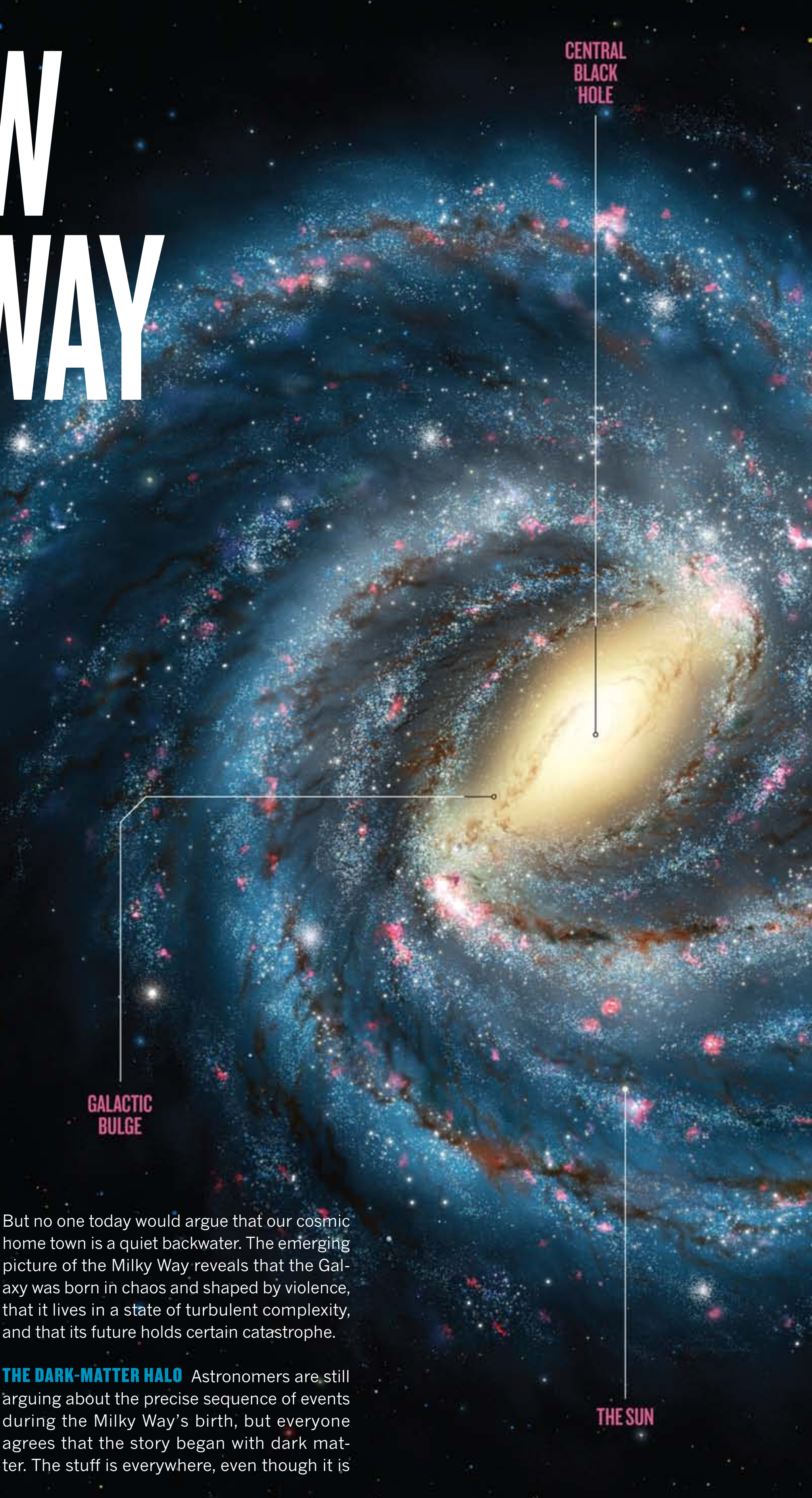
THE NEW MILKY WAY

A FRESH LOOK AT OUR GALAXY POINTS TO A CHAOTIC PAST AND A VIOLENT END.

