Tracing the Milky Way's History

By Cristina Chiappini

It was a cold, clear winter night in beautiful Monte Verde. I was still a kid, living in the city of São Paulo, Brazil, and our teacher's goal for this school trip was to show us the Milky Way — and to tell us that we were living inside another big "city," one made of stars! The sight fascinated me. Now I dedicate most of my time to understanding how the Milky Way — our home galaxy — was made.

Like other spiral galaxies, our Milky Way has several distinct structural components that probably appeared at different stages in its formation process. The stars belonging to each component have distinct chemical compositions, and they move through the galaxy in distinct ways. Such differences hold clues about how the Milky Way formed and evolved.

Stellar motions can be scrambled by a variety of processes, just as comet and asteroid orbits can be changed abruptly by close encounters with other bodies in our solar system. This compromises any solution to the puzzle of galaxy formation that relies solely on kinematic data — those telling us how stars are moving through the galaxy.

By contrast, the chemical composition of a star's outer layers is, for the most part, preserved from birth. Thus, chemical abundances — the amounts of various chemical elements seen in the spectra of stellar atmospheres — can, in some cases, provide a clearer picture of what happened in the past.

Of course, in an ideal world we would like to be able to
Only by painstakingly “fingerprinting” the chemical composition of ancient stars can we unravel our galaxy’s history.
study both the chemical and the kinematic properties of a large number of stars, and to compare such data to models for the Milky Way’s formation. This is not an easy task, since the best data available today come from stars that are confined to a small region around us. The field will take a quantum leap forward when the European Space Agency’s Gaia satellite launches six or seven years from now; Gaia will cover the distances, three-dimensional motions, chemical compositions, and many other physical properties of stars halfway across our galaxy.

But those of us who study the Milky Way are not idly waiting for Gaia’s launch. Ambitious surveys using ground-and space-based telescopes are now underway, and new discoveries are being reported almost daily. I would like to discuss some of these discoveries to show you what astronomers are learning about the formation of our galaxy and others like it.

**Stars: Cosmic Chemical Clocks**

First let’s quickly look at the life of a star. Not only are stars the main source of the visible light emitted by all galaxies; they are the “factories” where most of the chemical elements are produced.

One of the most notable triumphs of theoretical astrophysics has been gaining an understanding of the origins of chemical elements. We now know that only a few species, such as hydrogen, deuterium, helium, and lithium, were synthesized during the Big Bang, while almost everything else has been manufactured since then inside stars.

A star’s death is particularly important because it is then that most of the chemical elements produced during its life are ejected into the interstellar medium, or ISM, as the gas that exists between stars is called. These elements then are mixed with the gases already present, and they increase the ISM’s overall metallicity — its percentage of chemical elements heavier than hydrogen and helium. From this gas new stars eventually form, and they are enriched by the products of the nuclear-fusion processes that took place in previous stellar generations.

Stars of different masses will enrich the ISM with different chemical species. The more massive a star is, the higher the temperature attained in its core, increasing high temperatures, in turn, are needed to build successively heavier chemical elements by nuclear fusion. For example, only those stars that have more than about eight times the mass of our Sun can produce elements, like oxygen, that result from alpha particles (helium nuclei) smashing into one another.

Stars of different masses also die in different ways. A Type II supernova originates when a massive star abruptly explodes after exhausting its central reserves of nuclear fuel. Lower-mass stars, such as our Sun, gently expel most of their envelopes near the ends of their lives, creating beautiful planetary nebulae; their cores then become white dwarfs. If one star within a binary system becomes a white dwarf, its partner star’s evolution can later give rise to another type of spectacular explosion, a Type Ia supernova, which occurs when the white dwarf collects a critical amount of matter from its companion (S&T: November 2002, page 28).

Finally, stars of differing masses evolve on differing time scales, as do the long-lived binary systems that eventually give rise to Type Ia supernovae. The most massive stars explode as Type II supernovae after shining for just a few million years, while low-mass stars can shine for billions of years. Type Ia supernova precursors likewise can take a billion years or more to evolve. Because of this, the ISM is enriched quickly by elements produced by short-lived, massive stars (most notably oxygen) and slowly by those elements produced primarily by low- and intermediate-mass stars (most notably carbon and nitrogen) and by Type Ia supernovae (most notably iron). This means that the relative abundances of different chemical elements can be used as cosmic clocks to document star formation in various parts of our galaxy.
Our Galaxy, Piece by Piece

As shown at the top of the facing page, our galaxy can be described as a flattened disk of gas and stars with a stellar bulge in the center. The bulge and the disk (which actually comprises concentric, partially overlapping thin and thick disks) are both surrounded by a spherical halo made of old stars, globular clusters, and still-mysterious dark matter.

