

The Ghosts of Galaxies Past

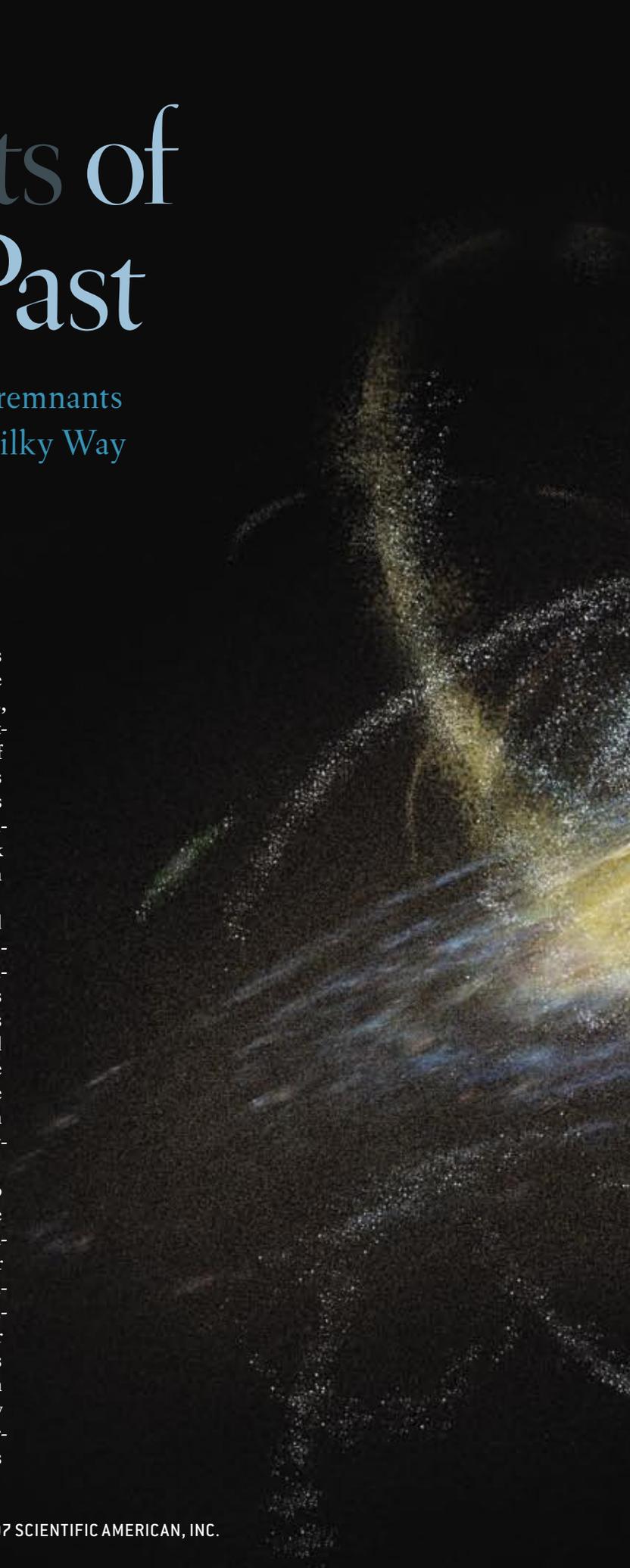
Strangely moving stars may be the remnants of past galaxies devoured by our Milky Way

