HOW THE MILKY WAY WAS BORN

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IMAGE: S. PAYNE-WARDENAAR, K. MALHAN / MPI FOR ASTRONOMY

The galaxies we see around us have had a turbulent past, full of collisions, plentiful gas flows, and bursts of increased star formation. Our home galaxy is no exception. A team led by Hans-Walter Rix at the Max Planck Institute for Astronomy is reconstructing the Milky Way's history in a process that resembles archaeological research.

Witnesses to past collisions: in the artistic representation of our Milky Way, streams of stars can be seen rising in wide arcs from the disc-shaped spiral galaxy, representing relics of mergers with other galaxies.

Our Milky Way is almost as old as the universe itself, and can look back on a rich history. Like most galaxies, it was formed within the first billion years after the Big Bang, making our home galaxy roughly 13 billion years old. Astronomers can now reconstruct details of its history quite accurately using observational data. “By doing so, we not only learn something about the beginning and early stages of our home galaxy, but also about the evolution of distant galaxies that we cannot observe in such detail,” explains Hans-Walter Rix, Director at the Max Planck Institute for Astronomy. His team is working on a comprehensive chronicle of the Milky Way, em-

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ploying methods similar to those used by historians or archaeologists when reconstructing the history of a city. In the case of a city, some buildings come with definite construction dates. For others, the clues are more indirect – the use of primitive building materials, or the characteristics of older architectural styles, can serve to indicate the relative age of a building. Finding remains of older buildings under newer structures also serves to establish relative age. And, last but not least, spatial patterns are important: in many cities, a central old town is surrounded by much newer neighborhoods.

For the Milky Way and similar galaxies, the situation is much the same. Here, the "buildings" are the stars. It is possible to deduce the age of certain types of stars through observation. In cases where this is not possible, the chemical composition of stars is analogous to the role of architectural styles, allowing for conclusions about the relative ages of the star in question. Cities undergo radical remodeling, with construction booms and re-districting, but can also experience gradual growth. Similarly, galaxies undergo collisions and mergers, but can also form stars more slowly, as fresh hydrogen gas – the raw material from which new stars are formed – flows into a galaxy from the surrounding regions over billions of years. A galaxy's history begins with smaller protogalaxies: regions where stars were already formed in the first billion years after the Big Bang. These are the seeds of the galaxies we know today. The Milky Way is likely to have come into being as three or four such protogalaxies, which, having formed in close proximity to one other, subsequently merged.

Reconstructing the evolution of a galaxy like our own requires the interplay of observation and simulation. "Modern large-scale surveys have helped us a lot in this regard," says Hans-Walter Rix. "They've given us dramatically improved and more comprehensive data than was previously available." In these surveys, telescopes scan substantial parts of the night sky to gather information such as the position and brightness of stars, but also spectra – the rainbow-like decomposition of starlight. Our Milky Way is special in that we have an inside view, and are able to observe many of its stars in detail.

SUMMARY

Using data from the Gaia space telescope, which determines the positions and motions of stars and provides information about their ages, a team from the Max Planck Institute for Astronomy is reconstructing the early history of the Milky Way.

When it was just a few billion years old, the Milky Way merged with the Gaia Enceladus/Gaia Sausage galaxy and subsequently went through a phase of intense star formation.

The core of the Milky Way contains stars that are more than 12.5 billion years old; these formed shortly after the merger of the protogalaxies – the precursors of our galaxy.

To carry out the archaeological work in the Milky Way, Hans-Walter Rix's team used surveys from ESA's Gaia satellite, the Sloan Digital Sky Survey, and China's Lamost telescope. To date, Gaia has determined the positions, orbits, and magnitudes of nearly two billion stars in the Milky Way – equivalent to about one percent of the total stellar population of our home galaxy. Lamost, in turn, measures the spectra of about ten million stars. Using this data, Hans-Walter Rix and Maosheng Xiang, a fellow researcher at the Max Planck Institute for Astronomy, first determined the surface temperature, luminosity, and chemical composition of 250,000 stars known as 'subgiants'. This is the term for a relatively short phase of stellar evolution, which has one key advantage: during this phase, it is possible to deduce the age of a star very accurately on the basis of its observable properties. By looking more closely at the Gaia and Lamost data, the researchers were able to obtain a clear picture of the history of the Milky Way between 11 and 8 billion years ago. In particular, they were able to discern the consequences of the Milky Way's most recent turbulent merger with another galaxy, which is known as either Gaia Enceladus or the Gaia Sausage.