By analyzing the abundance ratios in stars belonging to the halo, bulge, and disk, astronomers already have seen clear indications that in the halo and the bulge, star formation peaked in the distant past and has been very inefficient afterward. By contrast, stars have formed at a less intense but almost constant rate in our galaxy’s thin disk. (This seems to be true for other spiral galaxies as well.)

But that’s only the tip of the iceberg. Using the tools of spectroscopy and chemical analysis, let’s tour our galaxy in hopes of understanding in more detail how it assumed its present form. First we’ll look closely at each galactic component. Then we’ll try to get the “big picture” by putting all the pieces together.

THE HALO. This spherical component is traced by globular clusters and by stars following elongated orbits that are inclined steeply to the galaxy’s midplane. These stars are old and bereft of metals.

Although the halo’s existence was postulated in the 1930s, its distinct character wasn’t demonstrated until 1962, when Olin J. Eggen, Donald Lynden-Bell, and Allan R. Sandage first showed that one could combine stellar abundances and kinematics to study our galaxy’s formation.

Within a specially chosen sample of 221 fast-moving stars, these astronomers found a remarkable correlation between a chemical property and a kinematic one: stars with the lowest metallicity (the least iron) invariably were moving in highly eccentric orbits. In particular, Eggen, Lynden-Bell, and Sandage showed that the metal-poor stars reside in the halo. This suggested that the halo was created when a primumordial gas cloud collapsed relatively rapidly.

In 1978 Leonard Searle and Robert J. Zinn put forth a very different view of the halo’s formation. They argued that the halo grew gradually as our galaxy captured fragments such as dwarf galaxies. Because these fragments would have evolved independently, Searle and Zinn’s model could account for age and metallicity differences between our galaxy’s globular clusters.

There are in fact many pieces of evidence that our galaxy did not evolve in a “closed box,” with no new material becoming incorporated since the initial formation event. The most important example is the 1994 discovery by Rodrigo Ibata (then at Cambridge University, England) and his colleagues of the Sagittarius dwarf spheroidal galaxy, which currently is merging with the Milky Way (SciT May 1998, page 42). Other accretion debris is being found in our gal-

---

Chemical Signatures of Stellar Evolution

**Type II Supernova**

**Planetary Nebula**

**Type Ia Supernova (artist’s concept)**

Stars inject chemical elements into the interstellar medium when they die. Above, left: Stars packing 10 solar masses or more die abruptly as core-collapse supernovae, ejecting copious quantities of oxygen, magnesium, silicon, and sulfur—all elements built up from successively fusing alpha particles, or helium nuclei. Above, right: Relatively lightweight stars (those with 0.8 to 10 solar masses) eject their envelopes gently, forming planetary nebulae and seeding space with carbon and nitrogen. Left: White dwarfs in certain very tight binary-star systems can explode as Type Ia supernovae—our galaxy’s principal source of iron.
tracing the milky way’s history

Left: The stars whose deaths produce oxygen, magnesium, and related "alpha-particle" elements shine for only a few million years. Thus, oxygen (shown here by way of example) becomes abundant early in the galaxy’s history. Type II supernovae, by contrast, only gradually implant iron into the raw material that new generations of stars are made of. The disparate time scales shape any plot of stellar alpha-to-iron ratios versus iron abundances. Right: Because they formed shortly after a first generation of Type II supernovae sprayed oxygen into the ISM, stars in our galaxy’s bulge should have the highest oxygen-to-iron ratios. By contrast, dwarf galaxies like the Magellanic Clouds form stars very gradually, so most of their stars have a relatively enhanced iron content. Thin-disk stars near our Sun are an intermediate case.

axy’s halo in the course of several ongoing surveys. However, we must keep in mind that in the case of large spirals like ours, mergers with smaller objects are unavoidable. What we really want to know is how much of the Milky Way’s halo was formed by a fast, early collapse, and how much of it has since been assembled by accreting smaller systems.