BY ANN FINKBEINER



Arcing across the night sky is a pale band of light the Romans called the *via lactea* — the Milky Way. Astronomers have known since the 1920s that this band is an edge-on view of the Galaxy in which we live: a vast pinwheel teeming with nebulae, gas clouds and billions upon billions of stars. For most of the nine decades since, astronomers also thought that our Galaxy and others like it were rather quiet places: ponderous, slowly rotating structures that formed many eons ago and had settled into uneventful middle age.

But then they began to see the Milky Way with fresh eyes (see 'Galactic portrait'). Starting in the 1970s and 1980s, new generations of ground- and space-based telescopes began mapping the Milky Way at wavelengths ranging from microwaves to X-rays, revealing an unimagined richness. By the 2000s, systematic observing programmes were tracing galactic structures that sprawl across most of the heavens, and are so big that no one had noticed them before. By the present decade, teams of astronomers were racing to build ever-more powerful computer simulations to model the origins of galaxies on every scale from cosmos to star clusters. And by next year, the Atacama Large Millimeter/Submillimeter Array (ALMA) in Chile will be mapping the Galaxy at unprecedented levels of detail.

Astronomers are still struggling to assimilate all this new information. Disagreements, uncertainties and unanswered questions abound. But no one today would argue that our cosmic home town is a quiet backwater. The emerging picture of the Milky Way reveals that the Galaxy was born in chaos and shaped by violence, that it lives in a state of turbulent complexity, and that its future holds certain catastrophe.

THE DARK-MATTER HALO Astronomers are still arguing about the precise sequence of events during the Milky Way's birth, but everyone agrees that the story began with dark matter. The stuff is everywhere, even though it is

GALACTIC PORTRAIT
This artist's impression, based on the latest data from telescopes and simulations, shows the Milky Way viewed from outside the Galaxy.

ILLUSTRATIONS BY LYNETTE COOK

invisible and no one yet knows what it is. It outweighs ordinary matter — stars, gas and everything else made of atoms — by a factor of about five, and yet can be detected only through its gravitational pull on visible stars and galaxies. Astronomers have known since the 1970s that the Milky Way, like every other galaxy, is wrapped in a vast cocoon of dark matter; without it, the gravity generated by ordinary matter would be nowhere near enough to hold the Galaxy together.

In the immediate aftermath of the Big Bang, some 13.7 billion years ago, gravity caused tiny irregularities in the dark matter to grow, forming denser and denser clumps on every size scale. Simulations show that this clumping process invariably becomes a chaos of collisions and mergers. But within a billion years of the Big Bang things settle down slightly, and some of the dark-matter clumps begin to look much like the one that surrounds the Milky Way: a roughly spherical halo several hundred kiloparsecs (1 kiloparsec is about 3,200 light-years) across, with a mass of about 10^{12} times that of the Sun, and a multitude of subhalos all the way down to the mass of Earth.

Inside this halo was a thin haze of primordial hydrogen and helium gas that got pulled along by the dark matter's gravity. After a few hundred million years, as this gas cooled and condensed enough to start forming stars, it would become the raw material from which our Galaxy was created. But modelling that process is anything but simple. "Dark matter answers only to gravity and we understand gravity," says Piero Madau, an astronomer at the University of California, Santa Cruz. But marshalling ordinary matter into today's galactic structure involved collisions, dissipations, cooling, heating and explosions. "It's very complicated," says Madau.

DWARF GALAXIES One complication involves those dark-matter subhalos. Above a certain mass, yet to be determined, they would have pulled in enough gas to form stars and become dwarf galaxies — irregular aggregations of stars and gas with roughly 1% the mass of the modern Milky Way. But if that were the case, the Milky Way ought to have thousands of dwarf galaxies in orbit around it. So far, observers have found some two dozen.