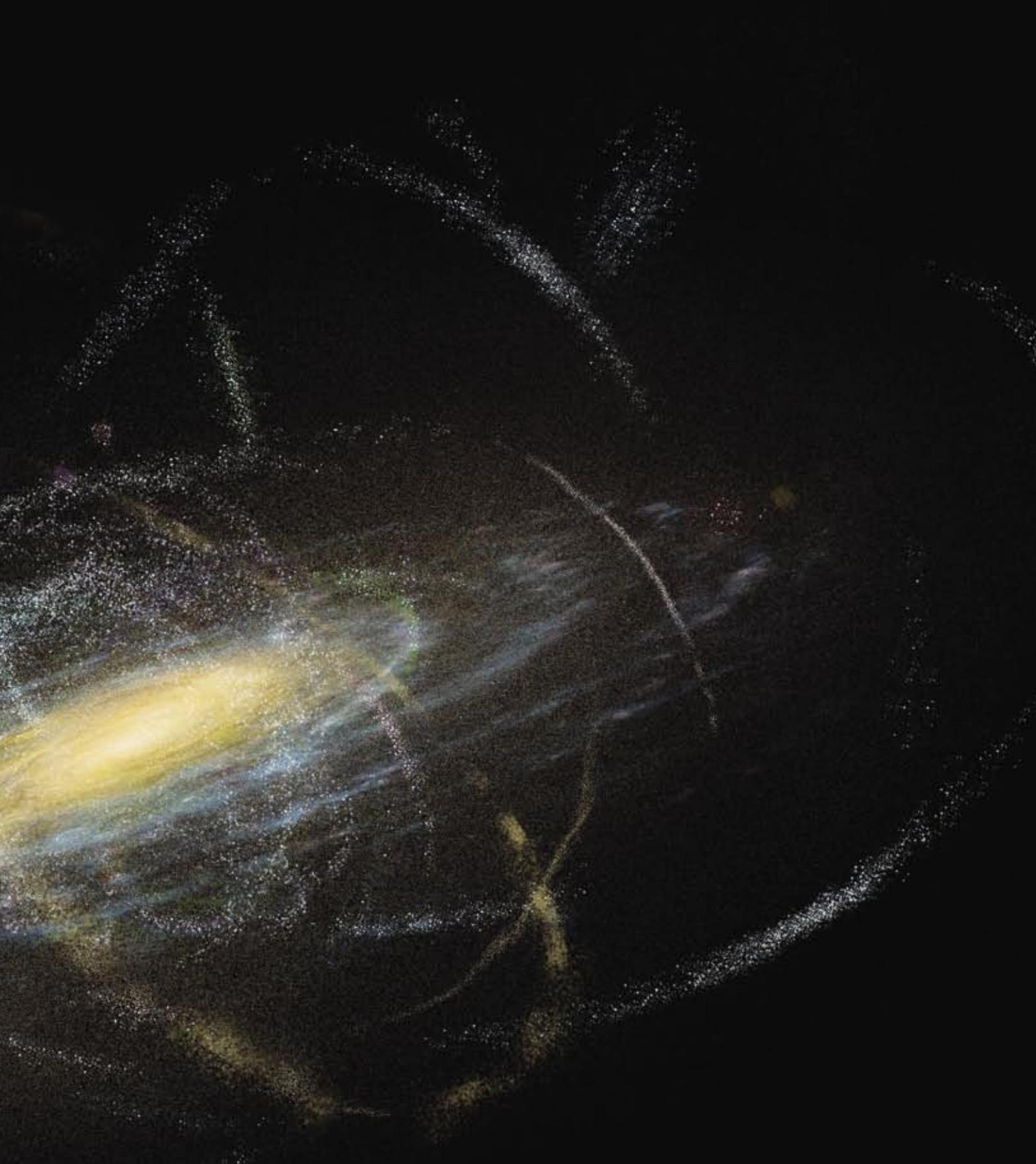
By Rodrigo Ibata and Brad Gibson

When you look up at the night sky, the stars that you see all reside in our own galaxy, the Milky Way. The nearest large galaxy to us, Andromeda, is more than two million light-years away, a distance 20 times the size of the main disk of our galaxy. With the unaided eye, you cannot make out its stars individually; they blend together into a faint fuzz. As far as our galaxy is concerned, those stars might as well inhabit a separate universe. Conversely, it is natural to think of the stars in our sky as native suns, born and bred within the confines of the Milky Way.

