AstroTalk: Behind the news headlines of September–October 2018

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Stellar motions reveal unexpected Milky Way history and more

The European Space Agency's Gaia mission has made a major breakthrough in unravelling the formation history of the Milky Way. Large galaxies like our Milky Way are the result of mergers of smaller galaxies. An outstanding question is whether a galaxy like the Milky Way is the product of many small mergers or of a few large ones. Professor Amina Helmi from the University of Groningen (Netherlands) has spent most of her career looking for 'fossils' in the Milky Way that might offer some hints as to its evolution. She uses the chemical composition, position and trajectory of stars in the halo to deduce their history, and thereby to identify the mergers that created the early Milky Way.

Helmi's team has now concluded that instead of forming alone, our Galaxy merged with another large galaxy early in its life, around 10 billion years ago. The evidence is littered across the sky all around us, but it has taken Gaia and its extraordinary precision to show us what has been hiding in plain sight all along.

Gaia measures the position, movement and brightness of stars to unprecedented levels of accuracy. Using the first 22 months of observations, the team looked at seven million stars – those for which the full 3D positions and velocities are available – and found that some 30,000 of them were part of an 'odd collection' moving through the Milky Way. The observed stars in particular are currently passing by our solar neighbourhood.

> "*We expected stars from fused satellites in the halo. What we didn't expect to find was that most halo stars actually have a shared origin in one very large merger*," says Helmi.

We are so deeply embedded in this collection that its stars surround us almost completely, and so can be seen across most of the sky. Even though they are interspersed with other stars, the stars in the collection stood out in the Gaia data because they all move along elongated trajectories in the opposite direction to the majority of the Milky Way's other hundred billion stars, including the Sun. They also stood out in the so-called Hertzprung–Russell diagram – which is used to compare the colours and brightnesses of stars – indicating that they belong to a clearly distinct stellar population.

The chemical signature of many halo stars was clearly different from the 'native' Milky Way stars. "*And they are a fairly homogenous group, which indicates they share a common origin*." By plotting both trajectory and chemical signature, the 'invaders' stood out clearly. Helmi says,

> "*The youngest invaders are actually younger than the native Milky Way stars in what is now the 'thick disk' region. This means that the progenitor*

> *of this thick disk was already present when the fusion happened, which shook it and puffed it up*."

The sheer number of odd-moving stars involved intrigued Helmi and her colleagues, who suspected they might have something to do with the Milky Way's formation history and set to work to understand their origins. In the past, Helmi and her research group had used computer simulations to study what happens to stars when two large galaxies merge. When she compared those to the Gaia data, the simulated results matched the observations.

> "*The collection of stars we found with Gaia has all the properties of what you would expect from the debris of a galactic merger*," she says.

In other words, the collection is what they expected from stars that were once part of another galaxy and have been consumed by the Milky Way. The stars now form most of our Galaxy's inner halo – a diffuse component of old stars that were born at early times and now surround the main bulk of the Milky Way known as the central bulge and disk.

The Milky Way's disk itself is composed of two parts. There is the thin disk, which is a few hundred light years deep and contains the pattern of spiral arms made by bright stars. And there is the thick disk, which is a few thousand light years deep. It contains about 10–20% of the Milky Way's stars yet its origins have been difficult to determine.
According to the team's simulations, as well as supplying the halo stars, the accreted galaxy could also have disturbed the Milky Way's pre-existing stars to help form the thick disk.

> "*We became only certain about our interpretation after complementing the Gaia data with additional information about the chemical composition of stars, supplied by the ground-based APOGEE survey*," says Carine Babusiaux (Université Grenoble Alpes, France).

Stars that form in different galaxies have unique chemical compositions that match the conditions of the home galaxy. If this star collection was indeed the remains of a galaxy that merged with our own, the stars should show an imprint of this in their composition. And they did.

The astronomers called this galaxy Gaia–Enceladus after one of the Giants in ancient Greek mythology, who was the offspring of Gaia, the Earth, and Uranus, the Sky.

> "*According to the legend, Enceladus was buried under Mount Etna, in Sicily (Italy), and responsible for local earthquakes. Similarly, the stars of Gaia–Enceladus were deeply buried in the Gaia data, and they have shaken the Milky Way, leading to the formation of its thick disk*," explains Helmi.

Even though no more evidence was really needed, the team also found hundreds of variable stars and 13 ancient 'globular' clusters in the Milky Way that follow similar trajectories as the stars from Gaia–Enceladus, indicating that they were originally part of that system. Globular clusters are groups of up to millions of stars, held together by their mutual gravity and orbiting the centre of a galaxy. The fact that so many clusters could be linked to Gaia–Enceladus is another indication that this must have once been a big galaxy in its own right, with its own entourage of globular clusters.