One possible explanation for this discrepancy is that there are many more dwarf galaxies, but they are vanishingly faint because they contain unusually high amounts of dark matter. The dwarf galaxy Segue 1, for example, has a thousand times more dark than shining matter[1].

"We are very, very interested in finding those vanishingly faint ones," says Connie Rockosi, an astronomer at the University of California, Santa Cruz, "because they tell us the threshold mass below which dark-matter subhalos don't form stars and host galaxies at all." Another possibility is that some subhalos are too small to have ever formed stars, and so are completely dark. Finding such a galaxy-less clump of dark matter means looking for its gravitational effect on nearby dwarf galaxies or on streams of stars, and the signatures of such effects haven't yet been convincingly seen. "We'd love to find a dark-matter subhalo without a galaxy in it," says Rockosi. "That's high up on the list of things I hope I see."

Still another possibility is that many more dwarf galaxies did form, but the first generation of stars were all so massive, hot and explosive that they blasted all the gas and stars out of all but the largest subhalos[2].

THE STELLAR HALO Either way, creation of the Galaxy continued apace, with gas and dwarf galaxies swirling inwards towards an ever-increasing mass of gas and stars accumulating at the dark-matter halo's centre: the proto-Milky Way. The dwarf galaxies were "whizzing all over the place", says Heather Morrison, an astronomer at Case Western Reserve University in Cleveland, Ohio. "Things were just a mess." Inevitably, some of them would have got too close to the ever-growing core and been pulled apart by its gravity.

The region just outside today's Milky Way seems to be laced with remnants of such events: distinct streams of stars that loop around the galaxy along the dwarf galaxy's original orbit. These streams are tricky to identify, because they are faint and extend across much of the sky. But teams of observers are finding more and more of them. In at least one case, that of the Sagittarius dwarf galaxy and its associated star stream, observers have found a dwarf galaxy in the act of disintegrating[3].

