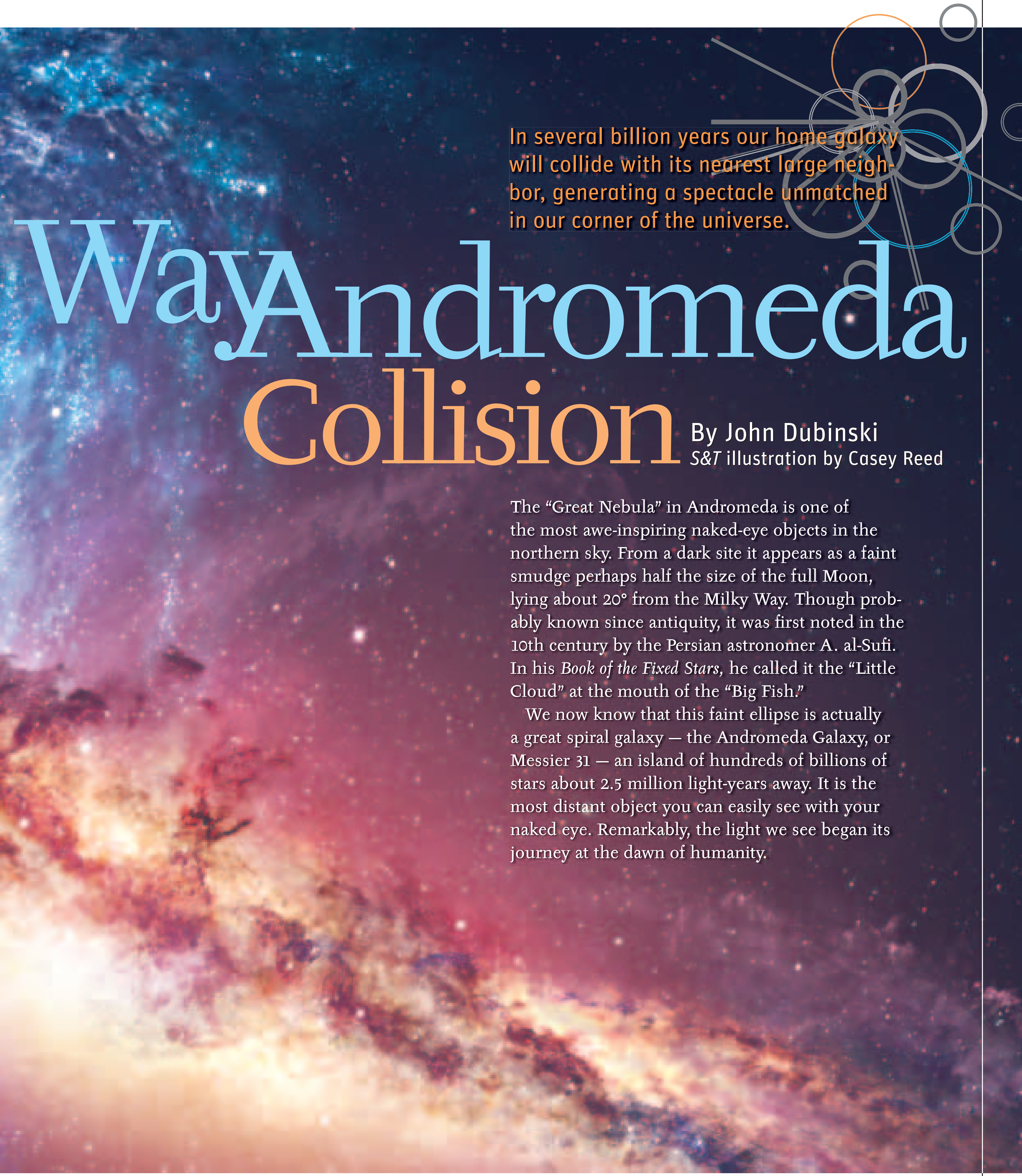

the great
Milky



In several billion years our home galaxy will collide with its nearest large neighbor, generating a spectacle unmatched in our corner of the universe.

