

Battle of the Titans:

The Milky Way vs. Andromeda

The Milky Way and Andromeda galaxies vie for Local Group supremacy.



MICHAEL RICH

Astronomers have long known that the Milky Way and Andromeda galaxies are approaching each other at 300 kilometers per second. Thanks to the Hubble Space

Telescope's exacting measurements of the relative motion of the two galaxies, it's a virtual certainty they will engage in a massive prizefight 3 to 5 billion years hence, with the result being a merger that will ultimately create a giant red elliptical galaxy. Similar bouts can be seen in progress right now: interacting spirals such as the Mice and the Antennae that will someday merge into ellipticals.

There will be no knockout in our contest, but it's interesting to consider how the two champions match up. Indeed, it's a surprisingly even competition, even though our contestants look quite different at first glance.

Our galactic neighborhood, the Local Group, is a relatively small cluster of galaxies about 6 million light-years across. It's dominated by the Milky Way and Andromeda (M31), whose centers lie 2.5 million light-years apart. Our cluster hosts about 100 far less massive galaxies, including M33 and the Magellanic Clouds. Think of the Milky Way and Andromeda as two major cities, flanked by numerous small suburbs — the dwarf galaxy members of the Local Group.

Sizing Up the Contestants

In our corner stands the Milky Way Galaxy. With its two major star-forming spiral arms and ancient central bar weighing in at 20 billion Suns, the Milky Way rules a retinue of nearly 160 globular clusters and 26 known dwarf galaxies. These include the prominent Magellanic Clouds, whose mass including their dark matter may be as high as 10% that of the Milky Way — respectable galaxies in their own right, with their own systems of globulars (*S&T*: Oct. 2012, p. 28). Both the Large and Small Magellanic Clouds are very likely newcomers to the Milky Way's environs, and both are wreathed in a stream of hydrogen gas (the Magellanic Stream) that winds around our galaxy.

The Sagittarius Dwarf Spheroidal Galaxy has mistakenly challenged the Milky Way: no bantamweight beats a heavyweight. Sagittarius has wrapped itself around our galaxy, with its core some 60,000 light-years from our galaxy's center. Sagittarius's stars will ultimately dissolve into the Milky Way's halo in a process that has probably repeated itself many times over the past 10 billion years. In dominating the Sagittarius dwarf, the Milky Way doesn't even have to lift a glove: gravity is delivering the

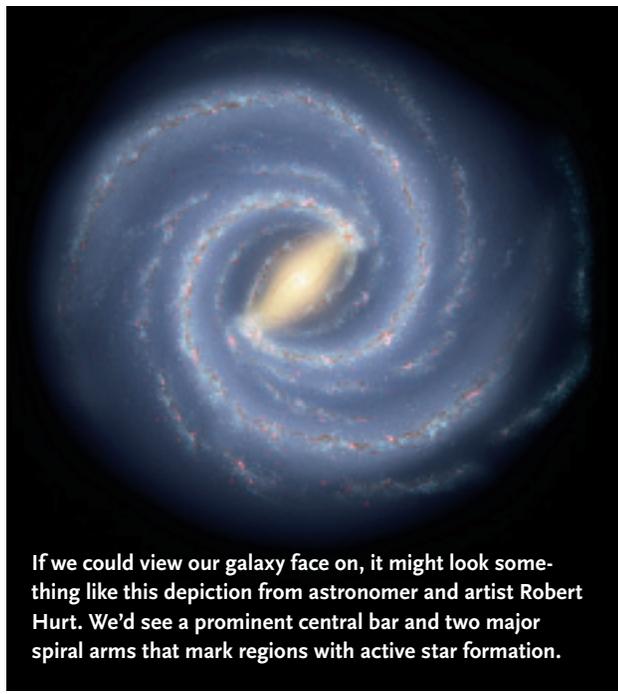
The Milky Way and Andromeda galaxies are moving inexorably closer, and will collide in 3 to 5 billion years. This photo illustration depicts M31 and the Milky Way's galactic plane looming large in the night sky when the two galaxies have come close. By this time, the expanding Sun will have roasted Earth to a cinder. NASA / ESA / Z. LEVAY / R. VAN DER MAREL (STSCI) / T. HALLAS / A. MELLINGER

blows in the form of tides (see "Tides," page 22). Numerous other dwarfs have suffered the same fate, and their remaining tidal streams litter the Milky Way's environs.

M31 features a whopping 500 globular clusters. It has three noteworthy galaxy companions, each roughly as massive as the Magellanic Clouds: the dwarf compact elliptical M32, the dwarf elliptical M110 (also known as NGC 205), and the spiral M33. In addition, M31 has nearly 40 identified dwarf satellite galaxies, with potentially many more to be discovered.

