AstroTalk: Behind the news headlines

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Our Milky Way is warped and twisted—and it oscillates!

From a great distance, our Milky Way would look like a thin disc of stars that rotates once every few hundred million years around its central region. There, hundreds of billions of stars provide the gravitational 'glue' to hold it all together.

Near the Sun, some 30,000 light years from the centre of our Milky Way, our galaxy is only about 3,000 light years thick. Its overall diameter is around 100,000 light years.

The pull of gravity is much weaker in the galaxy's far outer disc. There, the hydrogen clouds making up most of the Milky Way's gas disc are no longer confined to a thin plane. Instead, they give the disc an S-like, warped appearance.

Although the Milky Way's warped hydrogen gas layer had been known for decades, my international team of Chinese and Australian astronomers recently discovered that the S-like disc traced by young, massive stars is warped too, and in a progressively twisted spiral pattern. We were able to determine this twisted appearance after having developed the first accurate three-dimensional picture of the Milky Way's stellar disc out to its far outer regions.

Trying to determine the real shape of our galaxy is like standing in a Beijing park and attempting to determine the shape of China. The Milky Way is all around us, so to determine its shape, one would need to map the distributions of stars in all directions. While that is not particularly difficult in directions above and below the stellar disc plane, it becomes much harder along the Milky Way's plane.

Other than stars and hydrogen gas clouds in the Milky Way's plane our view is obscured by huge quantities of dust. The material astronomers call dust is made up of carbon particles. It is not too different from the soot that builds up in your home when you don't clean for a while.

Large quantities of dust obscure our view of what lies beyond, but dust also makes light look redder. This is so, because the size of those carbon particles is close to the wavelength of blue light. Therefore, blue light can be absorbed quite easily, while red light passes through without too much trouble.

But it's not just the presence of dust that makes mapping our Milky Way galaxy troublesome.

> "*It is notoriously difficult to determine distances from the Sun to parts of the Milky Way's outer disc without having a clear idea of what that disc actually looks like*," says Xiaodian Chen of the National Astronomical

Observatories (Chinese Academy of Sciences) in Beijing and lead author of the paper announcing these new results in the prestigious journal *Nature Astronomy*. "*We recently published a new catalogue of well-behaved variable stars known as classical Cepheids. These stars are among the best mileposts in astronomy: they can be used to determine very accurate distances with uncertainties of only three to five per cent*."

Our new catalogue was based on observations made with the Wide-field Infrared Survey Explorer (*WISE*), a space telescope operated by NASA and fitted with long-wavelength ('infrared') glasses, ideal to look through any dust in the Milky Way's disc.

Classical Cepheids are young stars that are some four to 20 times as massive as our Sun and up to 100,000 times as bright. Such high stellar masses imply that these stars live fast and die young, burning through the hydrogen fuel in their stellar interiors very quickly, sometimes in only a few million years.

Cepheids show day- to month-long pulsations, which can be observed quite easily as changes in their brightness. Combined with a Cepheid's observed mean brightness, the period of its pulsation cycle can be used to obtain an accurate distance.

Somewhat to our surprise, we found that our collection of 1,339 Cepheid stars and the Milky Way's gas disc follow each other closely. Until our recent study, it had not been possible to tie the distribution of young stars in the Milky Way's outer disc so well to the flaring and warped disc made up of hydrogen gas clouds. But perhaps more importantly, we discovered that the stellar disc is warped in a progressively twisted spiral pattern.

While many spiral galaxies are warped to varying extents, a dozen other galaxies were known to also show similarly twisted patterns in their outer discs. Combining our results with these earlier observations, we concluded that the Milky Way's warped and twisted spiral pattern is likely caused by forced 'torques' from the galaxy's massive inner disc.

"*This new map provides a crucial update for studies of our galaxy's stellar motions and the origins of the Milky Way's disc*," says Licai Deng, senior researcher at the Chinese Academy of Sciences and co-author on the paper.

This is particularly interesting today, given the wealth of information we anticipate to receive from the European Space Agency's *Gaia* satellite mission. *Gaia* aims to eventually map our Milky Way in unprecedented detail, based on the most accurate distance determinations to the galaxy's brightest stars ever obtained.