Way Andromeda Collision

By John Dubinski
S&T illustration by Casey Reed

The "Great Nebula" in Andromeda is one of the most awe-inspiring naked-eye objects in the northern sky. From a dark site it appears as a faint smudge perhaps half the size of the full Moon, lying about 20° from the Milky Way. Though probably known since antiquity, it was first noted in the 10th century by the Persian astronomer A. al-Sufi. In his *Book of the Fixed Stars,* he called it the "Little Cloud" at the mouth of the "Big Fish."

We now know that this faint ellipse is actually a great spiral galaxy — the Andromeda Galaxy, or Messier 31 — an island of hundreds of billions of stars about 2.5 million light-years away. It is the most distant object you can easily see with your naked eye. Remarkably, the light we see began its journey at the dawn of humanity.

This little cloud of light connects us to our past, but it also binds us to our future. Indeed, the fate of the entire Milky Way Galaxy, and perhaps Earth itself, may be intertwined with Andromeda. The latest astronomical evidence strongly suggests that the two giant spiral galaxies in our Local Group are on a collision course, with a merger possibly occurring even before our Sun expands into a red giant.

> Forget the scorched Earth. How about something even bigger, such as the mutual destruction of the Milky Way and Andromeda?

Collision Course

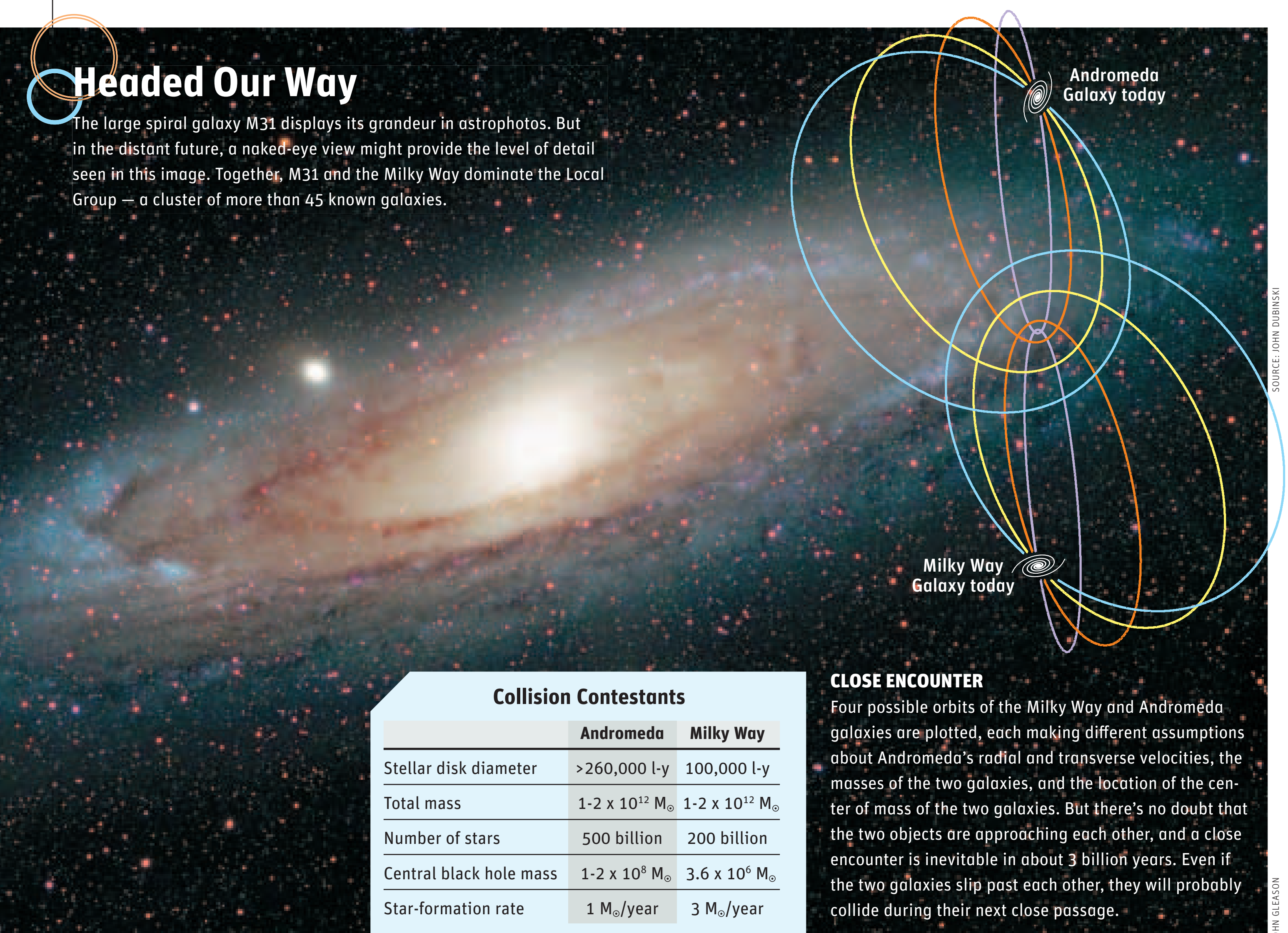
The discovery of Cepheid variable stars in M31 enabled Edwin Hubble to measure the vast distance to our sister spiral, and from that steppingstone he later established the expanding universe. But Andromeda, along with a handful of lesser galaxies in our Local Group, defies Hubble's law of cosmic expansion. Although distant galaxies recede with velocities proportional to their distances, Andromeda and a few neighbors are actually falling *toward* us. After correcting for the Sun's orbital motion around the galactic center, Andromeda is approaching the Milky Way with a speed of about 120 kilometers (75 miles) per second.

