5 billion years A.D.

Our galaxy's date with destruction

The Milky Way is on a collision course with its neighbor, the Andromeda Galaxy. What will the night sky look like after the crash? /// BY ABRAHAM LOEB AND T.J. COX

Our home galaxy, the Milky Way, and its nearest neighbor, the Andromeda Galaxy, are on a collision course. Billions of years from now, the merger will drastically alter the structure of both galaxies and spawn a new city of stars we have dubbed Milkomeda ("milk-AHM-mee-da"). The event will also radically transform the night sky. But into what?

Currently, the Milky Way's thin disk of stars, dust, and gas appears as a nebulous strip arching across the sky. As Andromeda grazes the Milky Way disk, we will see a second strip of stars looming across the night sky. After the final merger between these galaxies, the stars will no longer be confined to two narrow strips, but instead get scattered across the entire sky.

In our research, we have explored the Milky Way's fate by simulating the birth of Milkomeda in a supercomputer. The simulations are at a sufficient level of detail, or "resolution," to learn much about the coming merger and how it will change our perspective on the universe. Although we will not be alive to witness the event — nor to take responsibility for whether our forecast proves accurate — this is the first research in our

BILLIONS OF YEARS FROM NOW, the night sky will blaze with stars, dust, and gas from two galaxies: the Milky Way, in which we live, and the encroaching Andromeda Galaxy (M31). LYNETTE COOK FOR ASTRONOMY

THE ANDROMEDA GALAXY (M31) **is a typical spiral of stars, dust, and gas — the type of galaxy that dominates the night sky in the Local Universe. Fourteen small satellite galaxies accompany Andromeda, including the two visible in this image: M32 (above Andromeda) and NGC 205 (below).** TONY AND DAPHNE HALLAS

careers that has a chance of being cited in 5 billion years.

The Local group

The vastness of the night sky might suggest the Milky Way resides in a relatively remote part of the Universe. However, astronomers know the Milky Way to be the second largest member of the Local Group of galaxies. The largest in the Local Group is Andromeda. It contains somewhat more mass than the Milky Way, resides nearly 2.5 million light years away, and is visible in the northern sky with the naked eye. The remaining members of the Local Group — more than 30 galaxies — are a bevy of much smaller satellite galaxies. The satellites cluster near the Milky Way or Andromeda like celebrity entourages. Thus, the Milky Way and Andromeda are the celebrity couple of the Local Group.

In astronomical jargon, a galaxy group comprises two or more massive galaxies in relatively close proximity. As the headlights on a dark country road indicate the existence of an entire car, the luminous stars of a galaxy indicate the existence of an extended halo of "dark matter." The close proximity of galaxies in groups suggests that their dark halos are gravitationally bound and dynamically coupled to each other. "Dynamically coupled" simply means the haloes attract each other via their gravitational fields, and a change in one galaxy affects the fate of the other.

Evidence of the dynamical connection between the Milky Way and Andromeda comes from their relative motion. The galaxies are barreling toward each other at nearly 270,000 mph (120 kilometers per second). We know this because the spectral lines of Andromeda's light appear to be blueshifted — displaced toward the blue end of the spectrum — by the Doppler effect. This is in sharp contrast to most galaxies in the universe, which are flying away from the Milky Way. This spreading motion induces a redshift in the light from distant galaxies, a fact used to establish the expanding universe since the time of the American astronomer Edwin Hubble (1889 – 1953).

Timing is everything

Nearly 50 years ago, Franz Kahn and Lodewijk Woltjer pioneered the "timing argument." This hypothesis held that the Milky Way and Andromeda formed close to each other, during the dense, early stages of the universe. Subsequently, they were pulled apart by the general cosmological expansion. Later, the Milky Way and Andromeda reversed their outward paths owing to mutual gravitational attraction. Since then, they have now traced out nearly a full orbit of each other.

