

MYSTERY OF THE MISSING GALAXIES

Simulations show how the darkest galaxies in the universe get that way and appear to resolve a serious problem with the prevailing theory of how the universe evolves

EVOLUTION &
STRUCTURE OF
THE UNIVERSE //
MYSTERY
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GALAXIES



Stelios Kazantzidis



Lucio Mayer

Who knew? The Milky Way, our own galaxy, is a neighborhood bully. For 10 billion years, it's been picking on small galaxies that pass near, huffing and puffing and blowing away their interstellar gas.

Left with only a few stars and nearly emptied of the gas they need to form new ones, these small galaxies become ghostly shadow galaxies, composed almost entirely of "dark matter" — the mysterious invisible matter that has a huge effect on the structure of the universe. They are the "darkest" galaxies known to exist, so faint that — although it's likely they are speckled throughout the universe — only a few have been detected, all satellite galaxies of the Milky Way and nearby Andromeda.

Until recently, scientists lacked an explanation for how these dark galaxies come into being that could account for both their exceptional darkness and their nearness to much larger host galaxies. With innovative thinking and powerful supercomputing tools to test their ideas, a team of physicists led by Lucio Mayer of the University of Zürich and Stelios Kazantzidis of Stanford University appear to have solved this riddle.

Mayer, Kazantzidis and their colleagues — Chiara Mastropietro (University of Munich) and James Wadsley (McMaster University, Canada) — used supercomputers in Zürich and relied heavily on LeMieux, PSC's terascale system (now decommissioned), for simulations over a two to three-year period. Their findings, reported this February in *Nature*, show that a triad of physical processes — ultraviolet radiation, gravity and the pressure exerted by galactic gas — transform a normal gas-dominated, small galaxy into a dark-matter shadow of its former self. Their solution to the puzzle of very small, dark galaxies — called "dwarf spheroidals" because of their size and rounded shape — has large implications for what we know about the universe. The leading theoretical model for evolution of the cosmos, the cold dark-matter model (CDM), predicts that dwarf galaxies are the building blocks of large galaxies like the Milky Way and that these dwarves should be ubiquitous. Scientists, however, have so far detected very few of them, and this mismatch between theory and observation — often called the "missing satellites problem" — has been a major weakness of the CDM model.

Mayer and Kazantzidis' simulations suggest strongly that the missing satellites are dwarf spheroidals not yet detected. "There has been this problem," says Mayer, "that when you look at the number of luminous galaxies surrounding the Milky Way you see fewer than CDM theory predicts. Many people have used this to say that probably the CDM model is wrong. With this new work, we're saying, 'Look, these small faint galaxies exist, we simply haven't found them yet.'"

THE KEY INGREDIENT: RAM PRESSURE

Before Mayer and Kazantzidis took aim at the problem, the prevailing theory for the origin of dwarf spheroidals was that diffuse radiation — the "cosmic ultraviolet background" — from galaxies like the Milky Way evaporated the gas in small nearby galaxies. Detailed calculations, however, made it clear that UV evaporation by itself can't cause the gas loss from dwarf galaxies like those near the Milky Way. "The biggest galaxy that can undergo this kind of evaporation," says Mayer, "is about 10 times smaller than the dwarf galaxies we see."

Earlier work of Mayer's on dwarf galaxies gave him a clue that other forces might be involved. He and his colleagues wanted to understand why dwarf galaxies close to the Milky Way were spheroidal while those at greater distance are disk-shaped. The answer, they found, is gravity. Because the distant dwarves feel less gravitational pull from the Milky Way they maintain their disk structure, while closer dwarves that begin as disks morph into spheroids.

Could other interactions between large and much smaller galaxies, Mayer began to wonder, also affect other dwarf properties, such as gas and dark matter content? "I realized that a major ingredient was missing from the physics," says Mayer, "and that was ram pressure, the 'sweep' produced by gas around the big galaxy that blows away gas in the small galaxy." Similar to drag that an airplane experiences as it flies in Earth's atmosphere, ram pressure is force from a large galaxy's envelope of hot gas that pushes against a smaller galaxy moving through it. "This kind of mechanism has been known for awhile," says Mayer, "as an effect in galaxy clusters, where you have thousands of galaxies. But it had been overlooked for our own galaxy and its satellites."