Our study of the Milky Way's warped disc represents a new benchmark in this field. However, the outer disc of our Milky Way galaxy has long captured the interest of astronomers.

Last year, for instance, astronomers investigated a small population of stars in the halo of the Milky Way, which led them to conclude that its chemical composition closely matched that of the Galactic disc. This similarity provided compelling evidence that the stars they targeted originated from within the disc, rather than from merged dwarf galaxies as had been suspected. The reason for this stellar migration is thought to be theoretically proposed oscillations of the Milky Way disc as a whole, induced by the tidal interaction of the Milky Way with a passing massive satellite galaxy.

Although our position within our home galaxy gives us a front row seat to explore what is happening in such a spiral galaxy, as we already saw, our internal perspective presents some challenges in our quest to understand it, particularly in the context of for outlining its shape and extent. And yet another problem is time: How can we interpret galactic evolution if our own life span (and that of our telescopes) is far less than the blink of the cosmic eye?

Today, we have a fairly clear picture of the broad properties of the Milky Way and how it fits among other galaxies in the Universe. Astronomers classify it as a rather average, large spiral galaxy with the majority of its stars circling its centre within a disc, and a dusting of stars beyond that orbiting in the Galactic halo.

These halo stars seem not to be randomly distributed in the halo; instead, many are grouped together in giant structures such as immense streams and clouds (or overdensities) of stars, some entirely encircling the Milky Way. These structures have been interpreted as signatures of the Milky Way's tumultuous past—debris from the gravitational disruption of the many smaller galaxies that are thought to have invaded our galaxy in the past.

Researchers have tried to learn more about this violent history of the Milky Way by looking at properties of the stars in the debris left behind: their positions and motions can give us clues of the original path of the invader, while the types of stars they contain and the chemical compositions of those stars can tell us something about what the long-dead galaxy might have looked like.

An international team of astronomers led by Dr. Maria Bergemann from the Max Planck Institute for Astronomy in Heidelberg recently found compelling evidence that some of these halo structures might not be leftover debris from invading galaxies but rather originate from the Milky Way's disc itself!

The scientists investigated 14 stars located in two different structures in the Galactic halo, the Triangulum–Andromeda (Tri–And) and the A13 stellar overdensities, which lie at opposite sides of the Galactic disc plane. Earlier studies of motion of these two diffuse structures revealed that they are associated with each other through their stellar motions and that they could be related to the Monoceros Ring, a ring-like structure that twists around the Milky Way. However, the nature and origin of these two stellar structures was still not conclusively clarified. The position of the two stellar overdensities could be determined as each lying about 14,000 light years above and below the Galactic plane.

Bergemann and her team presented detailed chemical abundance patterns of these stars, obtained with high-resolution spectra taken with the Keck telescopes and the Very Large Telescope.

> "*The analysis of chemical abundances is a very powerful test, which allows, in a way similar to the DNA matching, to identify the parent population of the star. Different parent populations, such as the Milky Way disc or halo, dwarf satellite galaxies or globular clusters, are known to have radically different chemical compositions. So once we know what the stars are made of, we can immediately link them to their parent populations*," explains Bergemann.

When comparing the chemical compositions of these stars with the ones found in other cosmic structures, the scientists were surprised to find that the chemical compositions are almost identical, both within and between these groups, and closely match the abundance patterns of the Milky Way disc stars. This provides compelling evidence that these stars most likely originate from the Galactic thin disc (the younger part of Milky Way, concentrated towards the Galactic plane) itself, rather being debris from invasive galaxies!

But how did the stars get to these extreme positions above and below the Galactic disk? Theoretical calculations of the evolution of the Milky Way Galaxy predict this to happen, with stars being relocated to large vertical distances from their place of birth in the disc plane. This 'migration' of stars is theoretically explained by the oscillations of the disc as a whole. The favoured explanation for these oscillations is the tidal interaction of the Milky Way's dark matter halo and its disc with a passing massive satellite galaxy.

The results, published in the journal *Nature* by Bergemann and her colleagues, now provide the clearest evidence for these oscillations of the Milky Way's disc obtained so far!

These findings are very exciting, as they indicate that the Milky Way's disk and its dynamics are significantly more complex than previously thought.