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The timing argument, along with knowledge of the current separation, relative velocity, the age of the universe, yields an estimated total mass for the Local Group of more than 3 trillion times the Sun's mass (solar-masses). In addition, it suggests the Milky Way and Andromeda will make a close pass in about 4 billion years. The mass estimate, in particular, generated significant amount of interest at the time, because it is more than 10 times the mass of all visible matter. This result became one of the first pieces of evidence for the existence of dark matter.

Kahn and Woltjer inspired a generation of studies that further constrained the mass of the local group and revealed important characteristics of Andromeda's orbit, such as its total energy of motion, or "angular momentum." But the timing argument does not have the ability to follow the complex dynamics that accompany the merger of extended galaxies. Therefore, it cannot predict the future arrangement of the Local Group. For processes as complex as galaxy mergers, astronomers need more powerful tools: supercomputers.

FROM EARTH, we see the Milky Way from an insider's perspective. Only one of the galaxy's spiral arms is visible. JOHN CHUMACK

Simulating the Local Group

Numerical simulations are an indispensable tool to understand astronomical processes too complex to solve with pen and paper. A perfect example is the merger of two galaxies. Simple gravitational forces govern the structure of the galaxies, but the sheer number of atoms of matter interacting over time makes it difficult or impossible to solve without massive computer power.

To simulate the evolution of the Local Group, first we construct a physical model describing its present state. This task is straightforward for the Milky Way and Andromeda, since several decades of observations enable us to estimate the amount of gas and stars involved and the contribution from dark matter. Combined with cosmological simulations, a plausible mass model for the Milky Way and Andromeda can be determined to well beyond the visible inner portion of each galaxy.

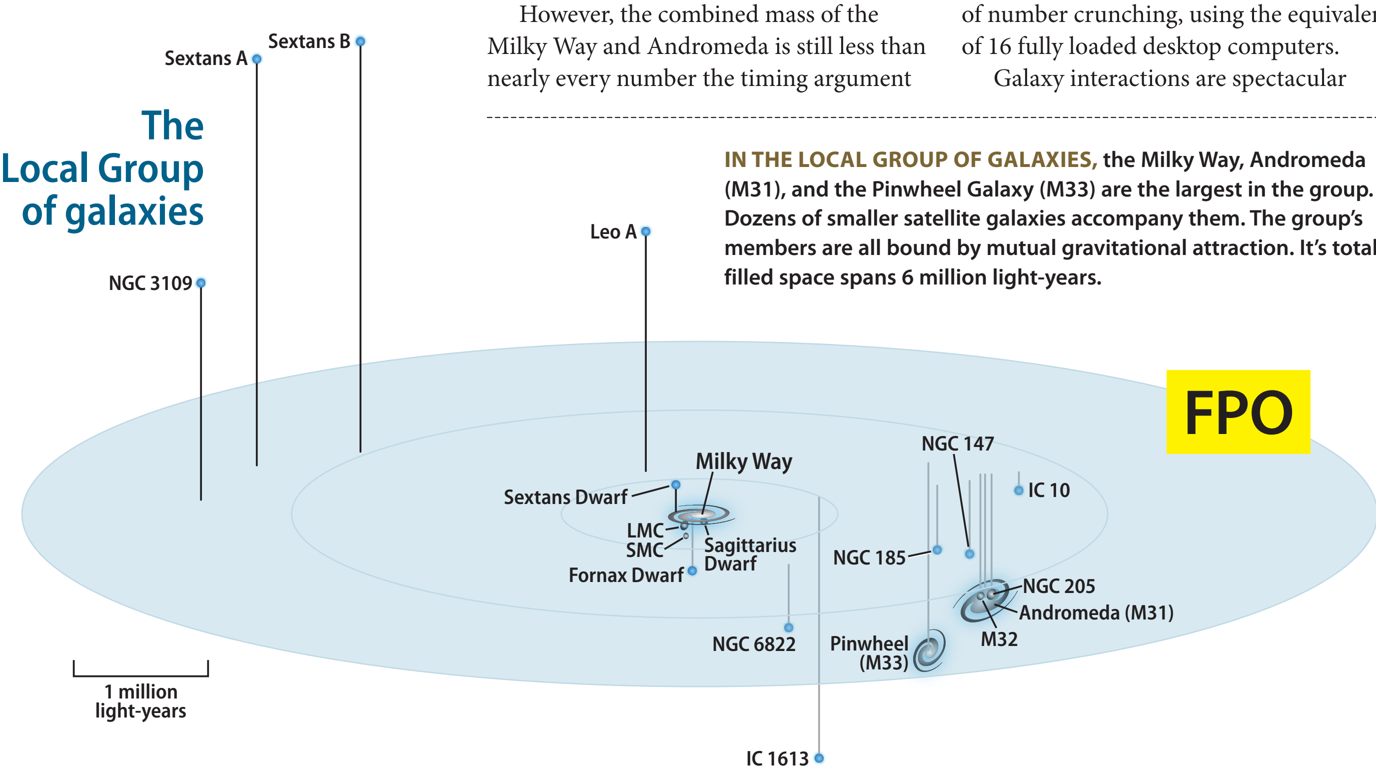
However, the combined mass of the Milky Way and Andromeda is still less than nearly every number the timing argument yields. This implies there is additional mass in the Local Group. The missing mass turned out to be the diffuse "intergalactic medium" of atoms, gas, and dust between the galaxies. Galaxies are simply the visible peaks of massive icebergs of matter. Much of the mass is not readily apparent, just as most of an iceberg's bulk lies beneath the waves.