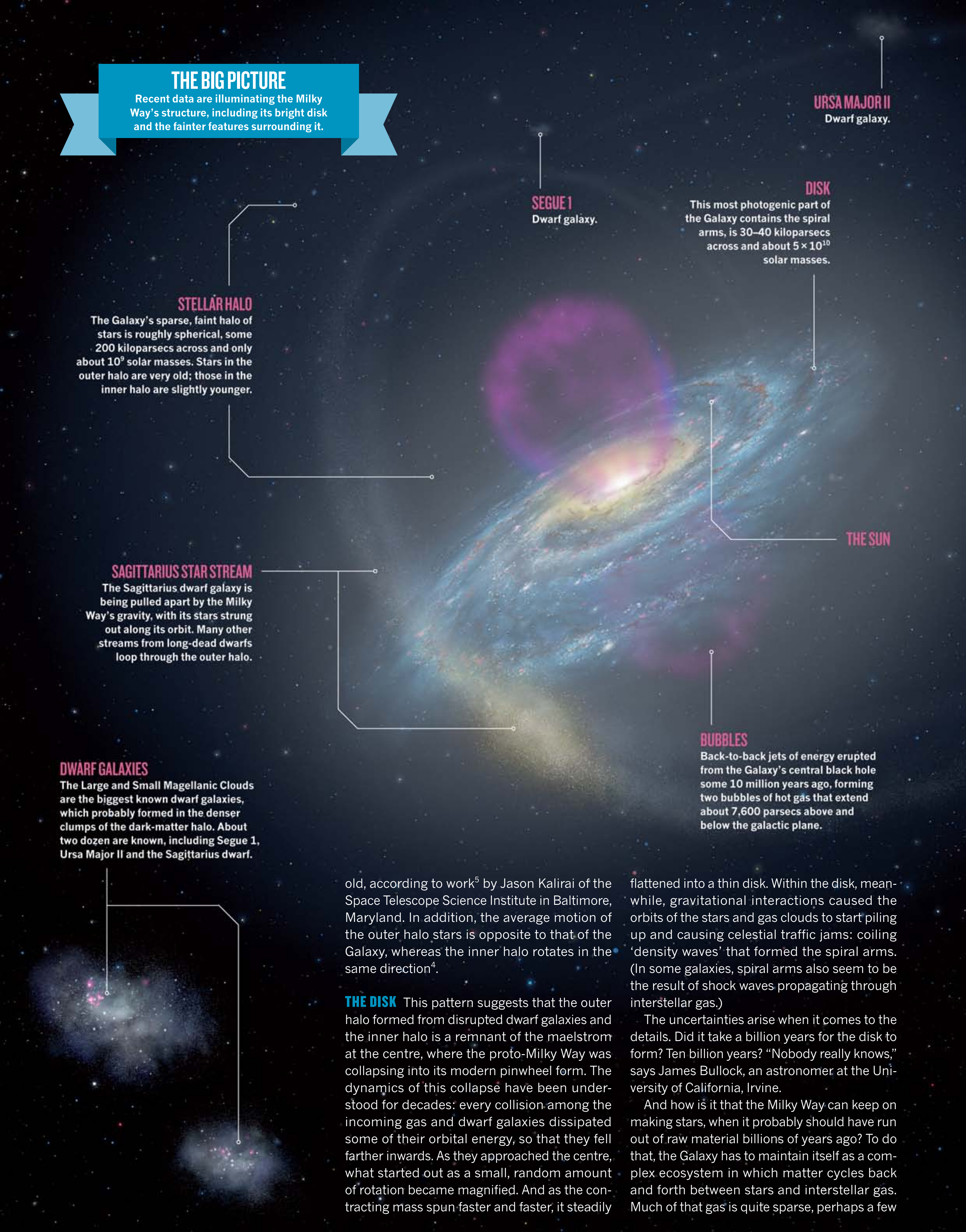
These streams thread through a faint, diffuse halo of stars that extends outwards from the Milky Way perhaps 100 kiloparsecs in every direction, forming a rough sphere with a total mass of about 10^9 times that of the Sun (see 'The big picture'). This stellar halo may be nothing more than the remnant of all the dwarf galaxies that got disrupted over billions of years. But the story may be a little more complicated than that.

In 2007, a team led by Daniela Carollo, now at Macquarie University in Sydney, Australia, and Timothy Beers, now director of the Kitt Peak National Observatory in Tucson, Arizona, confirmed earlier hints that the stellar halo is divided into inner and outer components[4]. Stars in the outer halo generally have spectra showing only trace amounts of heavy elements such as iron. This suggests that these stars are only one generation removed from the very first stars to form in the Universe, less than a billion years after the Big Bang. If nothing else, this means that the precise distribution of heavy elements in the outer halo should give astronomers a record of what those long-vanished first stars were like.

The stars in the inner halo contain higher amounts of heavy elements, and are somewhat younger — only about 11.4 billion years

THE BIG PICTURE

Recent data are illuminating the Milky Way's structure, including its bright disk and the fainter features surrounding it.



URSA MAJOR II
Dwarf galaxy.

SEGUE 1
Dwarf galaxy.

DISK
This most photogenic part of the Galaxy contains the spiral arms, is 30–40 kiloparsecs across and about 5×10^{10} solar masses.

STELLAR HALO
The Galaxy's sparse, faint halo of stars is roughly spherical, some 200 kiloparsecs across and only about 10^9 solar masses. Stars in the outer halo are very old; those in the inner halo are slightly younger.

THE SUN

SAGITTARIUS STAR STREAM
The Sagittarius dwarf galaxy is being pulled apart by the Milky Way's gravity, with its stars strung out along its orbit. Many other streams from long-dead dwarfs loop through the outer halo.

