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Resumo: The article discusses the study of the Milky Way galaxy's past by studying stellar streams, which are dwarf galaxies that are ripped apart by the Milky Way's gravity into long tails. Topics include a theory that the Milky Way grew by absorbing dwarf galaxies, the dark matter halo, which is the unseen matter in which galaxies are embedded, and the Apache Point Observatory's Sloan Digital Sky Survey (SDSS) in New Mexico that enables so-called galactic archaeologists to locate star streams.

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FOSSIL HUNTNING IN THE MILKY WAY

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ASTRONMY

Early in its history the Milky "ay gobbled up many tiny galaxies. The cosmic rubble it left behind is now yielding fresh clues into how our corner of the universe came to be By Kathryn V.Johnston

GO OUTSIDE ON A DARK, CLEAR NIGHT, FAR AWAY FROM THE GLARE OF CITY LIGHTS, and look up. You will see the glowing band of the Milky Way arching dramatically overhead. It has now been four centuries since Galileo Galilei first turned a telescope toward this awesome sight and noted that the "milk" is actually countless individual stars, too faint to be separated by the naked eye. It took another three centuries for astronomers to convince themselves that the Milky Way is just one of billions of galaxies in the universe.

In fact, the Milky Way itself is not simply one galaxy: recent work has shown that it has lured in and engulfed many smaller galaxies over time, integrating their stars into itself. At least 20 dwarf galaxies-ranging in size from one millionth to one hundredth the size of the Milky Way-are known to orbit it now, with dozens more probably still undiscovered. And the current satellites are thought to be just a tiny fraction of those that ever existed, the rest having been drawn into our galaxy by gravity and absorbed long ago. This ingestion started when the Milky Way was younger and smaller than it is now and continues today-the satellite galaxies that still exist may eventually be swallowed up.

Long after their demise, these victims of the Milky Way's gravitational appetite leave traces in the form of faint streams of stars that stretch across the sky. Over the past 15 years a relatively new field, which came to be called galactic archaeology, has revealed many of these streams. By studying these fossils from our galaxy's past, galactic archaeologists are piecing together events from the Milky Way's history and gaining clues to the way other so-called spiral galaxies arise and evolve.

Ideally one would study galaxies from the outside as well as within. We cannot do that for our own galaxy. But by taking advantage of our close-up view from inside the Milky Way, we can obtain detailed information that cannot be gained by examining other galaxies from without.

Already this field has helped confirm one process by which the Milky Way and other young galaxies get bigger. The discovery of multiple star streams from long-gone satellites supports the widely held theory that our galaxy started small and swelled in part by adding mass in large gulps-a process called hierarchical structure formation. Although many particulars of this scenario still remain mysterious, we are slowly but surely writing the biography of the Milky Way.

HOW TO BUILD A GALAXY

THE HIERARCHICAL THEORY of galaxy formation says that the main driver of growth for large galaxies resembling the Milky Way is not the baryonic matter-the stars, gas and dust that we can see, made of the same particles composing you and me. Rather the motive force is vast "halos," or spheres, of unseen dark matter in which galaxies are embedded. Small dark matter halos are thought to form first and gradually agglomerate into larger ones and thus to drive bigger galaxies to swallow smaller ones.

Today each galaxy's dark matter halo is many times more massive and more extended than the normal visible matter. Strangely, although astronomers have yet to discover the nature of dark matter (we perceive it only through its gravitational pull on everything else), we have some confidence in this vision of how it clumps because observed clustering and interaction rates of galaxies match predictions of models that posit dark matter agglomeration. The mystery of galaxy formation actually lies not with the dark matter but with the ordinary baryonic matter made of particles that interact in known ways we can study here on Earth.

The basic view of how baryonic matter contributes to the evolution of galaxies starts with the dark matter halo. This body pulls ordinary matter, in the form of gas, toward itself through the force of gravity. As the gas makes its way to the center of the halo, it can, given the right circumstances, form stars. When some of these stars reach the ends of their lifetimes, they explode, returning their atoms to the gas within and (possibly) beyond the galaxy and often triggering another generation of stars to form from any remaining gas and dust. In this way, the central heart (the "bulge") of the Milky Way and its spiral arms (the "disk") most likely formed.

But the Milky Way includes a vast sphere (also called a halo) of more diffuse stars surrounding the bulge and disk. Many of these stars are probably interlopers from long-destroyed dwarf galaxies. According to the hierarchical formation theory of how galaxies form, the stars join the halo in a sequence of events that goes something like this: As a dwarf galaxy orbits the Milky Way, it feels the gravitational pull of the big galaxy, which gets stronger as the satellite gets closer to the larger galaxy. The matter (stars, gas, dust and dark matter) located on the side of the satellite closest to the Milky Way experiences a slightly greater force of attraction than the matter at the far side.