When galaxies collide

After we construct a model that includes all the stars, gas, and dark matter in the Local Group, we evolve the system over time in a computer and see what happens. Full-scale simulations typically require 2 weeks of number crunching, using the equivalent of 16 fully loaded desktop computers.

Galaxy interactions are spectacular

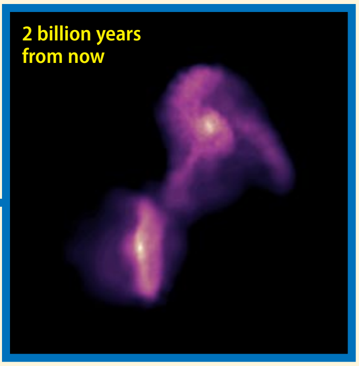
The Local Group of galaxies



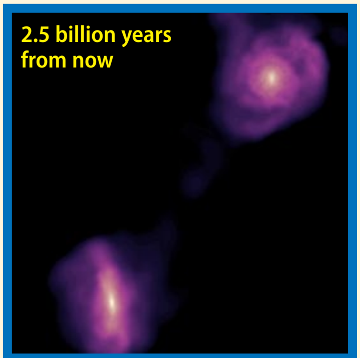
IN THE LOCAL GROUP OF GALAXIES, the Milky Way, Andromeda (M31), and the Pinwheel Galaxy (M33) are the largest in the group. Dozens of smaller satellite galaxies accompany them. The group's members are all bound by mutual gravitational attraction. It's total filled space spans 6 million light-years.

GALAXY MERGERS IN CYBERSPACE

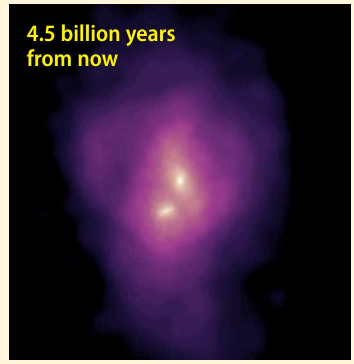
Astronomer astronomers don't simulate galaxy mergers just to create pretty pictures. The simulations are experiments to test hypotheses about how mergers work whether they are a significant process in the formation and evolution of galaxies. These images, taken for an animated film on T.J Cox' web site, depict the complex merger of the Milky Way and Andromeda. These frames highlight important features of the galaxies and the merger process. UNLESS OTHERWISE NOTED, MERGER IMAGES BY T.J. COX (HARVARD-SMITHSONIAN SFA)