Two very recent results challenge the primacy of mergers. The first comes from studying abundance ratios in very metal-poor stars. This has become possible only recently, thanks to very-high-resolution spectrographs such as the UVES instrument used with the Very Large Telescope, a quartet of 8-meter reflectors in Chile.

Using UVES, Roger Cayrel (Paris Observatory, France) and his many collaborators have derived the abundances of several elements for a fairly large sample of stars in which the iron abundance is \(\frac{1}{10,000}\) to \(\frac{1}{100,000}\) of the solar value. Their data, whose quality is without precedent, have revealed a striking homogeneity in the chemical properties of halo stars. This uniformity challenges the view that the whole galactic halo formed from the successive swellings of smaller stellar systems with independent evolutionary histories. Instead, it suggests that most, if not all, halo stars have precisely followed the same evolutionary pathway.

The primacy of mergers also has been challenged by astronomers who recently reported abundance-ratio measurements in stars belonging to nearby dwarf galaxies. Also using UVES and the VLT, Matthew D. Shetrone (McDonald Observatory) and five colleagues have concluded that the chemical signatures of stars in dwarf galaxies do not match those of most stars in the Milky Way’s halo: dwarf-galaxy stars show relatively low oxygen-to-iron and magnesium-to-iron abundance ratios — precisely what one would expect from systems that formed stars slowly. If the halo indeed was formed by accreting dwarf galaxies, those dwarfs must have been different from the ones we observe today.

THE BULGE. Our galaxy’s central bulge is very difficult to observe, as it is almost entirely hidden from view (especially in the visible part of the electromagnetic spectrum) by dust in the Milky Way’s midplane. However, some data have been obtained, thanks to infrared detectors. The data now available show that metal abundances range widely among bulge stars. They also show that the bulge is dominated by old stars. In fact, bulge stars seem to show oxygen-to-iron ratios greater than the Sun’s, as one would expect of systems that formed rapidly.

However, this interpretation is complicated by the existence of a bar in the inner parts of the Milky Way’s disk (September issue, page 52). Furthermore, some young stellar populations have been observed in the bulge. Some astronomers have suggested that while the bulge formed primarily in an early, fast collapse, more gas may have been pushed toward it since then by our galaxy’s bar, fueling a small but steady amount of star formation that continues today.

THE THIN DISK. Astronomers generally agree that stars began to form within the galaxy’s thin disk before it had finished growing. In fact, infalling gas may have been very important throughout the Milky Way’s history. Such material presumably has not been processed by successive generations of stars. Hence it presumably has a low, nearly primordial metallicity.

Infalling matter often has been invoked to explain the disk’s apparent shortage of stars with few heavy elements — a condition that researchers refer to the G-dearth problem. As the name suggests, G dwarfs are small stars, astronomically speaking (our Sun is one). Because they have modest masses, they fuse hydrogen into helium at modest rates and consequently can live for many billions of years. In fact, some date from the earliest stages of the Milky Way’s formation.

If the galaxy’s thin disk had maintained a constant mass from the beginning, astronomers have reasoned, then all its G dwarfs should have formed at the disk’s inception, and many of them should be metal-poor. In reality, there are relatively few metal-poor G dwarfs in our galaxy’s disk.
Infalling gas can solve the problem. If the disk began to form stars when only a small fraction of its present mass had been accumulated, only a relatively small number of its stars would form in an environment that was free of heavy elements. The heavy elements produced by this first generation of stars would be available for incorporation into the subsequent stellar generations that formed out of fresh fuel.

Using recently published G dwarf metallicity distributions, Francesca Matteucci (University of Trieste, Italy), Raffaele Gratton (University of Padua, Italy), and I have shown that the portion of the thin disk near the Sun formed as extragalactic gas fell into the Milky Way during a period that lasted about 7 billion years. Other data suggest that the inner portions of the thin disk formed earlier than the outer parts.

But where did the gas that formed (and perhaps still is forming) the thin disk come from? Some astronomers suggest that the material is simply the leftovers from the first fast collapse event that formed the halo. If so, these leftovers have taken a long time to settle into a disk because they have a lot of orbital angular momentum. Others suggest that the material is gas that was brought to our galaxy during a major impact with another large galaxy or during several mergers with small ones.

