AstroTalk: Behind the news headlines

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The Gaia 'Sausage' galaxy

Our Milky Way galaxy has most likely collided or otherwise interacted with numerous other galaxies during its lifetime. Indeed, such interactions are common cosmic occurrences.

Astronomers can deduce the history of mass accretion onto the Milky Way from a study of debris in the halo of the galaxy left as the tidal residue of such episodes. That approach has worked particularly well for studies of the most recent merger events, like the infall of the Sagittarius dwarf galaxy into the Milky Way's centre a few billion years ago, which left tidal streamers of stars visible in galaxy maps.

The damaging effects these encounters can cause to the Milky Way have, however, not been as well studied, and events even further in the past are even less obvious as they become blurred by the galaxy's natural motions and evolution.

Some episodes in the Milky Way's history, however, were so cataclysmic that they are difficult to hide. Scientists have known for some time that the Milky Way's halo of stars drastically changes in character with distance from the galactic centre, as revealed by the chemical composition—the 'metallicity'—of the stars, the stellar motions, and the stellar density.

Harvard astronomer Federico Marinacci and his colleagues recently analysed a suite of cosmological computer simulations and the galaxy interactions in them. In particular they analysed the history of galaxy halos as they evolved following a merger event.

They concluded that six to ten billion years ago the Milky Way merged in a head-on collision with a dwarf galaxy containing stars amounting to about one-to-ten billion solar masses, and that this collision could produce the character changes in stellar populations currently observed in the Milky Way's stellar halo.

Now, an international team of astronomers has discovered clear evidence of such an ancient and dramatic head-on collision between the Milky Way and a smaller object, dubbed the 'Sausage' galaxy. The cosmic crash was a defining event in the early history of the Milky Way and reshaped the structure of our galaxy, fashioning both its inner bulge and its outer halo, the astronomers reported in a series of new papers.

They propose that around eight to ten billion years ago, an unknown dwarf galaxy smashed into our own Milky Way. The dwarf did not survive the impact: It quickly fell apart, and the wreckage is now all around us.

> "*The collision ripped the dwarf to shreds, leaving its stars moving in very radial orbits*," which are long and narrow like needles, said Vasily Belokurov of the University of Cambridge (UK). The stars' paths take them "*very close to the centre of our galaxy. This is a telltale sign that the dwarf galaxy came in on a really eccentric orbit and its fate was sealed*."

The new papers outline the salient features of this extraordinary event. The team used data from the European Space Agency's *Gaia* satellite. This spacecraft has been mapping the stellar content of our galaxy, recording the journeys of stars as they travel through the Milky Way. Thanks to *Gaia*, astronomers now know the positions and trajectories of our celestial neighbours with unprecedented accuracy.

The paths of the stars from the galactic merger earned them the moniker 'the *Gaia* Sausage,' explained Wyn Evans, also based at the University of Cambridge.

> "*We plotted the velocities of the stars, and the sausage shape just jumped out at us. As the smaller galaxy broke up, its stars were thrown onto very radial orbits. These Sausage stars are what's left of the last major merger of the Milky Way*."

The Milky Way continues to collide with other galaxies, such as the puny Sagittarius dwarf galaxy. However, the Sausage galaxy was much more massive. Its total mass in gas, stars and dark matter was more than 10 billion times the mass of our sun—indeed, as predicted by Dr. Marinacci's computer simulations.

When the *Gaia* Sausage galaxy crashed into the young Milky Way, its piercing trajectory caused a lot of mayhem. The Milky Way's disk was probably puffed up or even fractured following the impact and would have needed to regrow. And Sausage debris was scattered all around the inner parts of the Milky Way, creating the prominent bulge at the galaxy's centre and the surrounding stellar halo.

New numerical simulations of the galactic mashup can reproduce these features, said Denis Erkal of the University of Surrey (UK). In simulations run by Erkal and colleagues, stars from the *Gaia* Sausage galaxy enter stretched-out orbits. The orbits are further elongated by the growing Milky Way disk, which swells and becomes thicker following the collision.

Evidence of this galactic remodelling is seen in the paths of stars inherited from the dwarf galaxy, said Alis Deason of Durham University (UK). "*The Sausage stars are all turning around at about the same distance from the centre of the galaxy*."