Franz Kahn and Lodewijk Woltjer realized this unexpected state of affairs in 1959 and made the bold suggestion that perhaps Andromeda and the Milky Way are in fact gravitationally bound, forming a binary galaxy system. They argued that the two galaxies were born close together soon after the Big Bang and initially moved apart due to cosmic expansion. The two stellar congregations have since started moving toward each other because of their mutual gravitational attraction.

If the galaxies follow a highly eccentric orbit like most comets, then given M31's known distance and relative speed, along with the universe's 13.7-billion-year age, astronomers can calculate the orbit, and most important, the total mass. This set of assumptions and the resulting calculation is known as the *timing argument* and gives the very large combined sum of 4.7 trillion solar masses. Kahn and Woltjer reasoned that there had to be an extra source

Headed Our Way

The large spiral galaxy M31 displays its grandeur in astrophotos. But in the distant future, a naked-eye view might provide the level of detail seen in this image. Together, M31 and the Milky Way dominate the Local Group — a cluster of more than 45 known galaxies.



CLOSE ENCOUNTER

Four possible orbits of the Milky Way and Andromeda galaxies are plotted, each making different assumptions about Andromeda's radial and transverse velocities, the masses of the two galaxies, and the location of the center of mass of the two galaxies. But there's no doubt that the two objects are approaching each other, and a close encounter is inevitable in about 3 billion years. Even if the two galaxies slip past each other, they will probably collide during their next close passage.

Collision Contestants

	Andromeda	Milky Way
Stellar disk diameter	>260,000 l-y	100,000 l-y
Total mass	1-2 x 10^{12} $M_\odot$	1-2 x 10^{12} $M_\odot$
Number of stars	500 billion	200 billion
Central black hole mass	1-2 x 10^{8} $M_\odot$	3.6 x 10^{6} $M_\odot$
Star-formation rate	1 $M_\odot$/year	3 $M_\odot$/year

All figures are uncertain; l-y = light-years; $M_\odot$ = solar masses.

of mass surrounding the galaxies, since stars, gas, and dust could account for only about a tenth of this amount. This was the first evidence for dark matter within the Local Group. Kahn and Woltjer's estimate based on the simple timing argument was remarkably close to modern values of around 3 trillion solar masses determined by analyzing the motions of satellite galaxies around the Milky Way and M31 (August issue, page 22).

Modern-day astronomers can carry the timing argument one step further. Andromeda is incoming, but when will it hit? The orbital solution (which assumes an eccentric orbit) predicts a head-on collision just over 3 billion years from now. That may seem like a long way off, but it still squeaks in before another impending deadline — the death of our Sun. The Sun is a G2 dwarf with a main-sequence lifetime of about 10 billion years. Given that it's already nearly 5 billion years old, it has only 5 billion years to go before it swells into a red giant and roasts Earth.