This question takes us to a completely open field that is, at the present, the focus of many hot debates among astronomers. If the outer disk indeed is still forming, as our chemical-evolution models seem to suggest, we might be able to observe infalling gas clouds right now. Suggestively, the Far Ultraviolet Spectroscopic Explorer (FUSE) spacecraft has shown that the Milky Way is surrounded by a huge, extended corona of hot gas, possibly a remnant of blobs that coalesced during the universe’s infancy. High-

---

**Milky Way Anatomy: Motion vs. Composition**

The Milky Way’s history is reflected both in the abundances of key chemical elements in stellar atmospheres and in stellar motions. (a) A star’s motion can be decomposed into a circular component (V), a radial motion within the disk (U), and a motion (W) perpendicular to our galaxy’s midplane. (b) Thin-disk stars follow nearly circular orbits, with their motions being mostly tangential; halo stars are equally likely to follow prograde or retrograde orbits and cross the midplane at high speeds. (c) These orbital distinctions are mirrored by differences in iron content, with halo stars being the most metal-poor, as if they formed from relatively primordial material. (d) The galaxy’s varied stellar populations also differ in their alpha-to-iron ratios, where “alpha” means oxygen and other elements built by core-collapse supernovae. Together these trends suggest that the Milky Way’s halo stars formed well before those in the thin disk, with the thick disk being intermediate.
velocity clouds (HVCs), patches of hydrogen gas that radio astronomers have seen falling into the galactic disk, could also be evidence for a slow buildup.

However, the origins of both the HVCs and the hot gas found by FUSE are still matters of debate. While some of their properties suggest that they could account for the infalling material we are talking about, others indicate that they are related to "galactic fountain" processes. In the galactic-fountain picture, supernova explosions within the disk blast out material, some of which now is falling back toward the disk in the form of HVCs. One very recent FUSE study supports the infall scenario. A large team led by Kenneth R. Sembach (Space Telescope Science Institute) measured a primordial deuterium-to-hydrogen ratio in an HVC complex that is falling onto the Milky Way.

**The Thick Disk.** If you haven't heard of our Milky Way's thick disk yet, don't feel bad: its existence was confirmed only in 1983, by Gerard F. Gilmore (Cambridge) and J. Neill Reid (now at the Space Telescope Science Institute).

The thick disk differs from the thin disk in a number of ways. The stars belonging to the thick disk tend to revolve around the galactic center, but not as rapidly as the thin-disk stars do. The thick disk is roughly two to four times thicker than the thin disk. Moreover, the metallicity distribution of thick-disk stars is intermediate between that of the thin disk and that of the halo. Finally, the stars constituting the thick disk are quite old—they can be as old as the younger halo stars (around 12 billion years).

Before accurate kinematic data enabled them to distinguish thin- and thick-disk stars, astronomers commonly thought that the thick disk was simply a transition population of stars whose properties bridged those of the stars making up the halo and the thin disk, respectively. But recent studies that combine kinematic and abundance data suggest that the two disks are discrete components that formed at different epochs and on different time scales. Intriguingly, Julianne Dalcanton (University of Washington) and Rebecca A. Bernstein (University of Michigan) have just discovered that the respective formation processes of the thick and thin disks are largely decoupled in other galaxies: the two components differ in age and shape within each of the edge-on spirals they scrutinized.

**Putting the Pieces Together.** In 1996 Gratton and his collaborators found compelling evidence that star formation came to a halt sometime between the halo and the thin-disk phases. Influenced by this finding and others like it, Gratton, Matteucci, and I proposed a "two infall model" for our galaxy's construction (see the top of the facing page). In our model, a first gaseous infall event gave  

---

The material out of which stars formed can be characterized by chemical-abundance ratios, themselves derived from spectra of those stars. (The ratios have been divided by the Sun's values throughout this article.) The curves running through the data points show predictions made by the author's model for our galaxy's formation. Left: Oxygen is formed in Type II supernovae, many of which exploded before Type Ia supernovae were able to inject iron into the interstellar medium. Right: Carbon is formed both by rapidly evolving Type II supernovae and by slowly evolving red giants, which contributed chemical elements to the interstellar medium long after the Milky Way's birth.
Above: Author Cristina Chiappini and her colleagues have proposed a two-infall model for the Milky Way's evolution. In this model, a primordial gas cloud's rapid collapse — the first infall event — creates the bulge and the halo. The first generations of stars explode as Type II supernovae within the bulge and the halo, quickly injecting heavy chemical elements (or "metals") into the formative galaxy. The thin disk grows from the inside out during a prolonged second infall event, as gas with a relatively primordial composition slowly accretes from beyond the Milky Way and mixes with the galaxy's interstellar medium, itself now enriched by both Type II and Type Ia supernovae.