The enormous amounts of gas carried by the two galaxies condensed during the merger, resulting in the rapid formation of large numbers of new stars. These accumulated in a region of the galaxy referred to in astronomy as the 'thick disk' of the Milky Way. Eventually, things calmed down with regard to star formation: "After the turbulent early period, there was much less hydrogen gas in the galaxy," explains Maosheng Xiang. "Further, steady inflow from the outside resulted in the structure we now call our galaxy's 'thin disk.'"

The reconstruction of the stellar aftermath of the Gaia Enceladus/Gaia Sausage merger was based on the special properties of sub-giants. But it contains hints of an even earlier history – involving the galactic analogue of architectural styles: the metallicity of stars, in other words the quantity of chemical elements in the stellar atmosphere that are heavier than helium. These types of elements, which astronomers (somewhat incongruously) call metals, are formed in the interior of stars by nuclear fusion. Massive stars blast those elements into space when they end their lives in supernova explosions. This enriches the interstellar gas with heavier elements. It is from this gas that the next generation of stars is formed, now with a higher initial metallicity. Stars with a higher metallicity therefore tend to be younger than those with a lower metallicity. The metallicities of the oldest sub-giants that Rix and Xiang had examined were already quite considerable, a clear indication that they were formed from the remnants of an earlier generation of stars.

"The existence of these earlier generations of stars is anything but surprising," says Hans-Walter Rix. "This has long been shown by simulations of cosmic history." Interestingly, those simulations also predict where representatives of the earlier generations of stars should still be found today: in the relatively compact core region of the Milky Way, just a few thousand light-years in diameter. This core region should incorporate stars from the first mergers of protogalaxies that formed the Milky Way.

"We then wanted to know how we could detect these stars from the old core of our galaxy," says Rix, who teamed up for this project with René Andrae, a researcher at the Max Planck Institute for Astronomy, and Vedant Chandra, a visiting doctoral student from Harvard University. "It was clear that we wouldn't get anywhere with subgiant data here." Subgiants are too faint to be observed beyond distances of about 7,000 light-years. Consequently, the researchers focused on a different type of star – red giant stars. Typical red giants are about a hundred times brighter than subgiants. It is, therefore, easy to observe them, even at the distance of the galactic center and its surrounding neighborhood. The Gaia measurements contain information about numerous red giants, and since the most recent data release in the summer of 2022, even the associated spectra. The red giants cannot be precisely dated in the same way as the subgiants, but using their metallicity, which can be determined based on the spectra, it is at least possible to estimate their approximate age.

Spectra analyzed by artificial intelligence

Gaia's spectra are, however, too poorly resolved for traditional analysis techniques that use a plethora of fine spectral lines associated with various chemical elements. Rix's team had to find a new way of analyzing these spectra, and they decided to employ