But forget the scorched Earth. How about something even bigger, such as the mutual destruction of the Milky Way and Andromeda?

Astronomers can't determine the timing of this grand collision with any precision, but it will almost certainly happen eventually. The assumption of an eccentric orbit and head-on collision depends on Andromeda having no appreciable proper motion, or transverse (sideways) velocity. If M31 has an appreciable transverse motion, the two galaxies might miss one another by a few hundred thousand light-years, but the loss of orbital energy during the close encounter will make a head-on collision likely during a second pass a few billion years later.

Since the introduction of the timing argument, astronomers have modeled the motions of Local Group galaxies. When taking into account the gravitational pull of other Local Group members, as well as the tidal influence of nearby groups, they estimate the transverse velocity of Andromeda to range somewhere between 0 and 150 km per second, corresponding to a tiny proper motion of 0 to 42 microarcseconds per year. NASA's Space Interferometry Mission or the European Space Agency's Gaia mission might detect this motion in a decade, but for now it remains unknown. For the time being, a near head-on collision between the Milky Way and Andromeda is a distinct possibility well before Earth's ultimate doom.

Galaxies in Collision

The future Milky Way–Andromeda collision is hardly a surprise, given that astronomers see merging galaxies near and far. It is not a particularly common event at the current time, with perhaps one out of every few hundred large galaxies in the nearby universe participating in a major collision. But if we look further back in time, the incidence of colliding galaxies increases dramatically. In the current picture, small blobs of gas and dark matter condensed from the primordial density fluctuations in the early universe and merged with one another to build up larger structures that eventually became galaxies. The collision and merging process remains the driving mechanism behind the birth and evolution of galaxies.

The Milky Way–Andromeda merger is just another step

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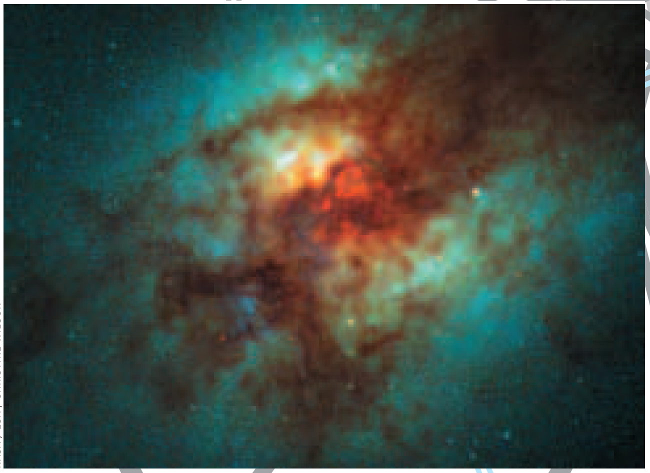

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Top: Collisions between large galaxies are rare in the modern-day universe as cosmic expansion tries to push galaxies apart. But as this Hubble Space Telescope image of NGC 4676 ("The Mice") shows, the mutual gravitational interaction of two neighboring large galaxies can overcome cosmic expansion and bring them together in titanic collisions. These colliding galaxies, 300 million light-years away in Corvus, display pronounced tidal tails. *Center:* When the Milky Way and M31 merge, the center of the new galaxy will likely resemble the dusty nucleus of Arp 220 in Serpens, seen in this Hubble image. More than 200 giant young star clusters that formed from the merger appear as blue-white dots, a result of the galaxy's 250-million-light-year distance. *Bottom:* The end product of the Milky Way–M31 merger will probably be an elliptical galaxy similar to NGC 5128 (also known as Centaurus A). This image, from the 4-meter Blanco telescope in Chile, has been computer processed to bring out detail, particularly in the dark dust lane and blue tidal arcs that are remnants of a cannibalized smaller galaxy.

in the ongoing process of structure formation. In fact, though we usually view a galaxy collision as a destructive event, it's more correctly viewed as a transformation. Computer simulations clearly show that the merger of two spirals inevitably leads to the formation of an elliptical galaxy. Although there is still some debate as to whether all elliptical galaxies form this way, some most certainly do.