But then what do you make of Arcturus, the second brightest star in the northern sky? Arcturus moves in a subtly different way and has a slightly different chemical composition from that of most stars in the Milky Way; it shares its curious properties with a few other stellar mavericks scattered throughout the galaxy. The origin of these and other atypical stars has been a matter of heated debate since the 1960s. Did the gravity of our galaxy's spiral arms force them into oddball orbits, or are they immigrants, formed in regions beyond the Milky Way from material that was never part of it?

By applying sophisticated forensic techniques akin to those employed elsewhere in the sciences, astronomers have discovered in recent years that the answer is: yes. Some galactic natives were indeed born in or pushed into peculiar orbits, but a surprisingly large number of the anomalies, including Arcturus, are genuine immigrants. A better metaphor than "immigrants" might be "kidnap victims" or "subject peoples," because astronomers think these stars were born into smaller galaxies that the Milky Way then captured, plundered and assimilated. Over time our galaxy may have vanquished hundreds of its neighbors. Their former inhabitants now intermingle with the Milky Way's





THEY GAVE THEIR LIVES TO BUILD THE MILKY WAY: Hundreds of small galaxies have been ripped apart by our galaxy, creating tenuous streams of stars that slowly mix into the Milky Way's indigenous population. As we speak, the Milky Way is shredding the Sagittarius dwarf galaxy, creating a stream [*gold*] that completely surrounds the central disk of the galaxy.

natives and retain only fading memories of home. By finding them out, observers can reconstruct the violent history of our galaxy and probe its darkest secret of all: the nature of the unseen dark matter that governs its existence.

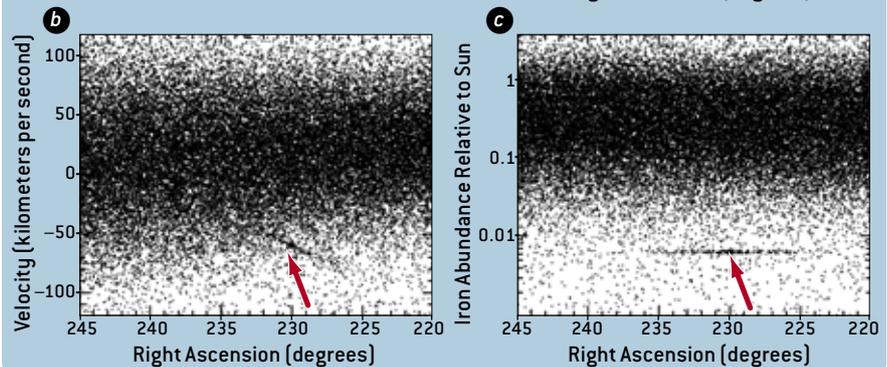
Space Invaders

SPOTTING STELLAR immigrants takes a sharp eye. In principle, they give themselves away by lining up in long streams, like a conga line on a crowded dance floor. Many streams lead back in a starry path to a globular star cluster or one of the Milky Way's satellite galaxies—presumably the original home of the stars in the stream or what is left of it. In practice, though, these streams are hard to find because they barely stand out against the relatively smoothly distributed native star populations. To overcome this problem, many recent discoveries have made use of the matched-filter technique developed during World War II to produce cleaner images of incoming aircraft. The technique filters out the native stars—given an approximate idea of what patterns they and the immigrants form.

Probably the most impressive of the known star streams is the Sagittarius stream, which one of us (Ibata) and his colleagues discovered in 1994. This stream is an immense necklace of stars encircling our galaxy. It stretches over a million light-years, contains an estimated 100 million stars and connects to the Sagittarius dwarf elliptical galaxy—one of

Hiding in the Crowd

If you simply look at an area of the sky, a stellar stream can be completely lost amid the foreground native stars of the Milky Way (a). But in terms of velocity (b) and composition (c), the stream is much more distinctive. This figure is a model for the region of sky around the Palomar 5 stream. (Right ascension and declination are sky coordinates.)



some 15 to 20 mini galaxies that orbit the Milky Way like moons around a planet. These range in size from the Large Magellanic Cloud (about a tenth the mass of our galaxy) to the Sagittarius dwarf (one-hundredth the mass) down to faint ones barely a millionth as massive.