> "*We showed that it may be fairly common for groups of stars in the disc to be relocated to more distant realms within the Milky Way—having been 'kicked out' by an invading satellite galaxy. Similar chemical patterns may also be found in other galaxies—indicating a potential galactic universality of this dynamic process*," said Allyson Shefield from LaGuardia Community College/City University of New York (USA), a co-author on the study.

As a next step, the astronomers plan to analyse the spectra of other stars both in the two overdensities, as well as stars in other stellar structures further away from the disc. They are also very keen on getting masses and ages of these stars in order to constrain the time limits when this interaction of the Milky Way and a dwarf galaxy happened.

"*We anticipate that ongoing and future surveys like 4MOST and Gaia will provide unique information about chemical composition and kinematics of stars in these overdensities. The two structures we have analysed already are, in our interpretation, associated with large-scale oscillations of the disc, induced by an interaction of the Milky Way and a dwarf galaxy. Gaia may have the potential to see the connection between the two structures, showing the full pattern of corrugations in the Galactic disc*," says Bergemann.

Figure 1: A slightly exaggerated impression of the real shape of our warped and twisted Milky Way. *(Image: Xiaodian Chen, National Astronomical Observatories, Chinese Academy of Sciences)*

Figure 2: The galaxy ESO 510-G13 is an edge-on warped spiral galaxy. Similar to the Milky Way, it has a pronounced warp in its gaseous disc and a less pronounced warp in its disc of stars. *(NASA/Space Telescope Science Institute)*

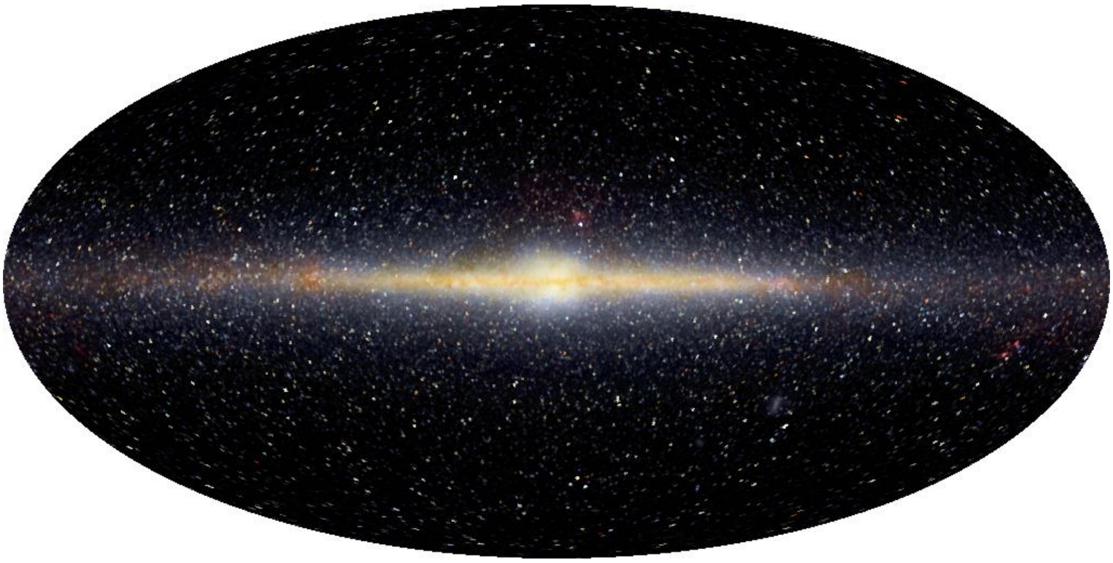

Figure 3: Image of the Milky Way disc obtained by the Cosmic Background Explorer (*COBE*) satellite. *(Ned Wright/NASA)*