Astronomers have been fascinated for decades with galaxy collisions and how they influence galaxy and cosmic evolution. In the early 1970s, various studies showed that the long filaments of stars observed in close pairs of galaxies originate naturally through gravitational tidal interactions. Brothers Alar Toomre (MIT) and Juri Toomre (now at the University of Colorado), who helped pioneer this research, called these structures tidal tails and bridges.

Their work shows how these filaments form. In an isolated spiral galaxy, the central gravitational force has just the right strength to keep stars on circular paths, maintaining the disk's shape. But when two galaxies come close together, their tidal forces are strong enough to overwhelm the central forces so that stars on opposite sides of each galaxy are launched outward like a volley of rocks released from a billion slingshots. The details depend somewhat on the orientations of the two galaxies during the collision, but the general result is the production of an open, two-armed spiral pattern.

In models, spiral galaxies consisting only of stars merge relatively quickly (within one orbit) and settle into a configuration looking remarkably like an elliptical galaxy. It may seem counterintuitive, but individual stars do *not* collide during these mergers because stars are tiny compared to the distances between them. The two galaxies pass right through each other like ghosts in the night. Complex gravitational interactions redistribute the energy in such a way that the two galaxies eventually merge into one.

But about 10% of a real spiral galaxy's mass is in the form of gas, and that fraction was probably higher early in its history. When modelers added gas to their simulations, they found that it would sink quickly to the merged galaxy's core and lead to an intense burst of star formation. The predications are in close accord with starbursts in merging galaxies, such as Arp 220 in Serpens.

Large galaxies also contain supermassive black holes in their centers. During a merger, the two black holes sink to the center of the newly formed elliptical, creating a tight binary that loses orbital energy as the pair gravitationally flings passing stars into higher orbits. When the black holes come within a light-year of each other they are destined to merge through the emission of gravitational waves (August issue, page 16). Gas dumped onto the new monster black hole can form an accretion disk that shines as an incredibly luminous quasar or a more modest active nucleus (July issue, page 40). All of these amazing phenomena will occur when the Milky Way and Andromeda merge, and the Sun will have to ride it out.

To explore the details of this scenario, we must build a model. About a decade ago, Chris Mihos (Case Western Reserve University), Lars Hernquist (Harvard-Smithsonian Center for Astrophysics), and I constructed a simple model of the Milky Way–Andromeda system built out of particles

DANIEL VERSCHATSE

BRAD WHITMORE / STScI / NASA (3)

that represent stars and dark matter as points of mass. Our goal was to investigate the properties of tidal tails. These models incorporated the current distance, relative radial velocity, and orientations of the two galaxies, as well as a low transverse velocity of 20 km per second in the direction of galactic rotation. These conditions permit a close encounter that will produce tidal tails.

Over the years, I have played with this model whenever new supercomputing facilities became available, partly as a test problem to break in new machines and new software, but mainly for fun. Simulations have grown in size from about 30,000 particles in the mid-1990s to 300 million in the calculation described in this article. Below I outline a plausible scenario resulting from our model and visualized from Earth's perspective.

> In that event, all that remained of human civilization would cross into oblivion, leaving behind one final remnant of our existence: a feeble hiccup of gravitational radiation dispersing through the cosmos at the speed of light.

Apocalypse How

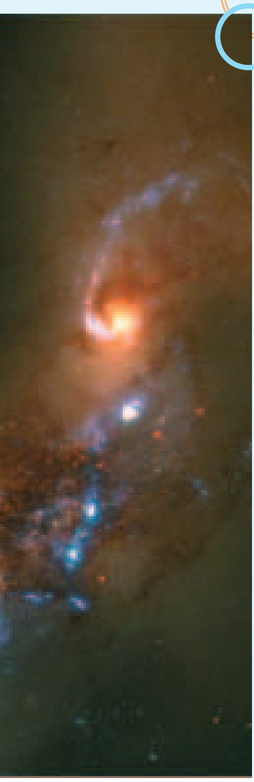
As the Sun proceeds on its orbit around the galactic center, and as our galaxy approaches M31, the night sky will continually morph. Since the Sun's orbit is roughly circular, the familiar arch of the Milky Way will not change significantly. But al-Sufi's Little Cloud will grow into a Big Cloud, and any skywatchers will enjoy their first close-up view of another galaxy filling the sky (July issue, page 108). It will have the same gossamer texture as the Milky Way, but its bulge and spiral pattern will be readily apparent.