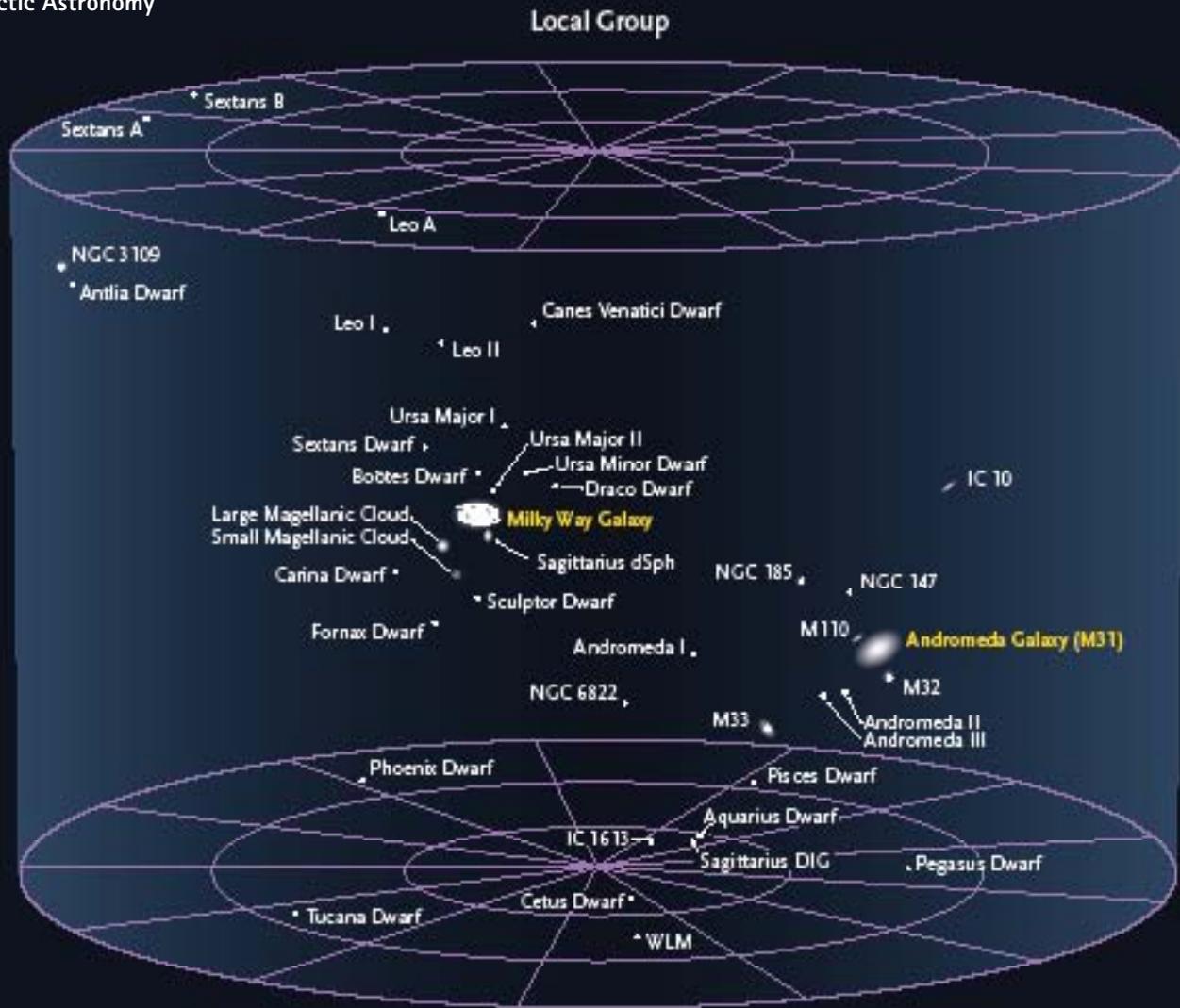
It appears that M32 has punched through the disk of M31 at least once. Although not scoring a knockout, this blow very likely cost M31 its grand-design spiral structure, leaving instead two rings of star formation, including the prominent Ring of Fire that surrounds the galaxy's nucleus at a distance of 30,000 light-years. First suggested as a possibility in 2006, recent simulations strongly suggest that the Ring of Fire is a consequence of M32 plowing through M31's disk 210 million years ago and triggering density waves in the gas that led to a burst of star formation.

Astronomers have weighed both contestants by applying Kepler's law to the motions of each galaxy's most distant satellites. In terms of *total* mass — 90% or more in the form of dark matter — both galaxies appear similar to the level of accuracy that we can measure: slightly greater than 10^{12} solar masses. Our perspective within the Milky Way makes these measurements somewhat more difficult, and determining the total mass (including the dark matter) of either galaxy requires painstaking measurements of the motions and velocities of a relatively small number of distant satellite galaxies as well as modeling



If we could view our galaxy face on, it might look something like this depiction from astronomer and artist Robert Hurt. We'd see a prominent central bar and two major spiral arms that mark regions with active star formation.