Living close to a giant galaxy is hardly cozy. These small satellites gradually become deformed and eventually are destroyed. Sagittarius has been going through its death throes for several billion years and is now a barely coherent

body in its final stages of dissolution. Its stars will disperse throughout our galaxy. The current streamlike coherence of their arrangement will be lost, and future astronomers will be hard put to distinguish them from natives of the Milky Way. Several other small galaxies are also being dismembered, and for some the stream is all that is left [see table on page 45]. In a few cases, such as the Large Magellanic Cloud, what is leaking away is not stars but gas [see “Our Growing, Breathing Galaxy,” by Bart P. Wakker and Philipp Richter; SCIENTIFIC AMERICAN, January 2004].

The mechanism of destruction is very familiar to us all: gravitational tides, the same process that causes the ebb and flow of the oceans on Earth. Tidal forces arise when different parts of a body experience different gravitational pulls. Earth's moon exerts a larger force on the side of Earth facing the moon than on the side facing away from it—the differential force is too weak to tear our planet apart but enough to cause the sea to bulge out slightly. The motions of the two bodies cause the bulge to sweep around the globe, raising and lowering the sea level in a regular

Overview/Star Streams

- The Milky Way galaxy has assembled itself from a kit of hundreds of galactic building blocks—and is still doing so. Whenever a small galaxy or star cluster passes too close for its own good, our galaxy's gravity tears it apart, draws its stars out into a long stream and absorbs them.
- Even recently formed streams are hard to see against the backdrop of the rest of the galaxy, and as they disperse the spatial pattern vanishes altogether. Nevertheless, subtle patterns in stars' motion and composition will forever betray their origin. By undertaking a thorough census of stars, astronomers aim to reveal these galactic immigrants and reconstruct how the Milky Way grew to its present size.
- Streams also provide a novel way to measure the enigmatic dark matter that envelops our galaxy. The shapes of the streams are sensitive to the amount and distribution of this unseen material.

cycle. Similarly, the Milky Way deforms a satellite galaxy or star cluster by pulling harder on one side of the stellar system than on the other. In so doing, it can literally lift off some of the stars [see box below]. The satellite loses more and more stars, which form a virtual trail of bread crumbs leading the way back to their former home.

A Work in Progress

THE SAGITTARIUS DWARF and other galactic satellites are therefore contributing to the buildup of our own galaxy. These observational findings have revolutionized theoretical understanding of galaxy formation. Astronomers once thought that all galaxies evolved directly from barely perceptible density enhancements in the otherwise smooth primordial universe, then experienced an early period of runaway growth and settled quickly into their present form. Today, based in part on observations of the star streams, researchers think that only dwarf galaxies (up to a billion suns in mass) went through such an abrupt

THE AUTHORS

RODRIGO IBATA and **BRAD GIBSON** started working together in 1997 to use observations of the Sagittarius dwarf elliptical galaxy to understand dark matter. Ibata is an observer who dabbles in theory, and Gibson is a theorist who dabbles in observation. Ibata, who works at the French National Center for Scientific Research, based at Strasbourg Observatory, keeps breaking his own records. He led the team that in 1994 discovered the Sagittarius dwarf, the closest known satellite galaxy of the Milky Way. In 2004 he and his colleagues found an even closer one, the Canis Major dwarf. He traces his love of science to physicist Steven Weinberg's book *The First Three Minutes*: "It certainly gave me a great impetus to learn math, which until then had appeared to be simply an exercise in patience." Gibson is Chair in Theoretical Astrophysics at the University of Central Lancashire in England. He pioneered computer simulations of galaxy formation and has studied mysterious anomalous velocity clouds orbiting the Milky Way.

formation period. Large galaxies such as the Milky Way (about one trillion suns) formed later through the accretion or progressive coalescence of dwarfs—a process that continues to this day, albeit at a more leisurely pace than in the past.