GONE WITH THE WIND

With ram pressure as a big clue to go on, Mayer, Kazantzidis and their colleagues revised a cosmological modeling program called GASOLINE, which they initially developed in the 1990s at the University of Washington with astrophysicist Thomas Quinn. Starting as a gravitational model, GASOLINE has expanded and become more diverse as the demand arose to include more physics. Wadsley added an approach called smoothed-particle hydrodynamics (SPH), which describes fluid properties, like interstellar gas, using millions of particles as tracers. Mayer contributed radiative cooling and heating.

The emphasis was on flexibility, so GASOLINE could run on a range of supercomputers. This led to its being used on projects as diverse as planet formation, asteroid collisions, and now dark matter in spheroidal dwarf galaxies. "Our work relies on fast, reliable supercomputing systems," says Kazantzidis. "GASOLINE is optimized to run efficiently on LeMieux, and this system has been ideal for these simulations."

The researchers added the physics of ram pressure to GASOLINE. They also accounted for tidal forces — like those that pull Earth's oceans toward the moon and create tides. The gravitational pull of the Milky Way similarly distorts nearby dwarf galaxies, stretching their gas and making it less dense, more easily acted on by ram pressure. The researchers also kept the physics of the cosmic ultraviolet background in the model. Although a relatively minor effect, the UV background heats the gas, keeping it loosely bound and thus more easily swept away by tides and ram pressure.

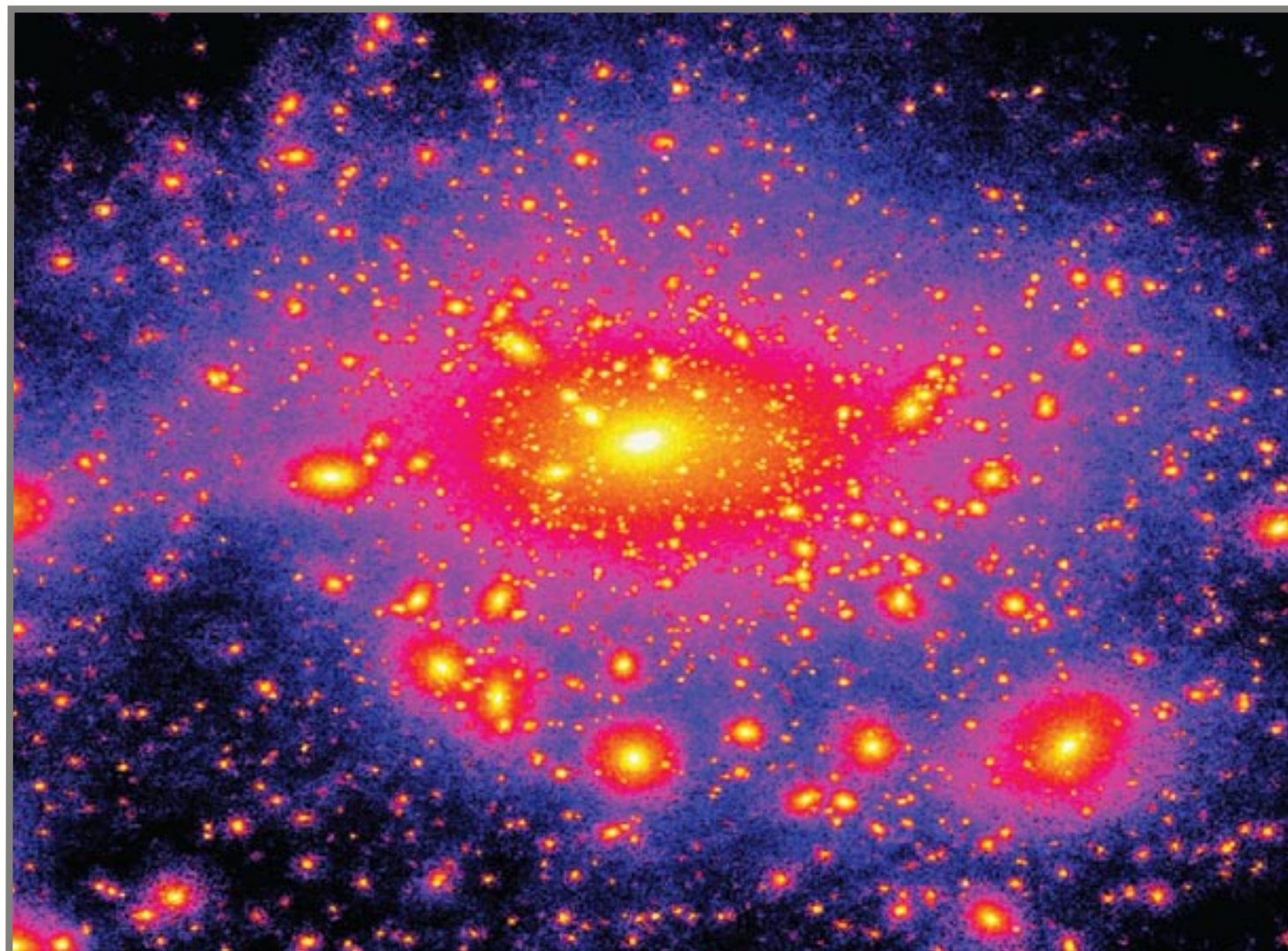
To represent a spheroidal dwarf galaxy and the outer portion of the Milky Way, the simulation included 3.2 million SPH particles and tracked them through 10 billion years of galactic evolution. For the final calculations, GASOLINE ran on 64 LeMieux processors for roughly 30,000 processor hours. Over a period of years, the dwarf-galaxy project used 150,000 to 200,000 LeMieux processor hours.