Further analysis revealed that this galaxy was about the size of one of the Magellanic Clouds – two satellite galaxies roughly ten times smaller than the current size of the Milky Way.

Ten billion years ago, however, when the merger with Gaia–Enceladus took place, the Milky Way itself was much smaller, so the ratio between the two was more like four to one. It was therefore clearly a major blow to our Galaxy.

> "*Seeing that we are now starting to unravel the formation history of the Milky Way is very exciting*," says Anthony Brown from Leiden University (Netherlands), chair of the Gaia Data Processing and Analysis Consortium Executive.

Since the very first discussions about building Gaia 25 years ago, one of the mission's key objectives was to examine the various stellar streams in the Milky Way, and reconstruct its early history. That vision is paying off.

> "*Gaia was built to answer such questions*," says Helmi. "*We can now say this is the way the Galaxy formed in those early epochs. It's fantastic. It's just so beautiful and makes you feel so big and so small at the same time*."

The data on kinematics, chemistry, age and spatial distribution from the native Milky Way stars and the remnants of Gaia–Enceladus reminded Helmi of simulations performed by a former Ph.D. student, some 10 years ago. His simulations of the merging of a large disk-shaped galaxy with the young Milky Way produced a distribution of stars from both objects, which is totally in line with the Gaia data. "*It was amazing to look at the new Gaia data and realize that I had seen it before*."

> "*By reading the motions of stars scattered across the sky, we are now able to rewind the history of the Milky Way and discover a major milestone in its formation, and this is possible thanks to Gaia*," concludes Timo Prusti, Gaia project scientist at ESA.

Gaia's database is rapidly turning into a real treasure trove. Professor Sally Oey from the University of Michigan (USA) led a team that used its data to study the Large and Small Magellanic Clouds.

Her team discovered that the southeast region, or 'Wing,' of the Small Magellanic Cloud is moving away from the main body of that dwarf galaxy, providing the first unambiguous evidence that the Small and Large Magellanic Clouds recently collided.

> "*This is really one of our exciting results*," said Oey. "*You can actually see that the Wing is its own separate region that's moving away from the rest of the Small Magellanic Cloud (or SMC)*."

Oey and undergraduate researcher Johnny Dorigo Jones were examining the SMC for 'runaway' stars, or stars that have been ejected from star clusters within the SMC.

> "*We've been looking at very massive, hot young stars – the hottest, most luminous stars, which are fairly rare*," Oey said. "*The beauty of the Small and the Large Magellanic Clouds is that they're their own galaxies, so we're looking at all of the massive stars in a single galaxy*."

Examining stars in a single galaxy helps astronomers in two ways: First, it provides a statistically complete sample of stars in one parent galaxy. Second, this gives the astronomers a uniform distance to all the stars, which helps them measure their individual velocities.

> "*It's really interesting that Gaia obtained the proper motions of these stars. These motions contain everything we're looking at*," Dorigo Jones said. "*For example, if we observe someone walking in the cabin of an airplane in flight, the motion we see contains that of the plane, as well as the much slower motion of the person walking."*
>
> "*So we removed the bulk motion of the entire SMC in order to learn more about the velocities of individual stars. We're interested in the velocity of individual stars because we're trying to understand the physical processes occurring within the Cloud*."

Oey and Dorigo Jones study runaway stars to determine how they have been ejected from these clusters. In one mechanism, called the 'binary supernova scenario,' one star in a gravitationally bound, binary pair explodes as a supernova, ejecting the other star like a slingshot. This mechanism produces X-ray-emitting binary stars.

Another mechanism is that a gravitationally unstable cluster of stars eventually ejects one or two stars from the group. This is called the 'dynamical ejection scenario,' which produces normal binary stars. The researchers found significant numbers of runaway stars among both X-ray binaries and normal binaries, indicating that both mechanisms are important in ejecting stars from clusters.
In looking at this data, the team also observed that all stars within the Wing – that southeast part of the SMC – are moving in a similar direction and speed. This demonstrates that the SMC and its larger neighbour, the Large Magellanic Cloud (or LMC) likely had a collision a few hundred million years ago.

Study contributor Gurtina Besla, an astronomer at the University of Arizona (USA), modelled the collision of the SMC and the LMC. She and her team predicted a few years ago that a direct collision would cause the SMC Wing region to move towards the LMC, whereas if the two galaxies simply passed near each other, the Wing stars would be moving in a perpendicular direction.