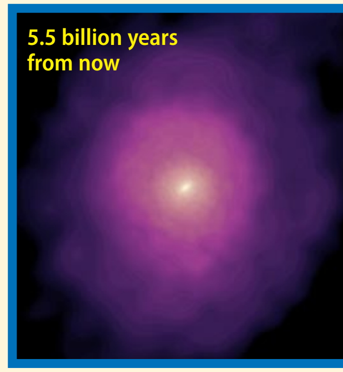
2 BILLION YEARS from the present, the galaxies loop around each other in a close pass. Mutual attraction draws tenuous "tidal tails" of stars and gas. Tidal tails are hallmarks of merger in the real universe (see image at right).



IN 2.5 BILLION YEARS, the galaxies are still moving apart. A ghostly bridge of gas and stars connects the galaxies. Stars in the bridge, perhaps some with planets, could end up literally lost of intergalactic space bridge dissipates.

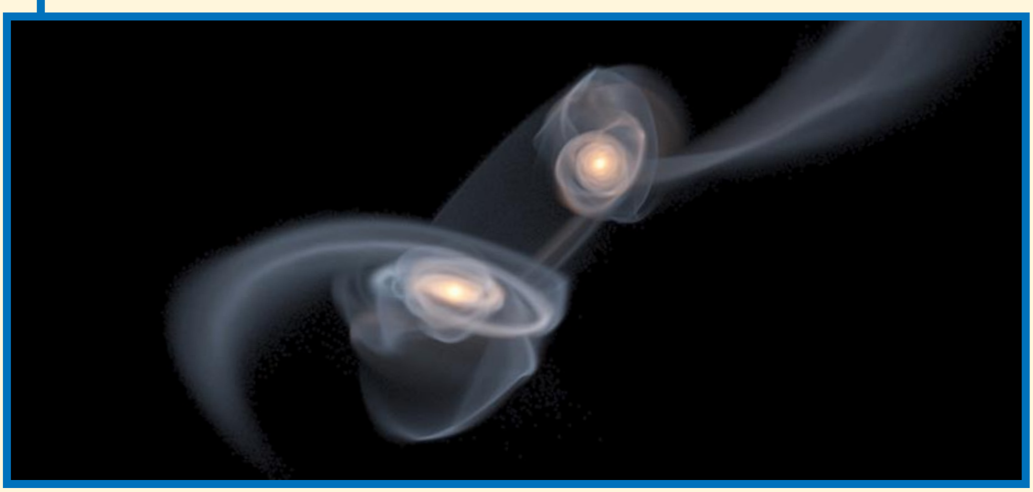


IN 4.5 BILLION YEARS, the galaxies loop around again and come back together to finally merge. Their dense cores, each harboring a supermassive black hole, gradually combine. The merging galaxies experience a brief pulse of star formation as the two black holes merge.



IN 5.5 BILLION YEARS, Milkomeda is born. Tidal swirls,tails, and eddies left over from the violent merger slowly relax and dissipate. Individual stars spread out, forming a more smooth, internally homogenous elliptical galaxy similalr to the barrEd elliptical galaxy IN CENTAURUS NGC 2207 at right.