MERGING GALAXIES FORM PAIRED SUPERMASSIVE BLACK HOLES

In another project simulating galaxy interactions, Mayer, Kazantzidis, Thomas Quinn and colleagues relied on GASOLINE and PSC's LeMieux to arrive at the first simulated formation of paired supermassive black holes, a binary SMBH. This work, reported in *Science Express* (June 7, 2007), simulates a Milky Way-size galaxy merging with its twin, forming a new type of structure — a central disk of gas from a hundred to a few thousand light-years wide and from a few hundred to a billion solar masses.

The simulations followed these processes over a range of spatial and temporal scales, finding that when this gas disk forms the SMBHs in most cases form a binary system. Earlier simulation studies of black-hole binaries, says Kazantzidis, have been restricted to late stages of the merger, after the black holes had already formed a loose pair. Understanding of binary black-holes is critical in testing the existence of gravitational waves, as predicted by Einstein's General Theory of Relativity. [MS]



The results were conclusive. As gas-rich progenitors of dwarf spheroidals fell into the Milky Way 10-billion years ago, radiation from the cosmic UV background heated the small galaxy's gas. The process of tidal shocks shakes away some of its stars and stretches and loosens the gas density. At the same time, ram pressure strips away the small galaxy's gas. After 10-billion years a dwarf spheroidal galaxy has replaced the

ASTRONOMERS ARE ALREADY LOOKING FOR MORE DARK GALAXIES LIKE THOSE PREDICTED BY THIS WORK.

gas-rich progenitor. "The winds are so strong in the universe around galaxies like the Milky Way," says Mayer, "that they completely blow away the gas from the small galaxy."

In this image from Mayer and Kazantzidis' simulation, brightness (blue-to-violet-to-red-to-yellow) corresponds to increasing concentration of dark matter. The bright central region corresponds roughly to the Milky Way's luminous matter of gas and stars. The blue outline represents a boundary of the galaxy's dark-matter halo, with dark-matter satellites shown as bright clumps. The simulation predicts that such dark-matter halos are "lumpy," filled with hundreds of small satellites of dark matter, a finding that presents a potential resolution to the "missing satellites problem" of the CDM model of the universe.

All that remains are the few stars that had already formed in the center of the dwarf galaxy and a huge halo of dark matter. The dark matter stays because ram pressure and UV radiation don't affect it. This is one of the mysterious properties of dark matter — it interacts gravitationally with matter we see, but not in other ways, such as magnetically or chemically. The size of the spheroidal dwarf galaxies predicted by this simulation matches those of observed dwarf galaxies, lending further credence to the model.

"Due to the combined action of three environmental effects — ram pressure, tidal shocking and the cosmic ultraviolet background," says Kazantzidis, "a dwarf galaxy transforms into a dwarf spheroidal. No previous work has been able to elucidate the combined effect of these various environmental mechanisms on the structure of dwarf galaxies." Observational astronomers are already looking for the tiny, dark galaxies predicted by this work. If found, they will lend new force to the CDM model that successfully explains many aspects of cosmic evolution.

Because dwarf spheroidals are the most dark-matter dominated galaxies in the universe, they are ideal targets, says Kazantzidis, for experiments that try to identify the elusive dark-matter particle. "Dark matter is one of the grandest challenges of modern-day science," he says. "This new understanding of the darkest galaxies known may lead to fundamental insights into the nature of dark matter." (TP)

MORE INFORMATION:

www.psc.edu/science/2007/darkgalaxies.html