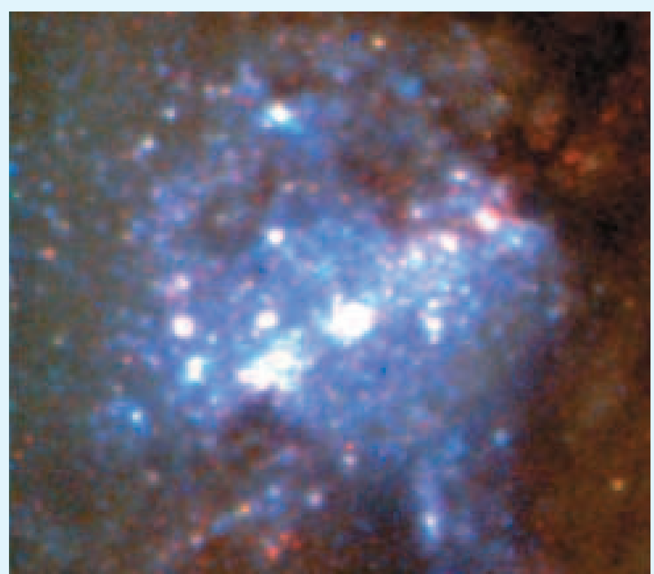
As the two galaxies overlap in about 3 billion years, Andromeda will tip edge-on from our perspective and form an interstellar intersection of two apparent Milky Ways in the night sky. Andromeda will then recede, but the strong tidal interaction will produce a two-armed spiral pattern and extended tidal tails, like those we see in the Antennae (NGC 4038 and NGC 4039 in Corvus). The pull of the Milky Way's dark halo will reduce Andromeda's orbital energy, limiting how far it can recede to a few hundred thousand light-years. M31 will then fall in for a second pass within a few hundred million years. This time the collision will be nearly head-on, and the two galaxies will undergo a final spasm of quick, convulsive encounters over 100 million years until they finally merge into a single elliptical galaxy, surrounded by fine shells, ripples, and two extended tidal tails.

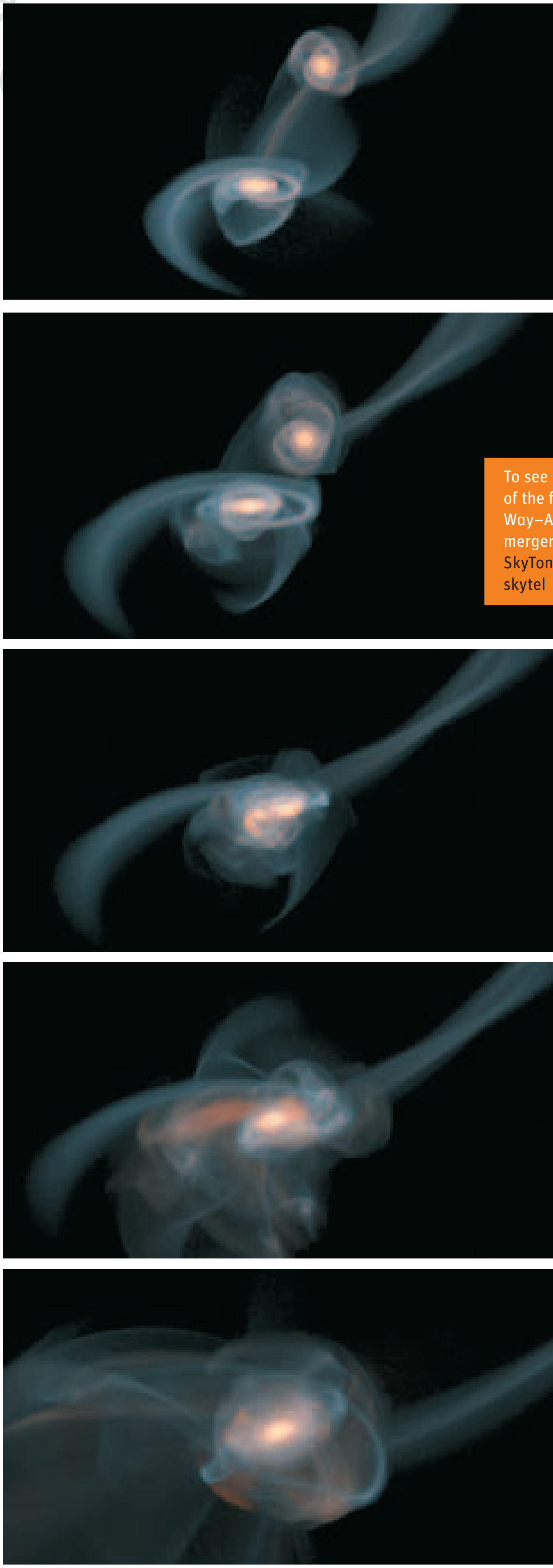
Right after the first encounter, the complex gravitational interactions will strongly perturb the Sun's circular orbit, plunging us through the heart of the galaxy. The night sky will oscillate between a distant view of two interacting spiral galaxies and a sky densely filled with bright stars as we fly through the galactic bulge.