NASA / JPLCALTECH / R. HURT (SSC/CALTECH)



S&T: LEAH TISCIONE

Tides

Earth is affected by tides that raise the seas twice a day. But as manifestations of gravity, tides affect galaxies too. Gravity is a “central force” — the force is a vector, having a magnitude and a direction that always points toward the center of mass. In our daily experience of gravity, we feel the same gravitational force throughout our bodies. But for very large objects in a gravitational field, such as a satellite galaxy orbiting our Milky Way, or eventually, when M31 and the Milky Way come closer, one side feels a much stronger amount of force than the other, giving rise to a stretch-and-squeeze effect. On galactic scales, the difference in gravitational force can cause stars to wander away from the parental herd. It’s this tidal force that’s tearing apart the Sagittarius Dwarf Spheroidal Galaxy, and that ultimately plays a major role in disassembling great galaxies as they collide.

The Milky Way and M31 dominate the Local Group, depicted in this illustration of its brightest members. This small cluster has roughly 100 galaxies stretching across 6 million light-years. The two big boys contain the large majority of the total stellar mass.

the motions of galaxies in an expanding universe. Astronomers are still debating the numbers; new models of the Local Group’s orbital dynamics suggest that the Milky Way’s mass might be a factor of two lower than the canonical 10^{12} Suns, making M31 twice the mass of our galaxy.

In terms of sheer size and brightness, M31 has the edge. It’s challenging to estimate the Milky Way’s total brightness from a vantage point within it, but it has an absolute visual magnitude of about -20.5 . Best current estimates find M31 to have about twice the brightness in stars, making it roughly one magnitude brighter. The easily visible part of M31’s disk of stars and gas is a whopping 150,000 light-years across compared to the Milky Way’s still impressive 90,000-light-year-diameter disk. Both galaxies have halos of stars and dark matter that extend far beyond the visible disk of stars. The stellar mass of M31’s

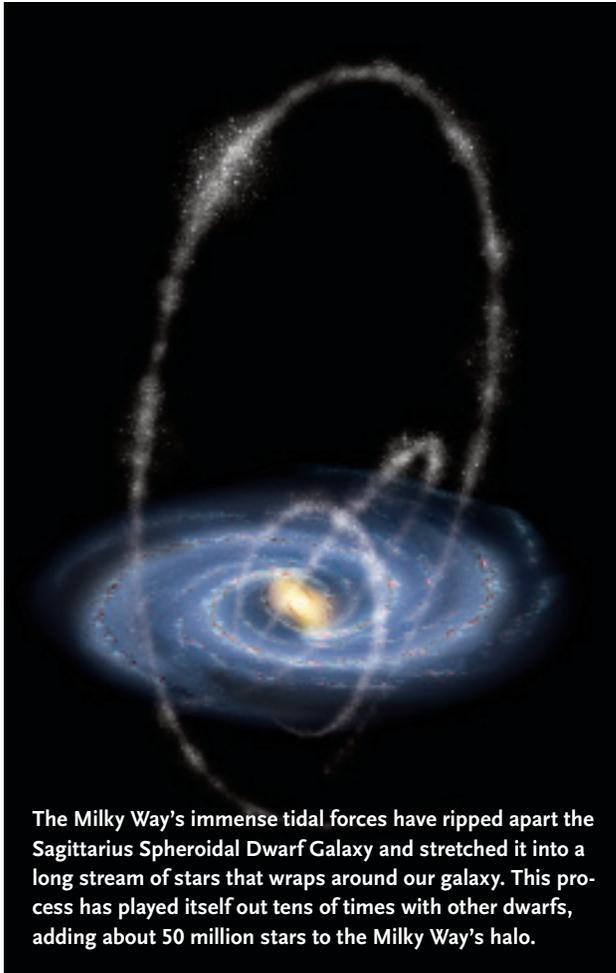
M31: ROBERT GENDLER; INSET: NASA / MICHAEL RICH (COLUMBIA UNIV), ET AL.



M31 has about twice as many stars as our Milky Way and a larger visible disk, but it lacks spiral arms. The satellite galaxies M32 and M110 are to M31's upper center and lower left.



Left: The author used Hubble to capture the Andromeda globular cluster G1, the largest globular in the Local Group. G1 has a black hole of about 20,000 solar masses, and is the only globular with strong evidence for a massive black hole.



S&P GREG DINDERMAN

The Milky Way's immense tidal forces have ripped apart the Sagittarius Spheroidal Dwarf Galaxy and stretched it into a long stream of stars that wraps around our galaxy. This process has played itself out tens of times with other dwarfs, adding about 50 million stars to the Milky Way's halo.

If we could view the Milky Way and M31 edge on from a large distance, we'd see galaxies that resemble NGC 4710 (*below*) and M104 (*below, facing page*), respectively. Like the Milky Way, NGC 4710 has a central bar, which resembles a peanut from the side. Note the faint X-shape flare. M31 has a more spherical bulge, like M104 (the Sombrero Galaxy), although M104's bulge is much larger and more extreme. Both images were taken by Hubble.