Instead, the Wing is moving away from the SMC, towards the LMC, said Oey, confirming that a direct collision occurred.

> "*We want as much information about these stars as possible to better constrain these ejection mechanisms*," Dorigo Jones said. "*Everyone loves marvelling at images of galaxies and nebulae that are incredibly far away. The SMC is so close to us, however, that we can see its beauty in the night sky with just our naked eye. This fact, along with the data from Gaia, allow us to analyse the complex motions of stars within the SMC and even determine factors of its evolution*."

Figure 1. A major event in the formation of the Milky Way, around 10 billion years ago.
Credit: ESA (artist's impression and composition); Koppelman, Villalobos and Helmi (simulation); NASA/ESA/Hubble (galaxy image), CC BY-SA 3.0 IGO

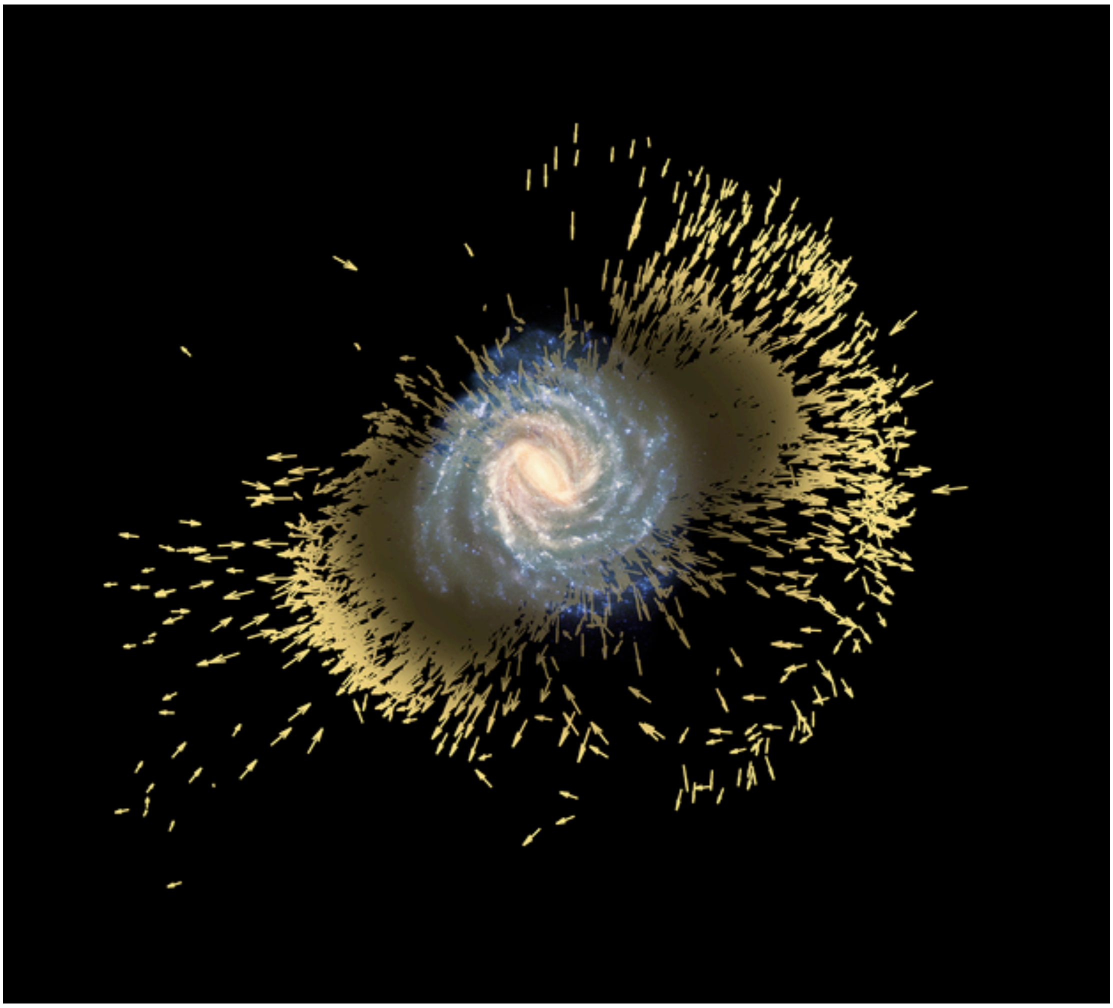

Figure 2. Stellar debris of galactic merger in the Milky Way. *Credit: ESA (artist's impression and composition); Koppelman, Villalobos and Helmi (simulation), CC BY-SA 3.0 IGO*