These U-turns cause the density in the Milky Way's stellar halo to decrease dramatically where the stars flip directions. This discovery was especially pleasing for Deason, who predicted this orbital pileup almost five years ago. The new work explains how the stars fell into such narrow orbits in the first place.

The new research also identified at least eight large, spherical clumps of stars called 'globular clusters' that were brought into the Milky Way by the *Gaia* Sausage galaxy. Small galaxies generally do not have globular clusters of their own, so the Sausage galaxy must have been big enough to host a collection of clusters.

> "*While there have been many dwarf satellites falling onto the Milky Way over its life, this was the largest of them all*," said Sergey Koposov of Carnegie Mellon University (USA), who has studied the kinematics of the Sausage stars and globular clusters in detail.

Since its discovery, chemical traces in the atmospheres of stars have been used to uncover new information the *Gaia* Sausage galaxy. Astrophysicists at the University of Birmingham (UK), in collaboration with colleagues at European institutions in Denmark and Italy, have been studying evidence of the chemical make-up of stars in this area of the Milky Way to try to pinpoint more accurately the age of the smaller galaxy.

Using only information about the chemical traces of *Gaia* Sausage stars obtained from the international APOGEE astronomical survey, the Birmingham researchers have managed to more precisely the age of the galaxy. By developing detailed models of the production, or 'nucleosynthesis,' of chemical elements by all kinds of stars and supernovae, they now estimate that the *Gaia* Sausage was formed around 12.5 billion years ago—2.5 billion years older than suggested by previous estimates.

> "*Chemical elements interact with light in different ways and so by studying the properties of light from the stars, we can infer the chemical make-up of those stars*," explains Fiorenzo Vincenzo of the University of Birmingham.

> "*All chemical elements heavier than helium are produced by stars via thermonuclear burning deep in the heart of the star. Different chemical elements are typically synthesised by different kinds of stars in the cosmos. The oxygen atoms that are so important for life processes, for example, were deposited in the interstellar medium by many successive generations of massive stars until they were incorporated by our planet about 4.5 billion years ago. We can measure the relative proportion of different chemical traces in the atmospheres of stars and use this measurement as a clock to determine their age*."

Calculating the ages of stars accurately is a complex process and the technique used by the team provides one piece of the puzzle. The next step, which is already being pursued by the team, will be to cross reference the chemical data with evidence from other techniques, such as studying the relative speeds at which stars move.

The merger between the two galaxies seems to have produced another effect, too. The team spotted a gap in the age distribution of stars in the Milky Way, which occurred at the same time as the merger, suggesting that the collision caused an interruption in star formation within the Milky Way.

> "*We speculate that the turbulence and heating caused by the merger of the Gaia Sausage with the Milky Way could have prevented the formation of stars at this time*," says Dr. Vincenzo. "*However to confirm this we would need even more precise measurements of the ages of the stars in the Milky Way and in the smaller galaxy*."

In this study, the team focused on the chemical traces left by three elements—iron, silicon and magnesium. The next step will be to incorporate measurements from other elements to build an increasingly accurate picture.

Chemical 'tagging,' the technical term for this kind of chemical analysis of Milky Way stars, with the aim to understand their origin, has become a mainstream research tool in recent years. Small stellar systems like dwarf galaxies are thought to be the main building blocks of the Milky Way, so chemical tagging is often used to work out the nature of the merger remnants. However, it is unclear how many and what kind of stars in our galaxy originated from satellite dwarf galaxies.

Last month, an international team led by Zhao Gang, a professor from the National Astronomical Observatories of the Chinese Academy of Sciences (NAOC), discovered a chemically peculiar star accreted from a disrupted dwarf galaxy. According to results obtained using the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST), as well as the Japanese Subaru telescope, the star has an unusually low amount of magnesium, the eighth most abundant element in the universe. Meanwhile, it contains an excessive amount of heavy elements such as europium, gold, and uranium. The team recently reported their findings in the prestigious scientific journal *Nature Astronomy*.

> "*Stars preserve chemical information of their birth sites. We can distinguish stars formed in the Milky Way from stars formed in dwarf galaxies based on their chemical abundances*," says Zhao.