Having dramatically caught the Milky Way in the act of assimilating nearby galaxies, astronomers are moving on to the next level of questions: What chemical makeup did these ancient galactic building blocks have? What is the fraction of immigrants to natives in giant galaxies of the present

day? How did the chemical elements that these small galaxies brought into the Milky Way alter its early history? Apart from their direct interest as fossil records of the galaxy assembly process, star streams are also of great use as probes of the distribution of dark matter [see box on next page].

To tease out the answers, astronomers need to know not only which stars are currently migrating to the galaxy but also which ones migrated in the past. The trouble is that once the immigrant stars and gas mix into the Milky Way,

THAT'S THE WAY THE GALAXY CRUMBLES

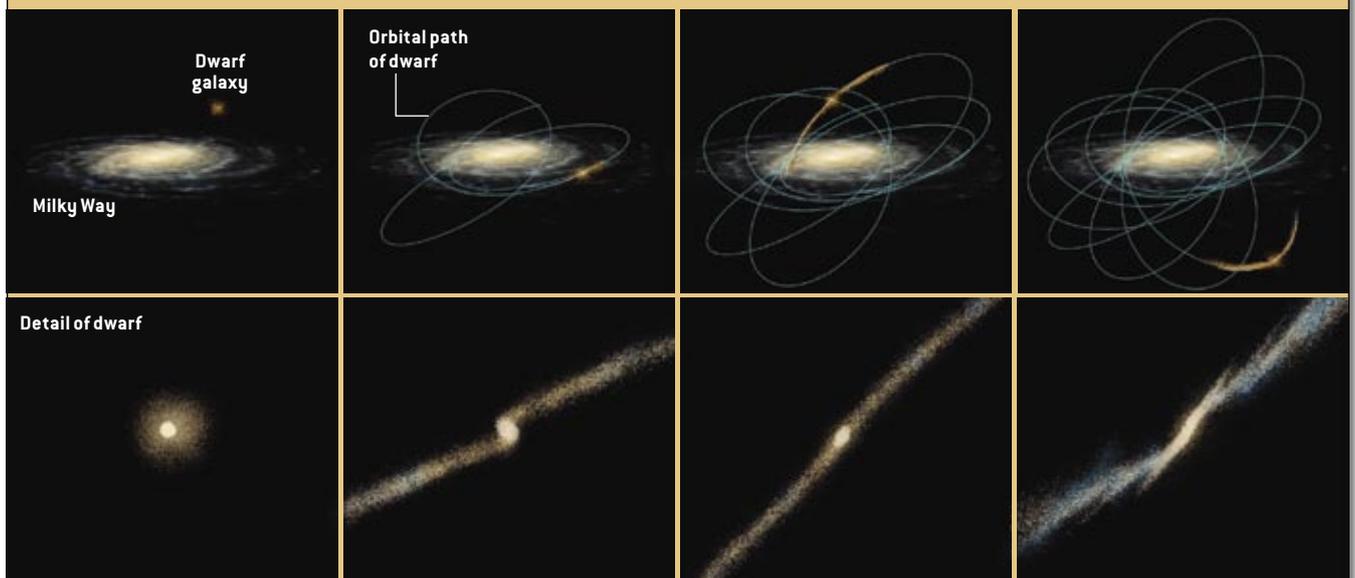
A computer simulation shows how tidal forces exerted by the Milky Way distort and eventually shred a hapless dwarf galaxy to bits.

▼ **3 BILLION YEARS AGO**
Having developed in relative isolation, the dwarf galaxy makes its first pass at the Milky Way.

▼ **2 BILLION YEARS AGO**
Four close encounters with our galaxy's disk have stretched the dwarf. Escaping stars either slow down and fall behind the dwarf or speed up and run ahead of it.