BUBBLES
Back-to-back jets of energy erupted from the Galaxy's central black hole some 10 million years ago, forming two bubbles of hot gas that extend about 7,600 parsecs above and below the galactic plane.

DWARF GALAXIES
The Large and Small Magellanic Clouds are the biggest known dwarf galaxies, which probably formed in the denser clumps of the dark-matter halo. About two dozen are known, including Segue 1, Ursa Major II and the Sagittarius dwarf.

old, according to work[5] by Jason Kalirai of the Space Telescope Science Institute in Baltimore, Maryland. In addition, the average motion of the outer halo stars is opposite to that of the Galaxy, whereas the inner halo rotates in the same direction[4].

THE DISK This pattern suggests that the outer halo formed from disrupted dwarf galaxies and the inner halo is a remnant of the maelstrom at the centre, where the proto-Milky Way was collapsing into its modern pinwheel form. The dynamics of this collapse have been understood for decades: every collision among the incoming gas and dwarf galaxies dissipated some of their orbital energy, so that they fell farther inwards. As they approached the centre, what started out as a small, random amount of rotation became magnified. And as the contracting mass spun faster and faster, it steadily flattened into a thin disk. Within the disk, meanwhile, gravitational interactions caused the orbits of the stars and gas clouds to start piling up and causing celestial traffic jams: coiling 'density waves' that formed the spiral arms. (In some galaxies, spiral arms also seem to be the result of shock waves propagating through interstellar gas.)

The uncertainties arise when it comes to the details. Did it take a billion years for the disk to form? Ten billion years? "Nobody really knows," says James Bullock, an astronomer at the University of California, Irvine.

And how is it that the Milky Way can keep on making stars, when it probably should have run out of raw material billions of years ago? To do that, the Galaxy has to maintain itself as a complex ecosystem in which matter cycles back and forth between stars and interstellar gas. Much of that gas is quite sparse, perhaps a few

hundred atoms per cubic metre, and, thanks to ultraviolet light from stars, it drifts through the disk in a hot, ionized form. But in the 1970s, astronomers discovered that sometimes, for reasons that still aren't completely clear, the gas can gather itself into clouds so dense that their interiors are shielded from starlight. The gas on the inside can get as cold as 10–30 K, allowing atoms in the gas to form molecules such as molecular hydrogen and carbon monoxide; thus the name 'molecular clouds'. But because of gravity, this density also brings instability. No sooner do the molecular clouds form than their thickest clumps collapse, heating up and igniting by thermonuclear fusion to become stars.

These star-forming regions of the clouds, often called the Galaxy's stellar nurseries, are tumultuous: newborn stars eject matter in the form of fierce stellar winds, along with floods of ultraviolet radiation. The most massive of them also quickly die in supernova explosions; others end their lives by expanding into red giants and shedding their outer layers. All of these processes blast gas back into the wider galaxy, where it will eventually cool, condense and start the cycle again.

The problem is that the Milky Way turns gas into stars at the rate of a few solar masses every year, a pace that by now should have used up all the available gas. But the Galaxy has been forming stars for at least the past 10 billion years. "It's got to get gas from somewhere," says Ken Freeman of the Australian National University in Canberra.

That somewhere may be an outside reservoir: a halo of gas that's been observed in X-ray and extreme-ultraviolet wavelengths surrounding the Milky Way's stellar halo[6,7]. Such reservoirs of gas have also been seen around other galaxies[8]. It is mostly ionized hydrogen at maybe 1,000,000 K, and extends a few hundred kiloparsecs from the centre. It is low density, around a hundred hydrogen atoms per cubic metre, but so large that its mass should be at least that of all the stars in the Galaxy — "a terrific reservoir", Freeman says, "and just a little of it coming in would kick off star formation" for billions of years.