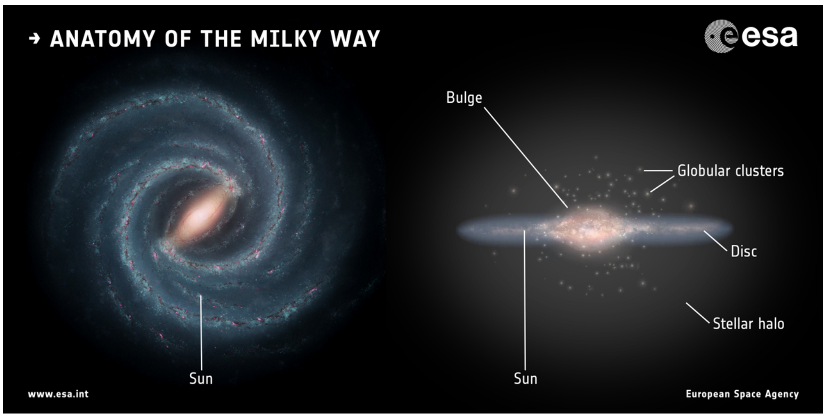

Figure 3. Anatomy of the Milky Way. *Credit: Left: NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab*

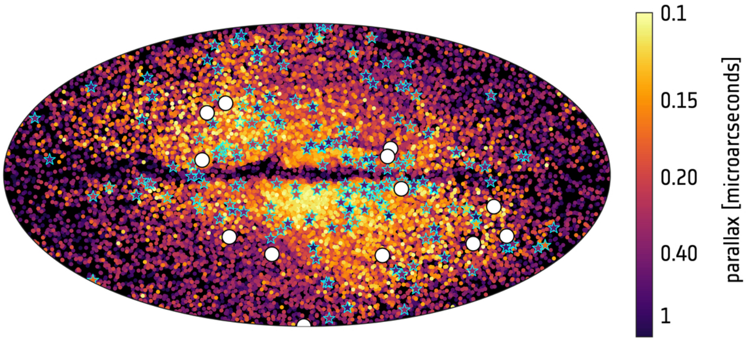

Figure 4. Gaia-Enceladus stars across the sky. *Credit: ESA/Gaia/DPAC; A. Helmi et al. 2018*