The chemical composition of this peculiar star suggests it originated from a dwarf galaxy that was disrupted by interaction with the Milky Way. The data was obtained by LAMOST, a spectroscopic survey telescope that takes 4,000 spectra in a single exposure. LAMOST is located at Xinglong Observatory, just outside of Beijing. So far, LAMOST has obtained more than 8 million stellar spectra for studies of the formation of the Milky Way.

> "*The massive spectra provided by the LAMOST survey give us a great opportunity to find chemically peculiar stars*," says Xing Qianfan, lead author of the paper. This type of star can be used to explore the chemical evolution of stellar systems.
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> Xing says, "*This newly discovered star with large excesses of heavy elements provides a window for exploring the chemical evolution of disrupted dwarf galaxies. The star formation in dwarf galaxies is relatively slow*

> *compared with larger galaxies, leading to chemical differences among their stellar populations. For instance, the magnesium to iron (Mg/Fe) element ratios in stars of dwarf galaxies currently found around the Milky Way are much smaller than those in the majority of stars in the Milky Way*."
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> "*This is the first discovery of a star having a very low amount of magnesium and an excessive amount of heavy elements*," says co-author Li Haining. "*The discovery of this chemically peculiar star is a good start of chemical identification of stars accreted from dwarf galaxies. Such stars will be good tracers for exploring the assembly history of the Milky Way*," says Zhao.

Evidence of guest stars in the Milky Way's halo is readily available. An international team of astronomers led by Giuseppina Battaglia, researcher at the Instituto de Astrofísica de Canarias (IAC) in Spain, recently found signs that the outer halo of the Milky Way contains stellar remains of massive dwarf galaxies that were devoured by our own.

For the first time, the chemical properties of the external regions of the halo of our galaxy were explored with high-resolution spectroscopy in the optical of a sample of 28 red giant stars at large distances from the sun. Spectroscopic analysis consists of separating the light of the stars into its individual frequencies to obtain information on the star's chemical composition. The analysis of the chemical properties of the stars can provide information on the characteristics of the environment in which they were born.

> Battaglia says, "*The abundance of some chemical elements in the stars in the external regions of the Milky Way halo was surprisingly different from the information we had concerning the inner regions of the halo*."

On the other hand, several similarities were discovered in the chemical compositions observed for stars in nearby massive dwarf galaxies, such as Sagittarius and the Large Magellanic Cloud. These signatures tells us that the external regions of the stellar halo might contain the remains of one, or more, massive dwarf galaxies devoured by the Milky Way.

Stellar haloes are a common component of galaxies like the Milky Way.

> "*The theory explaining the formation of structure and galaxies predicts that stellar halos, and in particular their outer regions, consist mainly of the stellar component of destroyed, smaller galaxies*," Battaglia says. "*Qualitatively, this is in agreement with the observational findings of this study, where we found remnants of cannibalised dwarf galaxies around the Milky Way*."

Figure 1: The colliding spiral galaxies in Arp 272 located in the constellation of Hercules. Astronomers have studied a suite of galaxy merger simulations to conclude that our own Milky Way galaxy suffered a similar kind of merger. In particular, they found that some of the peculiar features in the Galaxy's halo structure can be best explained by a head-on collision with a dwarf galaxy six to ten billion years ago. *Credit: NASA, ESA, the Hubble Heritage -STScI/AURA)-ESA/Hubble Collaboration, and K. Noll, STScI*

Figure 2: Impression of the encounter between the Milky Way galaxy and the smaller Sausage galaxy about 8 to 10 billion years ago. The record of this ancient encounter is still preserved in the velocities and chemistry of the stars. *Credit: V. Belokurov (Cambridge, UK); Based on image by ESO/Juan Carlos Muñoz*