If halo gas does cool and condense enough to fall into the Galaxy — "like dew settling out of a fog", says David Weinberg of Ohio State University in Columbus — it may give rise to what observers see as high-velocity clouds[9], falling towards the disk. These clouds, in turn, may be related to the 'fountains' that result when stars explode into supernovae and kick gas 10–100 kiloparsecs out of the disk[10]. The theory is that the fountains soar up into the gas halo, pick up some of the ionized gas, and fall back towards the disk as high-velocity clouds. "We see stuff going out and stuff coming in," says Weinberg, "but we don't know if they're the same things."

THE BULGE AND BAR At the Galaxy's centre, roughly 8 kiloparsecs from Earth, is the bulge: a collection of mostly elderly stars, around 10 billion years old, arranged in a sphere holding around 10^{10} solar masses. Bisecting the bulge is a roughly linear 'bar' of younger stars some 2–4 kiloparsecs long. Its origins are a matter of debate, but similar features are commonly seen in other 'barred' spiral galaxies.

And at the heart of the bulge is an enormous black hole, which sits at the precise centre of the Galaxy. At 4 million solar masses, our local black hole is on the small side as such objects go: most galaxies seem to have one, and they often reach billions of solar masses. Ours also happens to be inactive at present — that is, nothing is falling into it.

> "IN THE UNIVERSE, STAR FORMATION IS GRADUALLY SHUTTING DOWN AND THE DEAD ARE BUILDING UP."

It was once livelier. In 2010, Douglas Finkbeiner (no relation to this writer) at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, found two bubbles on either side of the bulge and perpendicular to the disk[11]. The bubbles were each 7,600 parsecs long and outlined by X-ray emissions; shooting into them from the galactic centre were small, faint γ-ray jets. Both bubbles and jets are signatures of an active black hole, formed when matter falling into the black hole sends out jets of energy and creates shockwaves in the surrounding gas. Active black holes in the centres of galaxies are fairly common and are probably a stage through which all galaxies pass. Finkbeiner estimates that the Milky Way's black hole was active somewhere around 10 million years ago, and probably at intervals before that too. "The black hole didn't get to be 4 million solar masses if nothing fell into it," he says.

THE FUTURE Observers have known for decades that the nearest large galaxy, the spiral M31 in the constellation Andromeda, is heading towards the Milky Way. But they didn't know whether a collision was inevitable because they hadn't been able to measure its movement sideways across the sky — a quantity known as 'proper motion'. In May, Roeland van der Marel at the Space Telescope Science Institute and his colleagues compared Andromeda's position over time with background galaxies, and measured its proper motion to an accuracy of 11 microarcseconds per year[12–14] — roughly equivalent to watching human fingernails grow from the distance of the Moon. They found that Andromeda and the Milky Way — now about 770 kiloparsecs apart and moving towards each other at 109 kilometres per second — will collide head on in about 6 billion years. They will then pass through each other and mutually orbit until, at 7 billion years, the two spiral galaxies will merge to form one elliptical galaxy.

Ellipticals are one of the two main shapes of galaxy. In contrast to the lively spiral galaxies, which tend to be actively forming stars, the ellipticals are more like featureless blobs containing little gas and few new stars. Oddly, only a minority of galaxies seem to be in transition; on the whole they're either lively or quiescent. Theorists' best explanation for this is that the merger between two big galaxies leads to a burst of star formation, which quickly uses up the available gas. Or maybe the merger reactivates the black holes in the galaxies' centres, and the resulting high-energy shocks and jets either drive the gas out of the galaxies or keep the gas stirred up and so hot that it can't form stars. One way or another, says Tim Heckman of Johns Hopkins University in Baltimore, Maryland, "infalling gas is cut off and the galaxy uses up the gas it's got".

The Universe holds only so much gas, and sooner or later — maybe as long again as galaxies have already existed — galaxies will have converted all their gas into stars. In the Universe, "star formation is gradually shutting down", says Heckman, "and the dead are building up". Little stars, one-tenth of a solar mass, can live quietly for a trillion years. But even they will eventually burn out — and that will be it. The end. ■

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