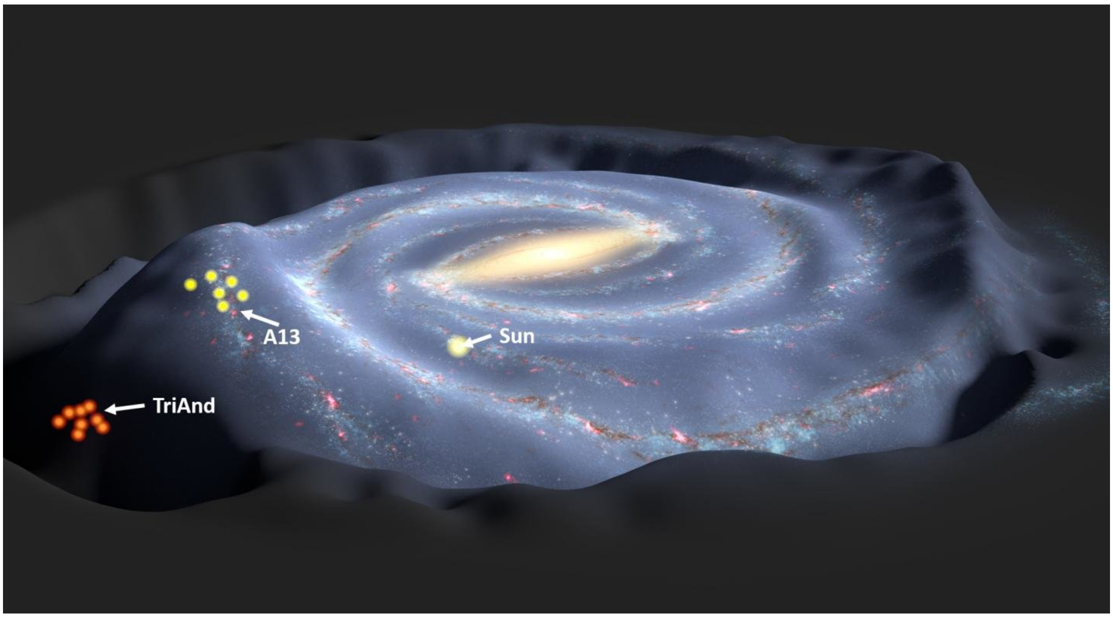

Figure 4: The Milky Way galaxy, perturbed by the tidal interaction with a dwarf galaxy, as predicted by *N*-body simulations. The locations of the observed stars above and below the disc, which are used to test the perturbation scenario, are indicated. *(Credit: T. Mueller/NASA/JPL-Caltech)*

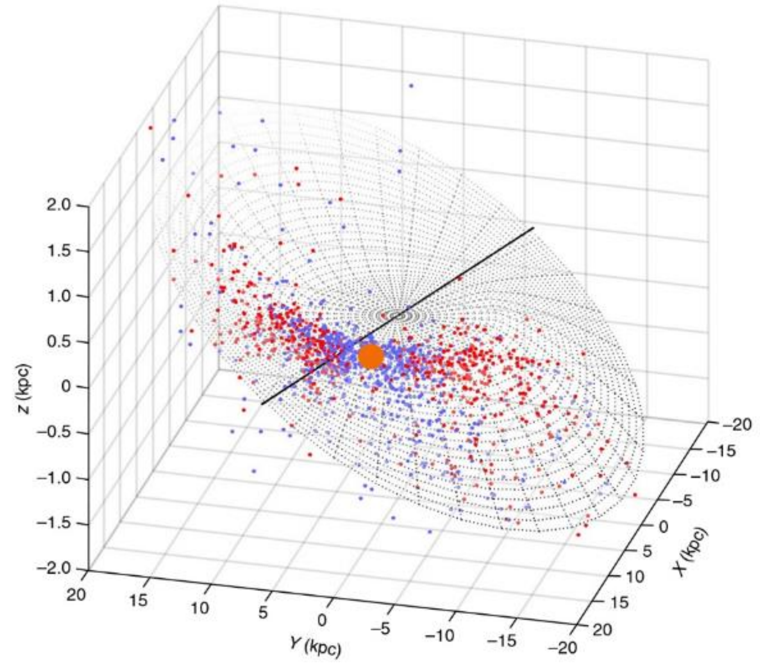

Figure 5: 3D distribution of the classical Cepheid variable stars in the Milky Way's warped disc (red and blue points) centred on the location of the Sun (shown as a large orange symbol). The units 'kpc' (kiloparsecs) along the image's three axes are used by astronomers to indicate distances on galaxy-wide scales. One kiloparsec is equivalent to about 3,262 light years. *(Chen et al., Nature Astronomy, 5 February 2019)*