NASA / ESA / PAUL GOUDFROOIJ (STSC)

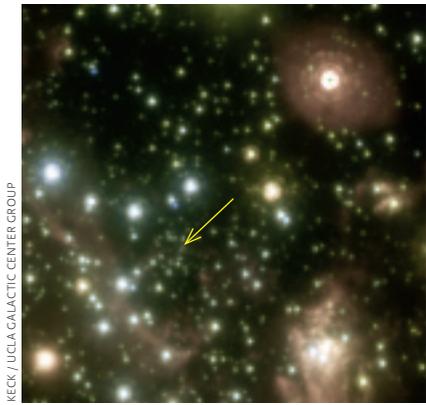
disk and bulge totals around 100 billion solar masses; the Milky Way's total is around 50 billion solar masses. M31 has 400 to 600 billion stars, roughly twice as many as the Milky Way.

Central Regions Compared

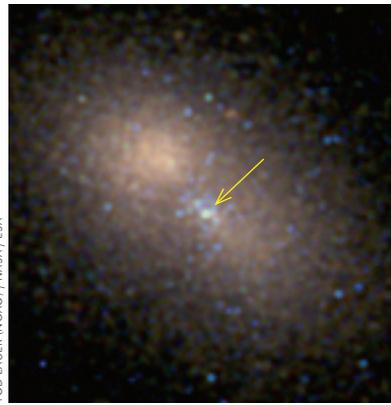
One of the most striking differences is the appearance of their central bulges. If we could see our Milky Way face on from "above," we'd see a bar that hosts an ancient stellar system whose members surprisingly contain, on average, roughly the same heavy-element abundance as our Sun. Considering both the bar's shape and stellar motions, theoretical modeling suggests that it buckled under its own gravity from a pre-existing massive protodisk that formed early in the Milky Way's history. As the stars orbited and interacted through mutual gravitation, the disk's central region evolved into a flattened, football-shaped structure, ultimately forming a central bar.

One mystery is how our Milky Way was able to evolve as a pure disk galaxy. The widely favored cold dark matter theory of galaxy formation posits that galaxies have grown in size through merging clumps of dark matter. In the early universe, these clumps also contained gas and stars that contributed to the fueling of the star-formation bursts that built galaxies, especially their bulges. But in the case of our Milky Way and other familiar spiral galaxies such as NGC 4565, the bulge appears to have formed from the disk. From the side, these bulges have a peanut shape, and viewed face on, they appear as bars. It's now known that our galaxy also has X-shaped lobes, a feature common in galaxies with prominent bars.

In contrast, M31's bulge looks more like an elliptical galaxy and has a feeble star-formation rate. Central galactic bulges appear to come in two flavors: bars such as the Milky Way's, and mini-elliptical galaxies such as M31's. The Sombrero (M104) has an extreme case of a classical "round" bulge, and that's the kind M31 appears to host. M31's bulge is about twice as massive as the Milky Way's.



KECK / UCLA GALACTIC CENTER GROUP



TOD LAUER (INDAO) / NASA / ESA

Far left: This remarkable image taken with one of the 10-meter Keck telescopes shows the Milky Way's central region in infrared light. Astronomers are using adaptive optics to study the orbits of dozens of stars caught in the grip of Sagittarius A* (arrowed), a strong radio source that marks the location of a 4.2-million-solar-mass black hole. Most of the bright stars in this image are orbiting the black hole at close range, whereas most of the fainter stars are in the foreground or background.

Near left: This Hubble image resolves M31's central region. Strangely, the brightest spot in visible light is offset 5 light-years from the central black hole (arrowed), which contains a whopping 100 million solar masses.

Using image-sharpening adaptive optics on the world's largest telescopes and (in the case of M31) the Hubble Space Telescope, astronomers have found overwhelming evidence that the Milky Way and Andromeda both host supermassive black holes at their centers. The Milky Way's central black hole weighs in at 4.2 million Suns. Independent teams led by my UCLA colleague Andrea Ghez, and Reinhold Genzel (Max Planck Institute for Extraterrestrial Physics, Germany), have measured this mass by determining the velocities of individual stars orbiting the black hole and then applying Kepler's laws.

M31's central black hole easily wins this contest, however. Best estimates of M31's black hole from Hubble observations place it at 100 million Suns, roughly 25 times more massive than our Milky Way's beast. Its high measured mass raises the possibility that M31 in its youth was among the most spectacular of cosmic heavyweights: a quasar. Although not in the billion-solar-mass class of central black holes in giant elliptical galaxies such as M87, Andromeda's monster likely blazed brightly in the first 2 billion years of its life, fueled by the ample gas from which the bulge formed.

Yet despite the black hole's high mass, M31's central realms are quiet, except for a small cluster of young

stars and a little gas. M31's nucleus is also quite peculiar because it appears to be double. The brightest peak in visible light is not where the black hole and a small young star cluster are located. Instead, it's 5 light-years away. Theoretical models suggest that this "false peak" resides in a disk of stars that orbit the black hole.