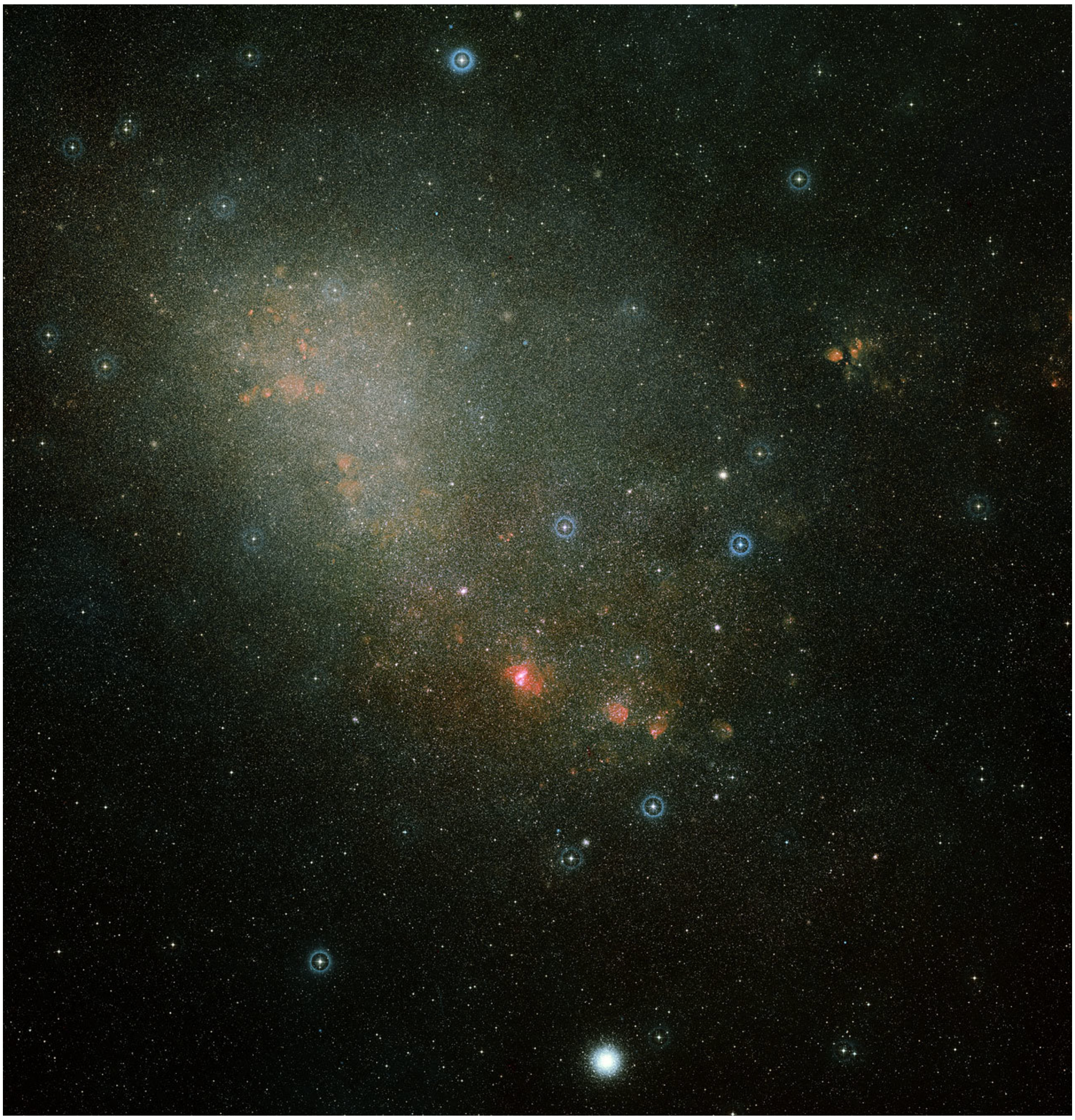

Figure 5. This image shows an overview of the full Small Magellanic Cloud and was composed from two images from the Digitized Sky Survey 2, which digitized photographic surveys of the night sky. *Credit: Davide De Martin (ESA/Hubble)*

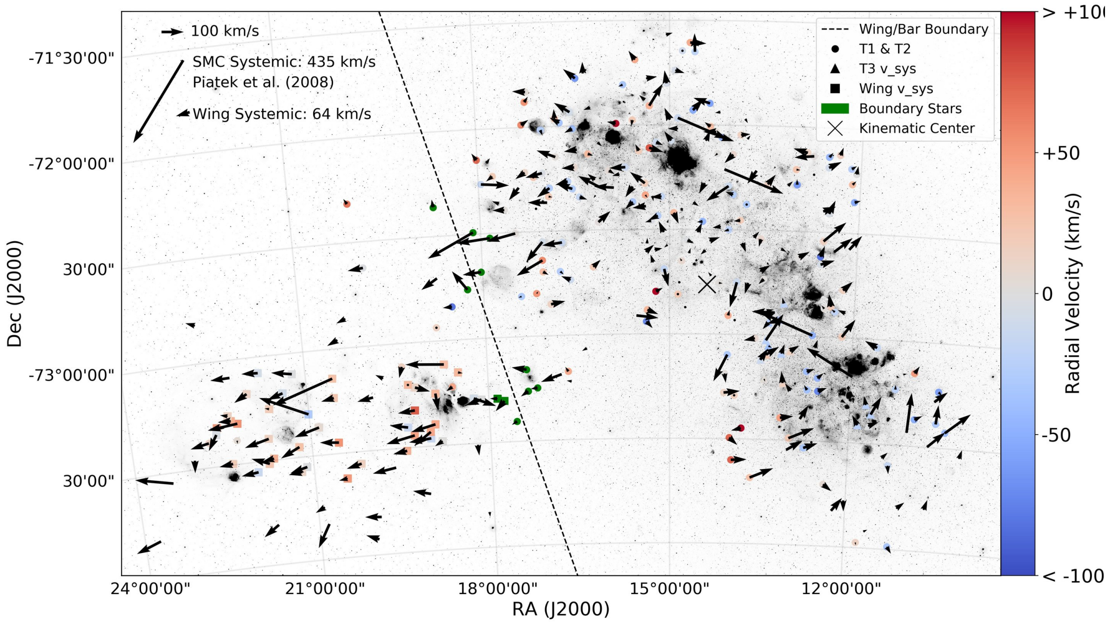

Figure 6. Arrows show the relative speed and directions of motion in the plane of the sky for the 315 targeted stars in the Small Magellanic Cloud. The red and blue colours show the relative speeds along the line of sight, with red and blue corresponding to motion away from, and towards, the Earth, respectively. To the left of the dashed line is the 'Wing' region, showing a bulk motion away from the rest of the galaxy. In this image, north is up and east to the left. *Credit: Johnny Dorigo Jones*