As a result, the dwarf gets stretched along the line between it and the larger galaxy. The stretching stems from so-called tidal forces-the same physics that causes the moon to raise the tides in Earth's oceans. Unlike the moon-Earth interaction, the tidal forces of the Milky Way on its satellites can be strong enough to actually remove matter-in this case, stars get pulled off from the body of the dwarf. Once removed, the stars stay in the grip of the Milky Way's gravity and continue along a path slightly offset from the satellite's own orbit. Over time the slight offset causes the debris to steadily spread, becoming more diffuse and moving away from the satellite to form stellar streams.

This theoretical picture makes a lot of sense, but for a long time scientists lacked observational evidence. Now they have it. The discovery of many star streams has revealed that the Milky Way began eating its neighbors billions of years ago, when it was young, and continues to munch on dwarfs today. And although we have seen proof of streams from dwarf companions mainly around our own galaxy, such streams probably occur around all similar spiral galaxies, although those distant streams would generally be too faint to be detected from afar.

Many details of the process of hierarchical formation still remain elusive, however, such as when the Milky Way absorbed most of its satellite galaxies, how often it eats dwarfs and how long it takes to incorporate their stars. To answer these questions, astronomers must locate more star streams amenable to thorough study, as well as the remnants of defunct streams.

DIGGING FOR GALACTIC FOSSILS

ASTRONOMERS SEEK STAR STREAMS in the Milky Way in multiple ways. First and most straightforwardly, we can look for groups of stars at the same distances that cluster together in long filaments. For this, we need a good three-dimensional map of our galaxy's stars that shows the distances and positions of as many stars as possible in all directions.

Over the past 15 years galactic archaeologists have gotten just that in the form of data from the Sloan Digital Sky Survey (SDSS). The survey used a dedicated telescope at Apache Point Observatory in New Mexico to create a database of more than 80 million stars within the Milky Way, along with information on their distances, colors and other characteristics, spread over one quarter of the sky. The vast number of stars in this catalogue offered a perfect dig site to look for fossils from the Milky Way's past.

The fraction of stars that were initially born in other galaxies and subsequently subsumed into our own galaxy is thought to be small, roughly 1 percent or less of the Milky Way's hundreds of billions of stars. But Sloan's map gave astronomers potentially almost one million interloper stars to examine for evidence of long-dead galaxies. Galactic archaeologists looked in this map for stars likely to be at the right distance to lie in the galactic halo. Among these stars, they located star streams by homing in on areas that were denser with stars than their surroundings and took the shape of tails. Astronomers knew what the tails would look like in part from computer simulations I created and published in 2005 in collaboration with cosmologist James Bullock of the University of California, Irvine. We used our understanding of how dark matter halos form hierarchically, combined with the physics of tidal forces, to predict the sizes and spreads of the stellar streams that will result as many dwarf galaxies get swallowed during the formation of the Milky Way.

The first convincing evidence of an extended star stream came in 2003, when astronomers led by Steve Majewski of the University of Virginia uncovered giant tails emanating from the Milky Way's closest known satellite, the Sagittarius dwarf galaxy, in data from the Two Micron All Sky Survey (a similar project to Sloan, conducted in infrared light). The streams lie close to Sagittarius's projected orbit and contain almost as many stars as are still in the Sagittarius galaxy itself. The tails are so long that they entirely encircle our own galaxy. We had caught the Milky Way in the act of attacking its own nearest (but apparently not dearest) neighbor.

Since that discovery, galactic archaeologists have unearthed about a dozen more star streams around our galaxy in the Sloan catalogue. From the length of Sagittarius's tails, we can say it has been losing stars for two billion to three billion years. The other streams that we see also look to be a few billion years old. These discoveries indicate that the Milky Way was digesting galaxies more often during its early history and has ramped down lately as the number of dwarfs available to be eaten has diminished. So far these findings are in line with what hierarchical formation theory predicts. The known stellar streams, though, are probably just a fraction of those that exist. Many more streams should be out there, too faint to see for now but harboring further insights into the galaxy's past.

NEW EXCAVATION TOOLS

RELYING ON STAR POSITIONS to find stellar streams will miss many older trails because over the course of a few billion years small differences in orbital properties between the stars can cause the streams to lengthen, diffuse and fade so much that they lose any obvious structure. Astronomers are now working on ways to exploit other stellar properties to find streams that are more dissolved, as well as remnants of streams that have come apart fully. These collections of stars will help scientists explore the most active epoch of galaxy formation, which occurred more than 10 billion years ago, within the first few billion years after the big bang, when most of the stars in the universe formed. That is the time during which not just a few but hundreds of small galaxies and star clusters were accreted to form the Milky Way.

One way to hunt for these leftovers from now defunct galaxies involves looking for stars with common orbits. Long after stars in streams have become too scattered to recognize from their positions, we can take advantage of their motion to identify stars that were once part of the same satellite galaxy and to learn how they joined the Milky Way. This goal is one of the many being pursued by the European Space Agency's Gaia satellite, launched in December 2013. Gaia will spend the next four years creating a game-changing data set for galactic archaeologists by measuring distances, positions and motions for more than a billion stars. This haul is exciting for our problem because of the sheer number of stars being catalogued and because the many dimensions of information being measured for each star will allow us to calculate their full orbits. Thus, we can pick out stars with similar orbital properties as likely to have come from the same original galaxy, even if their positions on the sky do not show us that they are related anymore.