Right: Evidence that our galaxy's disk has grown slowly, by gradually accreting gas and converting it into stars: late-type dwarf stars (K dwarfs are shown here) have higher metallicities than one would expect if they all formed early in our galaxy's history, before Type Ia supernovae had had time to inject iron into the interstellar medium. The bar chart shows iron-to-hydrogen measurements for nearby stars, while the two bell curves show predictions from a disk-building infall event lasting 2 billion years and one lasting 7 billion years.
rise to the inner halo, the thick disk, and the bulge. A second, completely distinct infall episode then formed the thin disk (and it may still be doing so today).

The inner halo formed within at most 1 billion years, we conclude, while the outer halo and the thick disk may have formed more slowly—albeit much more rapidly than the thin disk. Meanwhile, the outer halo and the thick disk may have gained some (but probably not most) of their stars from accreted dwarf galaxies.

Klaus Fuchs (Max Planck Institute for Extraterrestrial Physics, Germany) and his colleagues recently used the relative abundances of magnesium (like oxygen, a product of core-collapse supernovae) and iron to conclude that star formation ceased for a few billion years. In order to explain this gap, our model posits that stars stop forming whenever the gas density falls below a certain critical value. This seems to have happened after the thick disk formed.

Once star formation resumed, the thin disk formed slowly, mostly from gas that came from beyond the Milky Way. It also formed from the inside out, which explains why the metallicity of its innermost regions exceeds that of its outer edge—a trend that has been seen in essentially all spiral galaxies for which the relevant data exist.

On the Cusp of Discovery

As our tour makes clear, many new observations suggest that the Milky Way (and galaxies like it) formed in ways that are much more complex than envisioned in decades past. A full understanding of our galaxy's evolution remains elusive. Nevertheless, we have been able to reach important conclusions, largely by studying the chemical properties of successive stellar generations.

But we still are missing many of the pieces needed to complete the puzzle of galaxy formation. Some questions will be answered with telescopes even larger than those available today. Such telescopes will be able to chemically "fingerprint" very faint stars in our galaxy's halo and bulge.

However, to take in the whole galaxy-formation show one needs not only large "eyes" but eyes that are sensitive to a far wider slice of the spectrum than the narrow spectral rainbow called visible light. And while important clues already have been garnered with the Hubble Space Telescope, FUSE, and the Chandra X-ray Observatory, many other projects are poised to improve upon our understanding.

For instance, the Spitzer Space Telescope and Galaxy Evolution Explorer are now gathering data in the near-infrared and ultraviolet regions of the spectrum, respectively. Together, these spacecraft will provide a comprehensive view of star formation in other galaxies. Spitzer will also be able to unveil secrets contained in our own Milky Way's dust-cloaked starbirth regions.

Those of us who study our home galaxy are eagerly looking forward to the launch of the European Space Agency's Gaia spacecraft. With Gaia, we finally will be able to travel beyond our Sun's galactic neighborhood to get, for the first time, chemical abundances throughout the disk and the halo. Along with the precise proper motions and radial velocities that Gaia also will provide, these abundance measurements will enable us to take an enormous step forward in understanding how the Milky Way formed. Furthermore, by answering many of the still-open questions about the Milky Way's formation, we will be able to provide a framework for understanding how other galaxies have evolved throughout space and time.

By bringing radio waves to a focus with its gargantuan 100-by-110-meter "dish," the Green Bank Telescope recently revealed a swarm of diffuse clouds of hydrogen gas (shown in red in this false-color image) attending the Andromeda Galaxy, M31 (whose own much denser hydrogen gas, mapped with other instruments, is color-coded blue). This suggests that our Milky Way is not the only hefty spiral to fuel ongoing star formation by drawing in gas from beyond its borders.