▼ **1 BILLION YEARS AGO**
The dwarf is in serious trouble. Almost all its stars now form a stream for tens of thousands of light-years along its orbit.

▼ **TODAY**
The dwarf has utterly fallen apart. The tidal stream, meanwhile, is itself spreading out and mingling with the Milky Way's native stars.



DON DIXON

Seeing That Which Cannot Be Seen

In reconstructing the history of the Milky Way, astronomers naturally focus on what they can see: the stars. Yet stars are a very small fraction of galaxies. The bulk resides in a form unknown to science: the enigmatic dark matter. All that we know about it—which is not much—comes from observing its gravitational effect on the stars and gas we do see. Needless to say, it is extremely hard to map out something you cannot see.

What would-be surveyors crave is the ability to follow the motion of a star as it completes a full orbit around the galactic center. The star would slow down and speed up depending on the gravitational field—and hence would reveal the way mass is arranged in our galaxy. Unfortunately, astronomers' careers are much too short to undertake such observations, given that it takes a star several hundred million years to finish one orbit.

Streams of stars provide a way to overcome this handicap. The constituent stars follow similar orbits; the only difference is that they started at different times. Thus, they trace the path a single star would follow over hundreds of millions of years. Our team has already measured the shape of the Sagittarius stream and concluded that the dark matter around the Milky Way is distributed not as an ellipsoid, as computer simulations had predicted, but as a sphere. Interestingly, the behavior of the stream matches the predictions of certain nonstandard theories of gravity, such as modified Newtonian dynamics (MOND) [see "Does Dark Matter Really Exist?" by Mordehai Milgrom; *SCIENTIFIC AMERICAN*, August 2002].

This result has recently been corroborated by Michael Fellhauer of the University of Cambridge and his collaborators. A caveat is that the Sagittarius stream probes only a small portion of the dark-matter distribution. Measurements of multiple streams are required to determine whether the distribution truly is spherical.

Another question is whether dark matter is distributed smoothly or lumpily, which would bear on the dark matter's composition. If dark matter comprises particles that interact only via the force of gravity, there is nothing to stop them from clumping. If it comprises particles that can also interact by other means (such as the action of nuclear forces), they might resist clumping and smooth themselves out.

Observations of star streams are one of the few ways to look for lumpiness. By carefully mapping the positions and velocities of stars in thin streams, the Gaia satellite should be able to confirm or rule out the existence of dark matter lumps as small as 100 light-years across. In this way, star streams larger than an entire galaxy may one day reveal the properties of particles smaller than atoms.

—R.I. and B.G.



they become essentially impossible to recognize as distinct spatial features. Forensic astronomers must look for more subtle traces of the origins of these stars, such as harder-to-erase aspects of their motion and chemical composition.

We are all conditioned to characterize the movement of bodies in terms of position and velocity. But motion also has other properties, such as energy and angular momentum. Just as position is specified in terms of three-dimensional space, position plus momentum can be specified in terms of an abstract six-dimensional space, known as phase space. The advantage of phase space is that the arrangements of stars within it are more resilient than their arrangements in real space. Although the assimilation process can often destroy the spatial coherence of a stream, it cannot eliminate the stream's phase space coherence because of a key principle in statistical mechanics known as Liouville's theorem.

Thus, by measuring the energy, angular momentum and phase-space density of random samples of stars, researchers can discern stellar groups that are impossible to see directly. These are the ghosts of long-dissolved satellites. Several groups—including those led by Amina Helmi of Kapteyn Astronomical Institute in Groningen, the Netherlands, and Chris B. Brook of the University of Washington—have used the technique to uncover a number of fossils of satellite accretion. All are located in the neighborhood of the solar system, because instruments do not yet have enough precision to measure the full three-dimensional motion of more distant stars.