Furthermore, there is one sense in which stars never forget where they were born: their chemical composition. This chemistry provides another potential way to discover stellar streams. Stars are constantly changing their overall composition via the nuclear fusion in their cores, which synthesizes light elements into heavier ones. Yet nuclear fusion can take place only in the densest and hottest central regions of the star, and it is thought that the star's atmosphere, which is what astronomers measure, is identical to the gas from which it was born. Astronomers Kenneth Freeman of the Australian National University and Joss Bland-Hawthorn of the University of

Sydney aim to use this perfect memory not to find star streams but to group stars with identical chemical fingerprints into the clusters that birthed them, irrespective of where they sit in the sky now.

Freeman and Bland-Hawthorn's simple method of using a single chemical label will not work for identifying stars associated with a dwarf, because these galaxies themselves are likely to contain stars born in many different clusters having a range of chemical compositions. Nevertheless, the natures of cosmic history and of star formation conspire so that an analogous chemical approach might give us some information about the Milky Way's accretion history.

First, stars forming later within a given galaxy generally contain more heavy elements than those forming earlier because the material that constitutes them has already been enriched with the remains of previous generations of stars. Second, exactly how enrichment proceeds is informed by gas flows that are governed in part by the gravitational influence of the galaxy's dark matter halo. These two effects suggest that galaxies of roughly the same mass that are accreted and destroyed at roughly the same time should contribute stars with the same distribution of chemical compositions-meaning the same spread of abundances for many different elements. Conversely, differences in either a galaxy's mass or accretion time will lead to differences in the chemical distributions of the stars it contributes. Hence, the overall distribution of chemical compositions of stars around our Milky Way could allow us to discern what fraction come from similar mass galaxies at similar times, if not exactly the same galaxy.

Duane Lee investigated this idea while a graduate student in my group at Columbia University. His preliminary work suggests that chemical tags might be sensitive enough to recover contributions from even the smallest dwarf galaxies destroyed very early on in galactic history. By knowing which fractions of the Milky Way's stars arrived at different epochs, we can begin to sketch out a sequence of cannibalizations and to trace the accretion history of our galaxy, reaching back to the very earliest times. Two groups are now measuring chemical compositions for millions of stars, and their data could be used to tackle this problem. One is the GALactic Archaeology with HERMES (GALAH) survey led by Freeman and Bland-Hawthorn, which has a pilot survey currently under way. The other is called the APO Galactic Evolution Experiment (APOGEE); it started in 2011 as part of the ongoing Sloan survey.

Galactic archaeologists are just beginning to appreciate that studying the Milky Way is like studying 1,000 galaxies, because that many smaller objects have combined to build up the larger body. The fossils from those subsumed galaxies teach us not just about the Milky Way's history but also about the histories of all the smaller galaxies it includes. We should soon be able to study how galaxies of many different sizes were made at many different times, all in our own local laboratory. Such analyses in the next decade could potentially contribute as much to our understanding of galaxy formation as the stunning discoveries of stellar streams encircling the Milky Way have contributed in the past decade.

Ultimately we would like to know how the very first galaxies in the universe formed. The earliest progenitors of galaxies akin to our own are too small and distant to be directly detectable. Galactic archaeology, however, could reveal the remnants of these earliest seeds-the long-lived stars that still bear the imprints of their origins are scattered right here in the Milky Way. In a very real way, then, digging in our own backyard can give us a window on the early universe and the first steps of galaxy formation that is impossible to access by any other means.

MORE TO EXPLORE

Tracing the Milky Way's History. Cristina Chiappini in Sky & Telescope, Vol. 108, No. 4, pages 32-40; October 2004. Sloan Digital Sky Survey: www.sdss.org

FROM OUR ARCHIVES

The Ghosts of Galaxies Past. Rodrigo Ibata and Brad Gibson; April 2007. Dwarf Galaxies and the Dark Web. Noam I. Libeskind; March 2014.

From Dwarf Galaxy to Star Stream

The discovery of structures called star streams at the edge of the Milky Way has given astronomers evidence that our galaxy and others like it grow by cannibalizing smaller, "dwarf," galaxies. The streams are telltale signs that such ingestion has occurred. In our galaxy, the streams begin to form when a dwarf galaxy gets too close to the Milky Way for its own good ©. The larger galaxy's gravity creates tidal forces that pull more strongly on the near side than on the far side of the satellite. These tidal forces gradually stretch the dwarf along the line between it and the Milky Way ©. Individual stars get pulled off the dwarf and form stellar streams © that orbit along a path slightly offset from the dwarf galaxy. Over time these streams spread and become more diffuse. Streams from larger dwarf galaxies can eventually stretch to encircle the entire Milky Way

STARRY NIGHT: The Milky Way glows in the night sky over the Pacific Ocean off the coast of Chile's Atacama Desert.

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By Kathryn V. Johnston

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