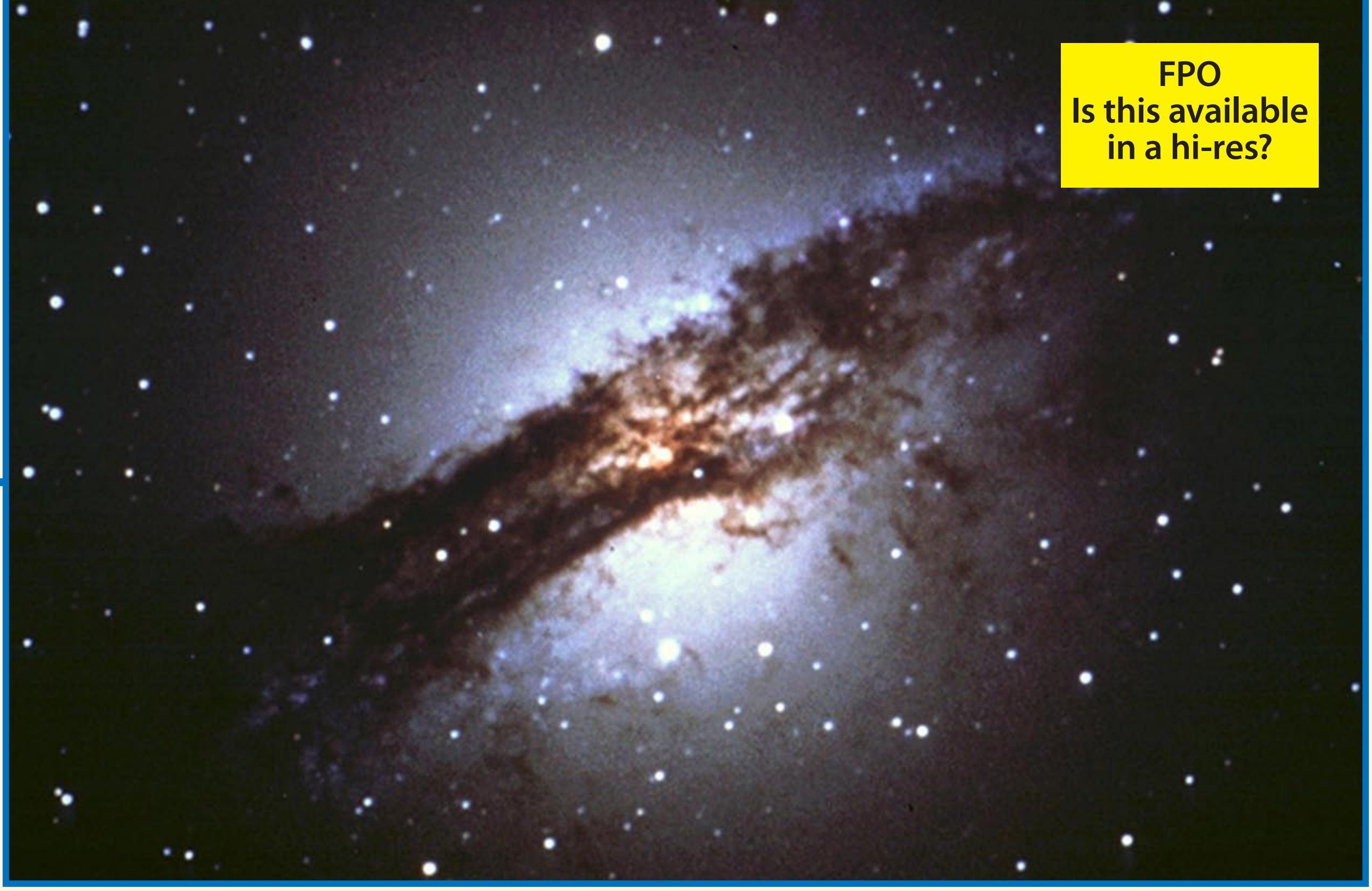
NGC 2207 (LEFT) merging with smaller IC 2163.
NASA/ESA/HUBBLE HERITAGE TEAMS (STSCI)



MONTREAL ASTRONOMY John Dubinski created this image of the merger of the Milky Way with Andromeda. It highlights to fine, elegant contours of Milkomeda in the making, although at a cost of less detailed scientific contting in the images. The Dubinsky image reflects the skeletal structure of the margin

events. Since the early days of astronomy, merging galaxies have remained curiosities owing to their complex and irregular shapes. But astronomers now appreciate that mergers are one of the most significant drivers of galaxy evolution. For example, galaxy mergers touch off huge bursts of star formation (starbursts), trigger the birth of quasars, and transform rotating spiral galaxies, such as the Milky Way and Andromeda, into smooth spheroidal or "elliptical" galaxies. (see "What happens when galaxies collide?," March 2008.)