Which Ones Are Not Like the Others

ANOTHER EXCITING TECHNIQUE, which astronomers are only beginning to test, is so-called chemical fingerprinting. Most stars are not born in isolation but instead in groups of several thousand to tens of thousands, all of which emerge from the same parent cloud of gas. Each cloud has a unique and homogeneous mix of chemical elements and isotopes, which its stellar progeny inherits. Even when the stars disperse, they

retain their unique chemical tag, allowing forensic astronomers to trace them back to their birthplace. As Kim A. Venn of the University of Victoria in British Columbia and her colleagues have shown, stars born in dwarf galaxies have a very different chemical makeup from that of typical Milky Way natives.

A more difficult question is whether it will be possible to trace individual stars back to their birthplaces. Gayandhi De Silva of the European Southern Observatory and her collaborators recently did a detailed chemical study of one of the Milky Way's best-known star clusters, the Hyades. They found that stars in this cluster all have an essentially identical distribution of chemical elements, suggesting that chemical fingerprinting will indeed allow astronomers to identify stars of common origin. They may one day be able to identify the sun's own siblings—stars formed from the same gas cloud as the sun but now spread far and wide over the galaxy.

Having verified the plausibility of chemical fingerprinting, astronomers have started to put these ideas into practice. RAVE (Radial Velocity Experiment) at the Anglo-Australian Observatory and SEGUE (Sloan Extension for Galactic Understanding and Exploration) at the Sloan telescope have measured the velocities and chemical compositions of more than 100,000 nearby stars. They, in turn, are precursors to the European Space Agency's Gaia mission and the NASA Space Interferometry Mission (SIM). From late 2011 through 2020, Gaia, the most technologically ambitious space telescope ever attempted, will aim to map the three-dimensional structure of our galaxy, obtaining precise positional and velocity measurements for an astonishing one billion stars—nearly 1 percent of the galaxy. The satellite is also intended to measure the chemical compositions of several million of these stars. Working on a comparable timescale, SIM should provide positional information for a subsample of faint stars, thereby probing the most tenuous star streams. These two missions therefore represent the best of both worlds: a sensitive but nar-

Field of Streams

Astronomers have discovered just under a dozen stellar streams. If current theories of galaxy formation are correct, the Milky Way has devoured hundreds of small stellar systems, most now so thoroughly mixed into the Milky Way that they may never be found.

Stream	Probable Origin	Approximate Mass	Approximate Length	Composition	Year of Discovery
Arcturus stream	A defunct dwarf galaxy	Unknown	Unknown	Old stars (deficient in heavy elements)	1971
Magellanic stream	Large and Small Magellanic clouds	200 million solar masses	1 million light-years	Hydrogen gas	1972
Sagittarius stream	Sagittarius dwarf galaxy	100 million solar masses	1 million light-years	Wide variety of stars	1994
Helmi stream	A defunct dwarf galaxy	10 million to 100 million solar masses	Wrapped several times about the Milky Way's disk	Old stars	1999
Palomar 5 stream	Globular cluster Palomar 5	5,000 solar masses	30,000 light-years	Old stars	2001
Monoceros ring	Canis Major dwarf galaxy	100 million solar masses	200,000 light-years	Intermediate-age stars	2002
Anticenter stream	A defunct dwarf galaxy	Unknown	30,000 light-years	Old stars	2006
NGC 5466 stream	Globular cluster NGC 5466	10,000 solar masses	60,000 light-years	Very old stars	2006
Orphan stream	Ursa Major II dwarf galaxy	100,000 solar masses	20,000 light-years	Old stars	2006

row survey (SIM) and a broad but less sensitive one (Gaia).

A decade ago, when we discovered the stellar stream of the Sagittarius dwarf galaxy, many of our colleagues considered it a mere curiosity with no broader significance. But it soon became the poster child for the Milky

Way's tangled history of merging and accreting—processes now thought to be the main drivers of galaxy formation and evolution. Assimilated galaxies have brought new stars, gas and dark matter and have triggered waves of star formation. These immigrants have kept our galaxy a vibrant place. SA

MORE TO EXPLORE

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