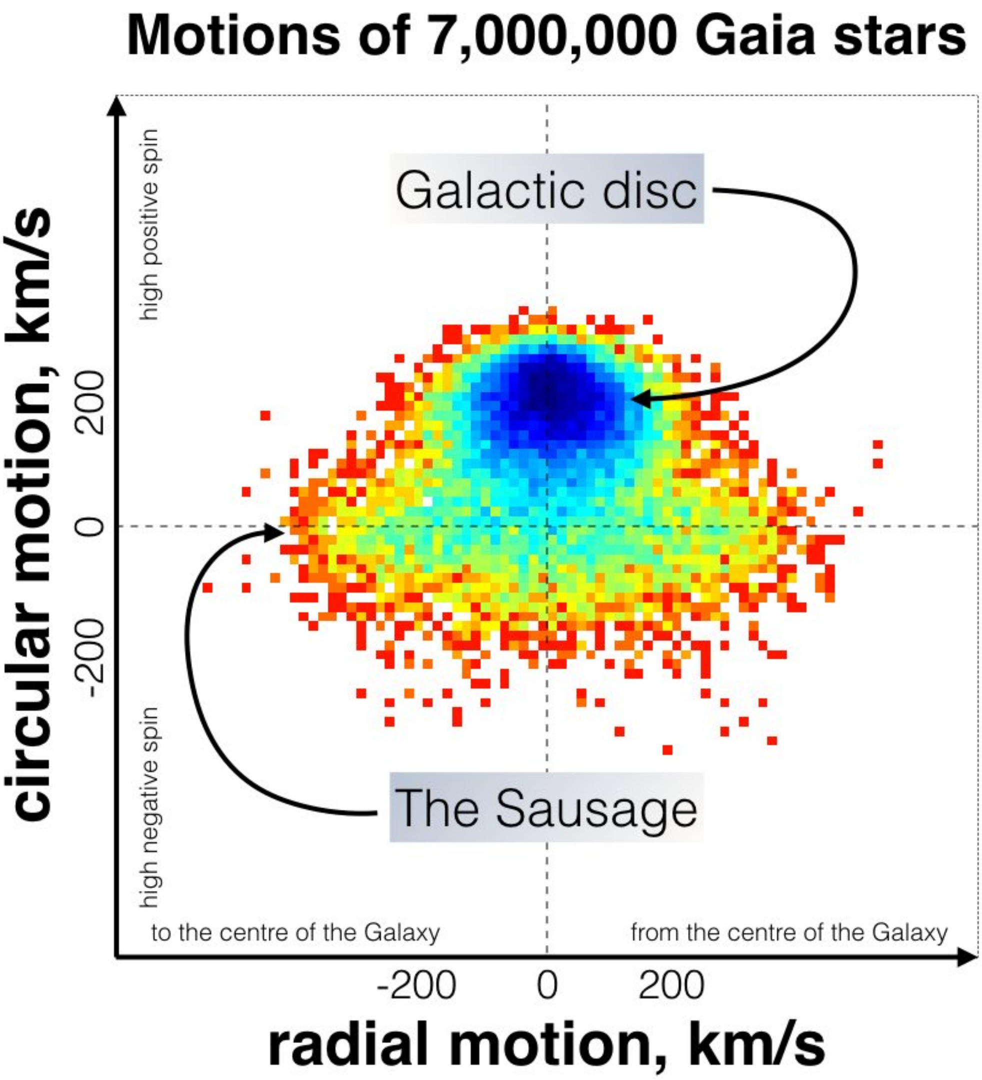

Figure 3: When looking at the distribution of star velocities in the Milky Way, the stars of the Sausage galaxy form a characteristic sausage-like shape. This unique shape is caused by the strong radial motions of the stars. As the sun lies in the centre of this enormous cloud of stars, the distribution does not include the slowed-down stars currently making a U-turn back toward the galaxy's centre. *Credit: V. Belokurov (Cambridge, UK) and Gaia/ESA*

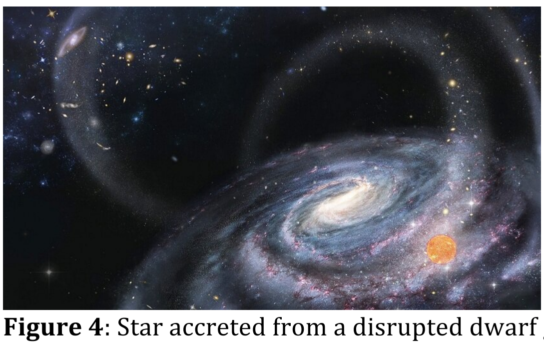

Figure 4: Star accreted from a disrupted dwarf galaxy. *Credit: NAOC*