with higher velocities, the lower velocity component must lie 'in front' (and vice versa).

The method is based on the use of the stellar radial velocities as a structural probe, although the Gaia DR3 astrometry was also used to help define both APOGEE and Gaia star samples by providing a robust membership probe. For their APOGEE sample, they started with 5938 stars within a 9° radius of the SMC centre, further restricting the sample to 2407 SMC members based on proper motion and radial velocity criteria.

The Gaia sample, selected through parallax and proper motion criteria, yielded just over 2 million initial SMC members. Further restricting the Gaia sources to those with accurate radial velocities from the Radial Velocity Spectrometer (and bearing in mind that the DR3 radial velocity catalogue is restricted to $G < 16$ mag), and within an appropriate radial velocity interval, resulted in a Gaia radial velocity sample of 3707 stars.

The colour–magnitude diagrams (G versus BP–RP) of the both the Gaia and APOGEE samples are shown in the figure above, with the red supergiants occupying the blue highlighted region. The effect of the magnitude limit of the Gaia radial velocity sample is evident in the left figure, but so is the very large number of brighter stars. For the 548 stars in common between the APOGEE and Gaia samples, the radial velocities agree to within $0.03^{+2.2}_{-1.6}$ km s^{-1}. The combined sample comprises 1947 stars (1165 from Gaia, 782 from APOGEE).

Details aside, their results are simply stated. By comparing the average dust extinction towards nearly 2000 stars with accurate radial velocities (from Gaia and APOGEE), and with membership rigorously established on the basis of the Gaia DR3 astrometry, they conclude that the inner ±4° of the Small Magellanic Cloud is composed of two structures with distinct stellar and gaseous chemical compositions. Specifically, the interstellar medium is organised into two, superimposed, star-forming systems with similar gas mass, separated by ~5 kpc along the line-of-sight.

The Gaia data have, in short, led to a radically new picture of this relatively nearby, well-studied, system.