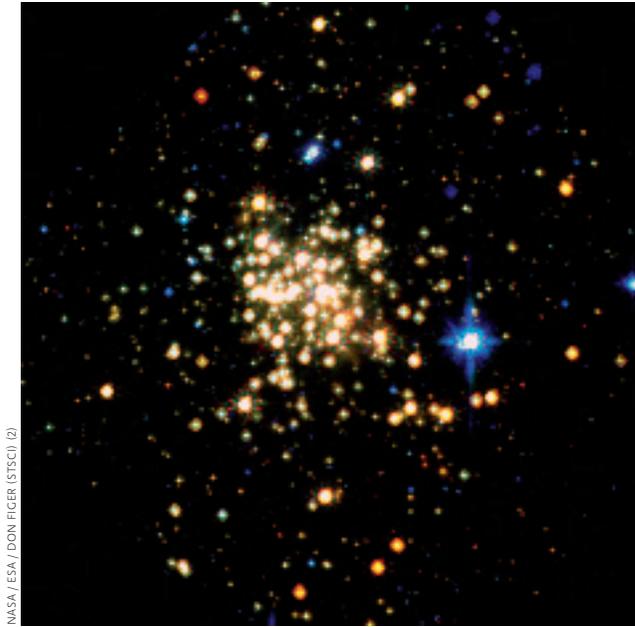
Unlike M31, the Milky Way's central region is abuzz with star formation, as exhibited by the recently minted Arches and Quintuplet star clusters. The Arches has some 100 stars weighing up to 100 solar masses and shining with 1 million or more solar luminosities. These behemoths are only about 2 million years old. The galactic center is also the site of twisted and complex magnetic

Andromeda's Satellite Plane

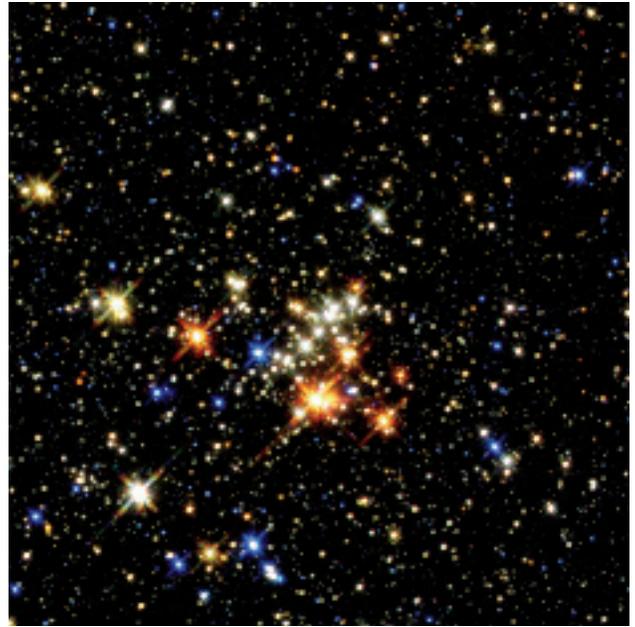
I'm a member of a team led by Rodrigo Ibata (Strasbourg Observatory, France) that has measured distances and velocities of M31 dwarf galaxies using red giants. We recently showed that 13 of the dwarfs are arrayed in a narrow plane 1.3 million light-years across. Nothing like this structure is known around the Milky Way, and theories of galaxy formation struggle to explain its existence.



NASA / HUBBLE HERITAGE TEAM (STSCI / AURA)



NASA / ESA / DON FIGER (STSCI) (2)



The Milky Way's central region features two large clusters of massive, highly luminous young stars, the Arches (*left*) and Quintuplet (*right*). How these clusters formed remains a mystery. M31 has no central star clusters of comparable size and youth.

fields, and additional massive young stars are clustered around the black hole. The origin of these stars is a deep mystery, because the extreme tidal forces near the black hole should prevent stars from forming, and we don't know an obvious way to move stars there in a short time.

The Galactic Boondocks

Both galaxies have diaphanous, extended halos. M31's has been traced to a radius of 500,000 light-years — about 50% larger than the Milky Way's. As mentioned earlier, M31's halo has an extraordinary endowment of 500 globular clusters, three times that of the Milky Way. Almost all of the globulars in both galaxies are ancient stellar

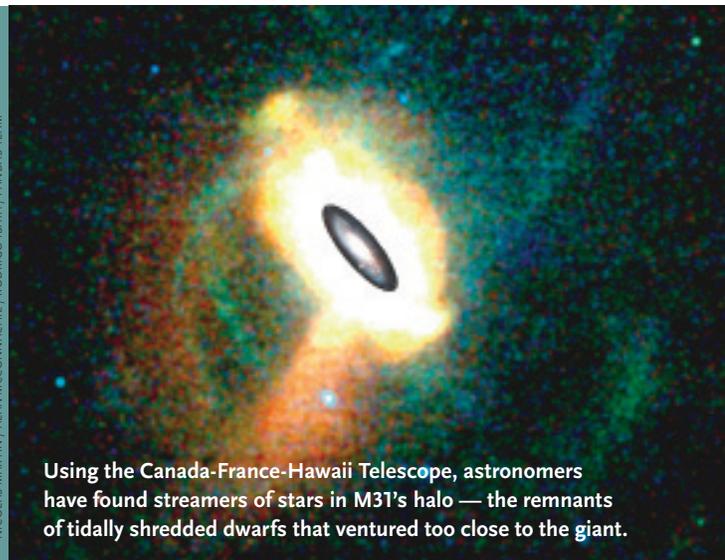
systems. The oldest datable Milky Way stars range from 11 to 12.5 billion years.