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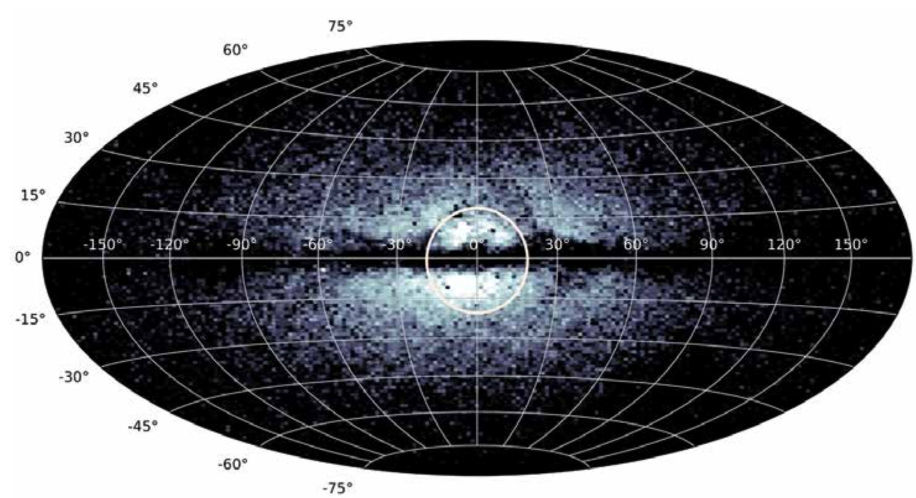
GLOSSARY

METALLICITY
in astronomy refers to the abundance of chemical elements that are heavier than hydrogen and helium. It can be determined from the spectrum of a star and provides a rough measurement of its age.

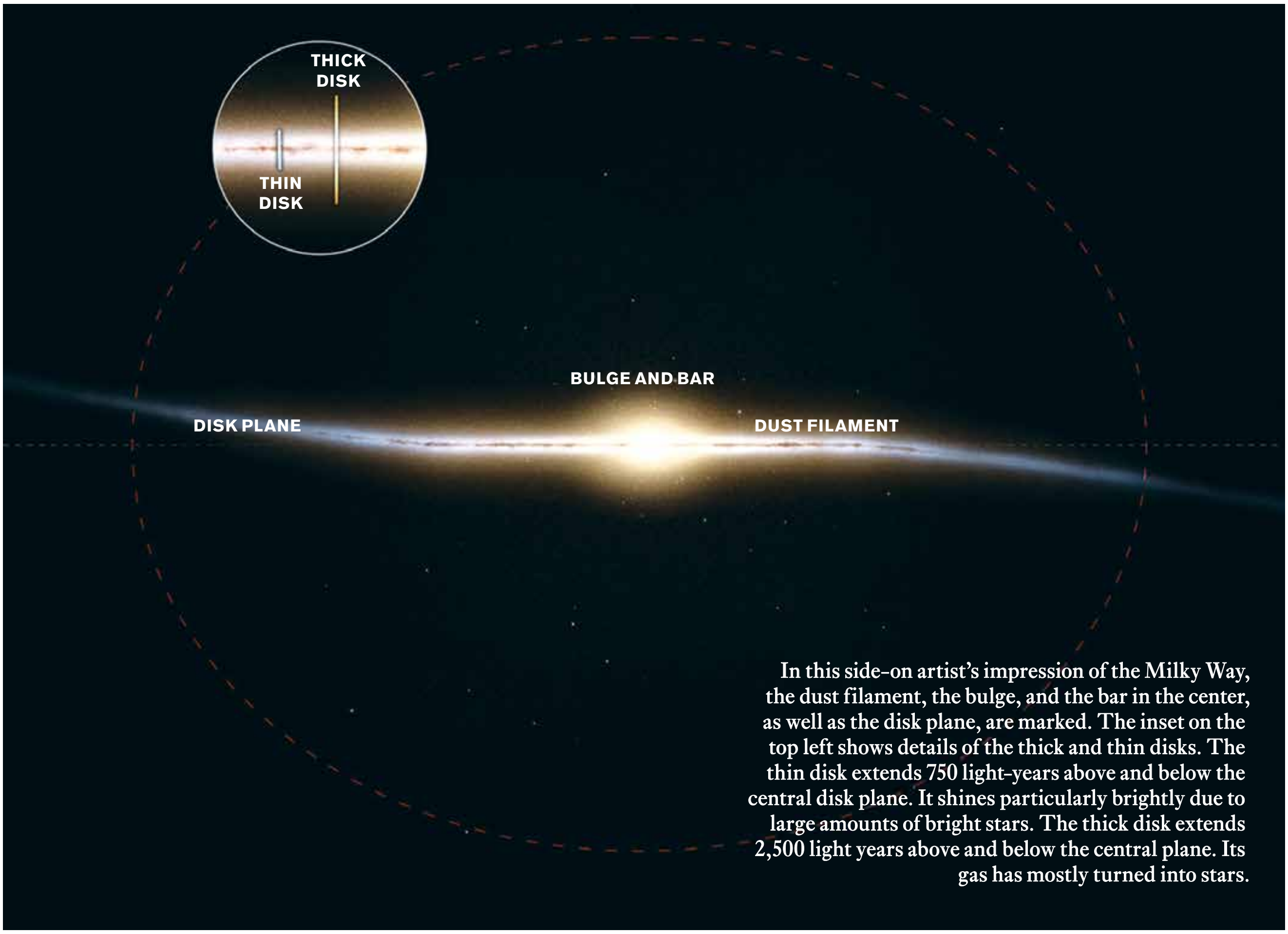
GIANT STARS
are stars that have exhausted their hydrogen fuel supply and, as a result, have undergone significant expansion. Astronomy makes a distinction between subgiants and red giants. Subgiants are in a relatively short stage of development, which allows for a precise determination of their age. Red giants are up to 100 times larger and up to 1000 times more luminous than our Sun, but they are relatively cool and therefore, appear reddish.