You can view numerous spectacular images of interacting galaxies captured by the Hubble Space Telescope and other great observatories. These images are snapshots of the dynamic merger process and paint an amazing story. One of the distinguishing characteristics of galaxy interactions is the appearance of long streams of stars and gas that stretch from one or both of the participant galaxies. These features are typically referred to as "tidal tails," and result from the powerful gravitational forces at work between merging galaxies. As the tails form, they rip material from the host galaxy



THE MERGER OF SPIRALS often produces a single, new sphere-shaped type of galaxy called an elliptical. The galaxy above, Centaurus A (NGC 5128), is a "peculiar elliptical" visible in the Southern Hemisphere. NOAO/AURA/NSF

and hurl it into intergalactic space.

As the Local Group evolves, the Milky Way and Andromeda will begin to have a dynamical impact upon each other owing to their mutual gravitation. As a result, it's possible the Sun — and Earth and the other planets — will be dragged into a tidal tail. During this period, an observer will have one of the most unique vantage points ever imagined. Torn shreds of the Milky Way will fill a large fraction of the night sky as our galaxy experiences its gravitational dance with Andromeda.

Because only a small fraction of a galaxy's mass ends up in tidal tails, it is more likely the Sun will go for a much less dramatic ride. Most of the stars in merging galaxies remain relatively close to their host galaxies. The chance of the Sun being banished to the tidal-tail boondocks is relatively small, based on our simulations. There is also a 3 percent change the Sun will end up in Andromeda after its second close encounter with the Milky Way. In that case, earthly observers could gaze across space at their own former home, seeing it truly for the first time.

Change of fortune

However, the Sun's peaceful orbit around the center of the Milky Way — which it has traversed nearly 20 times since its birth — will forever change. Its new path will be far more chaotic owing to the rapid fluctuations in gravity induced by the merger. What would this mean for the Earth and its residents?

Our computer studies suggest the Milky Way and Andromeda will begin to strongly interact 2 billion years from now, and then complete the merger in about 5 billion years. The latter date is notable, because it coincides with the Sun's remaining lifespan. Currently, our Sun is about halfway through its lifetime and will soon begin to expand as it slowly consumes all available hydrogen and evolves toward a red giant phase within 5 billion years. In short, the Sun will be in its death throes on Milkomeda's birthday.

The Sun's red-giant stage will make life on Earth rather uncomfortable. Indeed, it will spell the end of life (as we know it). However, it does not preclude the possibility for colonization of habitable planets around nearby stars, and thus it is possible that future astronomers will be able to witness some, if not all, of the Local Group evolution we have simulated.

Although the Milky Way and Andromeda will merge, stars within the two galaxies, such as our Sun, will not physically collide. The reason is the extremely large distances between individual stars in galaxies. For example, if the Sun was the size of a ping pong ball, the nearest star (Proxima Centauri) would be another ping pong ball nearly 1,000 miles (1,600 km) away.

Our final resting place

The Sun's orbit will follow a chaotic path until the merger concludes and the system relaxes and expands. At this point, the Sun will reside inside a new galaxy, Milkomeda. It will look very different from either the Milky Way or Andromeda.

The Milky Way and Andromeda are spiral galaxies, with most stars concentrated into a disk and moving in nearly circular orbits around the galactic center. In contrast, Milkomeda will be nearly spherical in shape and much smoother in appearance than any spiral galaxy. Stars within Milkomeda will follow more complex