Each halo also has streams of stars that are almost certainly the debris of unlucky cosmic contestants — systems similar to the Sagittarius Dwarf Spheroidal Galaxy. In an observational tour de force, Thomas Brown (Space Telescope Science Institute) and a team to which I belong imaged a number of different locations in M31's halo and found old stellar populations, as well as stars a few billion years younger — a population we don't see in the Milky Way's halo. Using the MegaCam imager on the 3.6-meter Canada-France-Hawaii Telescope to cover an area of sky nearly $20^\circ \times 20^\circ$, the Pan Andromeda Archaeological Sur-

The Milky Way and Andromeda Compared

	MILKY WAY	ANDROMEDA
Globular clusters	160	500
Known satellites	26	38
Absolute magnitude	-20.5	-21.5
Stars	200 to 300 billion	400 to 600 billion
Mass	5×10^{11} to 10^{12} solar masses	$\sim 10^{12}$ solar masses
Disk diameter	90,000 light-years	150,000 light-years
Halo radius	300,000 light-years	500,000 light-years
Central black hole	4.2 million solar masses	100 million solar masses
Star-formation rate	~ 2 solar masses per year	~ 1 solar mass per year

NICOLAS MARTINI / ALAN MCCONNACHIE / RODRIGO IBATA / PANDAS TEAM



Using the Canada-France-Hawaii Telescope, astronomers have found streamers of stars in M31's halo — the remnants of tidally shredded dwarfs that ventured too close to the giant.

vey, led by Alan McConnachie (NRC Herzberg Institute of Astrophysics, British Columbia), produced a map of M31's halo (from measurements of 10 million red giants) that shows spectacular streamers and arcs. The most prominent feature, the so-called Giant Stream, may be the debris left by the infall of a disk galaxy about the mass of M33.

Another noteworthy feature of M31's halo is its large population of stars with high heavy-element abundances. The typical star in the Milky Way's halo has around 2% the Sun's iron abundance whereas the typical star in M31's halo is 10 times more metal-rich than this. The new Hyper Suprime-Cam on the 8-meter Subaru Telescope, along with an advanced spectrograph currently being built, may help provide many more abundance and velocity measurements for M31 halo stars, helping settle the mystery of how and when this galaxy assembled. The planned Thirty Meter Telescope will also have a spectrograph capable of studying faint stars in M31's halo.

Stellar Populations Compared

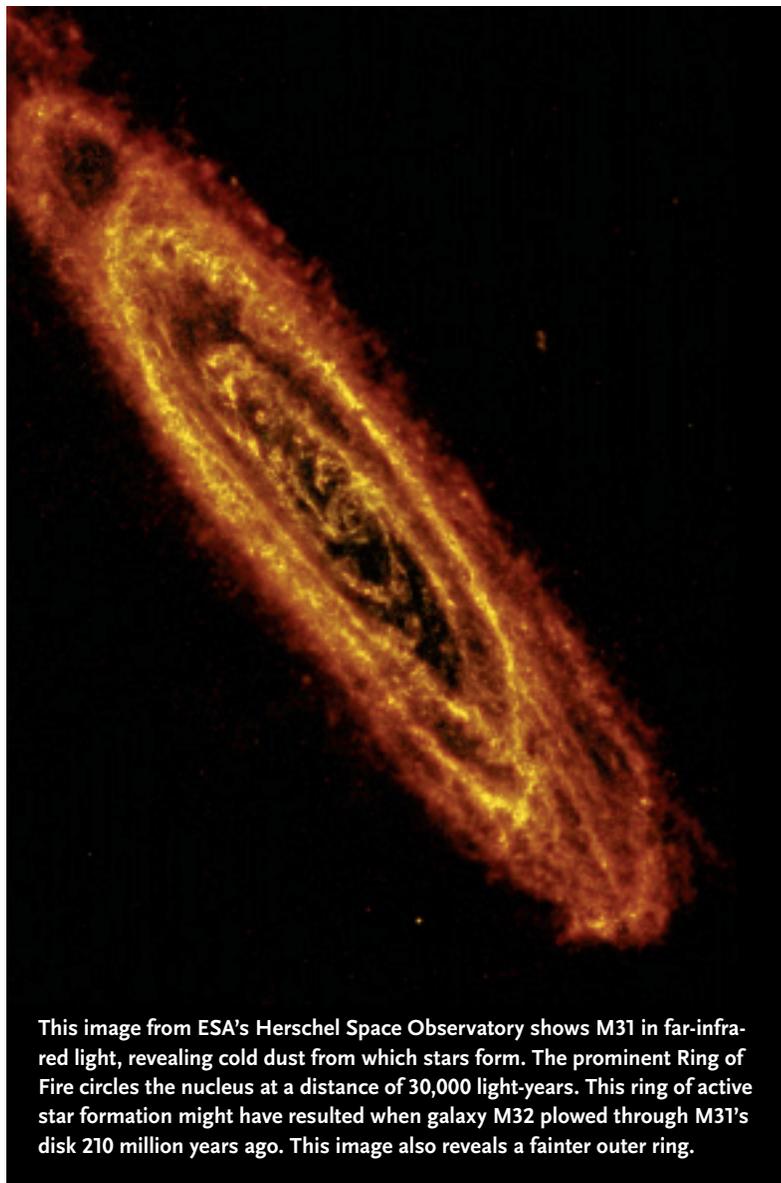
The recently decommissioned Galaxy Evolution Explorer (GALEX) satellite produced one of the greatest M31 portraits, combining far- and near-ultraviolet imaging (*S&T*: April 2012, page 20). The light of massive young stars illuminates the spiral arms, whereas the bulge is seen not by the light of young stars but by the ultraviolet light of ancient stars whose energy is produced by helium (not hydrogen) fusion.