SPECTRUM
describes the distribution intensity, for example, of light with respect to wavelength. Lines in the spectrum of a star are characteristic of chemical elements in its atmosphere.



The ancient heart of our galaxy: the map shows the distribution of red giant stars in the Milky Way in much the same way that certain world maps show the surface of the Earth. The galaxy's disk, where gas and dust obscure the view of the stars, bisects the map from left to right. In the center (white circle) are stars that are already more than 12.5 billion years old.

IMAGE: HANS-WALTER RIX / MPI FOR ASTRONOMY



In this side-on artist's impression of the Milky Way, the dust filament, the bulge, and the bar in the center, as well as the disk plane, are marked. The inset on the top left shows details of the thick and thin disks. The thin disk extends 750 light-years above and below the central disk plane. It shines particularly brightly due to large amounts of bright stars. The thick disk extends 2,500 light years above and below the central plane. Its gas has mostly turned into stars.

IMAGE: STEFAN PAYNE-WARDENAAR / MPI FOR ASTRONOMY

machine-learning methods. This AI-based approach requires an algorithm to be trained for the specific task in question. For a number of the stars studied by Gaia, suitable training data is available in the form of more detailed spectra recorded by ground-based telescopes. Using this training data, the algorithm learned to deduce metallicity from Gaia spectra. To check whether the artificial intelligence was up to the task after training, the researchers used spectra of stars whose metallicity was also known, but which had not been used for training. The tests indicated that the algorithm was able to determine the metallicity from the Gaia spectra with impressive accuracy. This was convincing evidence that the AI would be able to provide reliable metallicity values for the two million Gaia spectra of red giants in the inner regions of the Milky Way. From the results, the team was able to identify a population of stars with appropriately low metallicities that form the ancient heart of the Milky Way galaxy. A comparison with the subgiants, whose ages Rix and Xiang had determined in the prior study, indicates that this core of the Milky Way must be older than roughly 12.5 billion years. The stars are all located at a maximum distance of about 15,000 light-years from the center – for comparison: the entire Milky Way stretches over almost 200,000 light-years.

The hunt for protogalactic stars

Further examination of the chemical makeup of some of the stars, where more detailed data was available, revealed that they most likely formed in the Milky Way not long after the protogalaxies had merged. "We have now validated what cosmological simulations had suggested about the early development of our galaxy," says Hans-Walter Rix. Next, the researchers hope to use high-resolution spectra from additional sky surveys to pinpoint the positions and even the movement patterns of stars in the Milky Way's core. If the stars can be assigned to distinguishable groups, each with a characteristic motion pattern, these groups might well correspond to the protogalaxies from which the Milky Way was formed. The archaeological reconstruction by Hans-Walter Rix and his team would then truly have arrived at the origin of the Milky Way.

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