The Antennae Smashup

Far left: The tidal tails in the merging galaxies NGC 4038 and NGC 4039 stretch across hundreds of thousands of light-years. Astronomers have nicknamed the system "The Antennae" because of the tidal tails' resemblance to insect antennae. The two galaxies are similar in size to the Milky Way and M31. *Below:* Hubble Space Telescope images reveal how the collision has caused gas clouds in both galaxies to collapse, leading to blazing starbirth that has formed numerous clusters of massive, hot, blue stars.







The author and his colleagues have simulated the future collision of the Milky Way and Andromeda galaxies. These frames show the interaction as it unfolds over 44 million years. The galaxies approach each other and form tidal tails and bridges. They then move apart before a second collision produces the merger. The result is a classic elliptical galaxy surrounded by shells and ripples. Each frame represents a region of space 1 million light-years wide and 590,000 light-years high.

Our simulation does not contain gas, but a similar version that incorporates gas and star formation is now playing at the *Cosmic Collisions* planetarium show at New York's Rose Center for Earth and Space (August issue, page 94). The collision of two gaseous disks leads inevitably to a starburst that increases the supernova rate from about two per century to perhaps one per year. As the Sun passes through the center of the merging galaxies, observers may be treated to an annual display of an exploding star, which could very well rival the brightness of all other stars in the night sky. There's a small chance that a supernova will go off very close to Earth, further endangering whatever surface life has survived to that point.

To see animations of the future Milky Way–Andromeda merger, visit SkyTonight.com/skytel

The galaxy collision will also produce a tight binary black hole whose members will eventually merge. But according to some calculations, their inward migration may stall for millions of years before proceeding to this fate. With the Sun's new plunging orbit, our star might fly right past the binary, providing a close-up view of a black-hole event horizon and perhaps a newborn accretion disk. That would be a sight to behold, but it may be too close and warm for comfort.

The gravity of the twin monsters will probably eject the Sun right out of the galaxy, where it can die quietly and alone in intergalactic space. Supermassive-black-hole event horizons are only about the size of our solar system, but there is a small chance that the Sun could be flung across the threshold of one of these boundaries. In that event, all that remained of human civilization would cross into oblivion, leaving behind one final remnant of our existence: a feeble hiccup of gravitational radiation dispersing through the cosmos at the speed of light.

Contemplating Earth's demise might be viewed as a grim exercise, but 18th-century British astronomer Thomas Wright thought otherwise. In a time when science mixed freely with religion, he reflected wistfully on the vastness of the universe and our rather small place within it: "In this great celestial creation, the catastrophy of a world, such as ours, or even the total dissolution of a system of worlds, may possibly be no more to the great Author of Nature, than the most common accident in life with us, and in all probability such final and general Doomsdays may be as frequent there, as even Birthdays or mortality with us upon the earth. This idea has something so cheerful in it, that I know I can never look upon the stars without wondering why the whole world does not become astronomers." ✴

University of Toronto astronomer John Dubinski *works in the field of galaxy dynamics. He has recently focused his efforts on the creation of high-resolution animations for illustrating complex, dynamical cosmic phenomena; see www.galaxydynamics.org.*