The spectacular GALEX image belies a different reality. Although astronomers estimate that both M31 and the Milky Way are currently forming about 1 star per year, both galaxies appear to be transitioning from a lively star-forming spiral galaxy of youth to a quiescent, massive galaxy of maturity — a denizen of the so-called “red sequence” populated by ellipticals and massive spirals. Most of M31's light arises from older stars, and there appears to be relatively few stars formed in the past 100 million years.

Within M31 there is one major exception: the Ring of Fire includes the molecular hydrogen (H_2) and carbon-monoxide (CO) gas needed to form new stellar generations. Still, our galaxy appears to have about three times more molecular gas than M31. It's possible that M31 experienced more significant interactions (like the possible collision with M32) that caused it to form more stars than the Milky Way, and thus it used up its inventory of gas, or that the formation of its more massive bulge encouraged it to convert more of its gas into stars in its youth.

End Game

Precision Hubble measurements of the space motions of the Milky Way and M31 support the long-standing suspicion that these contestants are falling toward each other. However, the first blow will not take place for billions of years. In the early rounds, computer simulations suggest

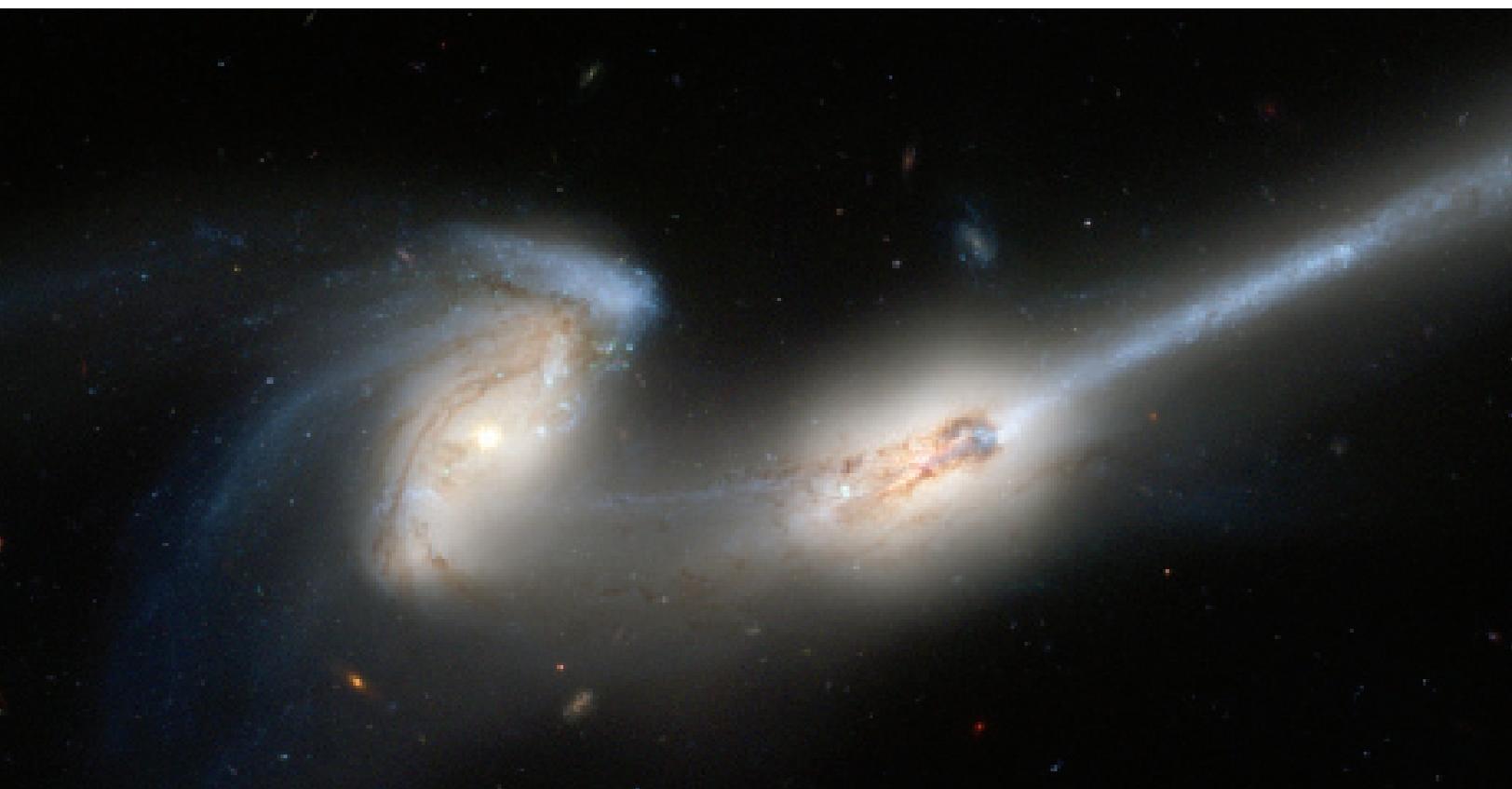


This image from ESA's Herschel Space Observatory shows M31 in far-infrared light, revealing cold dust from which stars form. The prominent Ring of Fire circles the nucleus at a distance of 30,000 light-years. This ring of active star formation might have resulted when galaxy M32 plowed through M31's disk 210 million years ago. This image also reveals a fainter outer ring.

ESA / HERSCHEL / PACS / SPIRE / J. FRITZ / U. GENT

Andromeda's Three Big Black Holes

Unlike the Milky Way and its solitary supermassive black hole, Andromeda and its satellites host at least three. Besides M31's 100-million-solar-mass monster, its companion elliptical galaxy M32 hosts a black hole of 2.5 million Suns. The nuclei of the nearby galaxies M33 and M110 have been inspected carefully with Hubble's spectrograph and the telltale signatures for supermassive black holes are lacking. Now consider M31's peculiar globular cluster G1 (the most luminous and massive globular cluster in the Local Group), whose appearance resembles a mini-M32, with a compact nucleus. Its odd appearance inspired me to search for a massive black hole in its core. From analyzing the velocities of stars in the “integrated” or unresolved light of G1's nucleus, Karl Gebhardt (University of Texas, Austin), Luis Ho (Carnegie Observatories), and I found that G1 hosts a 20,000-solar-mass black hole. G1 remains the most widely accepted case for a very massive black hole in a globular cluster.



NASA / HOLLAND FORD (JHU), ET AL. / ACS SCIENCE TEAM / ESA