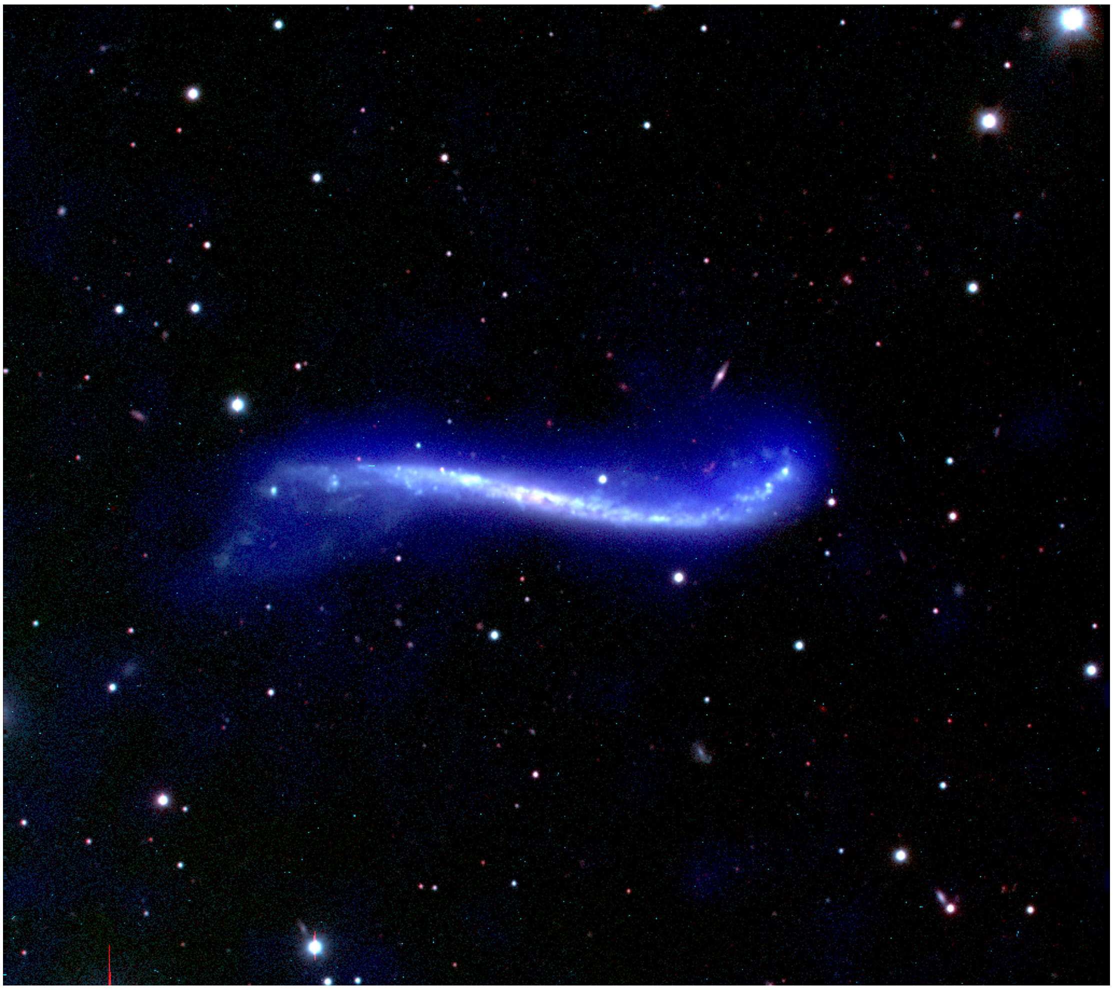

Figure 6: The "Integral Sign" galaxy, UGC 3697 is an edge-on spiral galaxy with an unusually pronounced warp in both its stellar and gaseous disks. The neutral hydrogen gas, represented in blue, is overlaid on an optical image of the stars of the galaxy. Unlike in normal spiral galaxies, the brightest concentration of neutral hydrogen is not found near the centre of UGC 3697 but along its western edge. In addition, plumes of gas extend to considerable height above and below the disc of the galaxy. *(Credit: NRAO/AUI/NSF)*