This Hubble image of the Mice (NGC 4676) gives us a sneak preview of the Milky Way–Andromeda collision that will take place 3 to 5 billion years from now. Tidal forces create the tails that give the Mice its nickname. Regions of vigorous star formation appear blue.

that spectacular tidal streamers will be expelled, making the Milky Way/Andromeda pair potentially resemble the Antennae Galaxies (NGC 4038/4039), the Mice (NGC 4676), or perhaps after some time, the Atoms for Peace Galaxy (NGC 7252), with the Milky Way appearing to arc crazily over the entire sky as seen from the perspective of our solar system (*S&T*: Oct. 2006, p. 30). The interaction will set alight all the remaining gas in the two galaxies, and the end result will be the consumption of virtually all of the gas in spectacular bursts of star formation.

Eventually, the Milky Way and Andromeda will collide and merge, forming a giant elliptical galaxy. Among the more interesting finales will be the orbital dance of two or even three supermassive black holes in the center of that newly minted elliptical. Theory predicts that much of the gas in both galaxies will collide and flow to the center. If this occurs, a new quasar may flare for hundreds of millions of years. If any of our descendants are around to view the bout, it's unlikely they will be living on Earth. By then, the Sun will have evolved into a red giant and our planet will cease to be a comfortable place.

The appearances of the Milky Way and M31 have likely been molded by their extensive history of absorbing cosmic blows. M31's more classical bulge may reflect a merger in its youth, and passage of M32 through its disk

may have sparked additional star formation and depleted much of its gas. M31's Giant Stream and the Milky Way's Sagittarius dwarf are both remnants of small galaxies that tangled with the heavyweights. Our Milky Way's central bar more likely owes its existence to the force of gravity acting on the protodisk, and the bar channels gas to the galactic center where it forms spectacular star clusters.

A more precise comparison awaits a new generation of studies of Andromeda, and future work on the Milky Way that may reveal more details about its geometry and clarify the structure of its spiral arms. Although the Milky Way and Andromeda galaxies have prominent disks and similar masses, they have strikingly different appearances, and their origins and histories remain to be fully understood. The galactic contestants are now inexorably moving quietly from their corners of the celestial ring toward their date with destiny. ♦

Michael Rich is an astronomer at the University of California, Los Angeles, who has studied M31 using the Galaxy Evolution Explorer (GALEX), W. M. Keck Observatory, and the Hubble Space Telescope. He helped advance Neil deGrasse Tyson's career in astronomy by serving as his Ph.D. thesis advisor at Columbia University. Rich also authored the feature article about GALEX in the April 2012 issue.