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COLLIDING DWARF GALAXY TRIGGERED FORMATION OF MILKY WAY'S SPIRAL ARMS REVEALED BY SUPERCOMPUTER SIMULATION AT UNIVERSITY OF CALIFORNIA, IRVINE

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A dwarf galaxy that has collided twice with our own Milky Way galaxy, and that is now coming around once again for a third impact, may well have triggered the formation of the Milky Way's beautiful spiral arms beginning more than two billion years ago. That is the main conclusion of a paper by Chris W. Purcell and four coauthors published today in the internationally renowned British research journal *Nature*. Purcell's findings are based on supercomputer simulations conducted for his Ph.D. dissertation completed in 2010 at the University of California, Irvine, a member of the University of California High-Performance AstroComputing Center (UC-HiPACC).

The fact that a dwarf galaxy—called the Sagittarius Dwarf for the constellation in which it is seen from the earth—is in the process of colliding and merging with our own Milky Way has been known for seventeen years. Up to now, most astronomical research has focused on the effects of the collision on the Sagittarius dwarf itself, because the vast gravity and tidal forces exerted by the large Milky Way is ripping the smaller galaxy apart into long streamers of stars wrapping around our own Galaxy.

In computations for his dissertation research, however, Purcell explored a new and important question: what effects have the repeated collisions of the dwarf galaxy, with its invisible but massive halo of dark matter, had on the larger Milky Way itself? "The Sagittarius Dwarf has clearly slammed into the disk of the Milky Way. We wanted to find out what it did to our Galaxy in the process," said James S. Bullock, a coauthor on the study.

The results were surprising, even to the coauthors. "The Sagittarius Dwarf impact triggered spiral arms in the Milky Way," concluded Purcell, who is now a postdoctoral research associate at the University of Pittsburgh. The supercomputer simulations revealed that far more important in the collision than the Sagittarius Dwarf's stars were its dark matter halo, which was itself about equal in mass to all the stars in the Milky Way. "When all that dark matter smacked into the Milky Way, 80 to 90 percent of it was stripped off," Purcell explained. "But the whirling disk of stars that was the Milky Way at this time was a very tenuous, chaotic system. That first impact produced instabilities that were amplified and quickly formed spiral arms and associated ring-like structures in the outskirts of our Galaxy."

Purcell's research paper, "The Sagittarius impact as an architect of spirality and outer rings in the Milky Way," which he wrote with four coauthors, has been published as a Letter in the September 15, 2011 issue of *Nature*. The full article is online, along with still images and movies from the simulations (see images and links at the end of this release).

Background

The Sagittarius Dwarf is a galaxy discovered in 1994. It is in a polar orbit (that is, in orbit over the north and south galactic poles) around our Milky Way galaxy. In 2003, infrared telescopes and supercomputers that traced the orbital motions of its stars has revealed that the Sagittarius Dwarf had actually collided with the Milky Way twice—once 1.9 billion years ago and again 0.9 billion years ago—and that it is now coming in for a third collision in just another 10 million years.

For a dwarf galaxy, the Sagittarius Dwarf is actually quite large, ranking in size (number of stars) somewhere between the Milky Way's two well-known irregular galaxy companions, the Small and Large Magellanic Clouds (which are visible to the naked eye from the southern hemisphere). Indeed, the Sagittarius Dwarf may have originally been as large as 10 percent the size of the Milky Way.

But visible matter—known to physicists as "baryonic" matter because ordinary atoms are made of particles classified as baryons—makes up only 4.6 percent of the universe. Nearly five times that much—23 percent—of the universe is made of invisible, transparent "dark matter," whose existence is felt through its gravitational influence. It is now known that every galaxy, including the Sagittarius Dwarf (pre-collision) and our own Milky Way, resides at the center of a giant halo of dark matter several times larger in radius and many times greater in mass.

Best cosmological estimates suggest that the dark matter mass of the Sagittarius Dwarf may have originally been somewhere between 30 and 100 billion (between 3×10^{10} and 10^{11}) times the mass of the sun—likely greater than the mass of all the visible stars in the Milky Way. Thus, using the GreenPlanet supercomputer cluster at the University of California, Irvine, Purcell and his colleagues ran two simulations of the dwarf galaxy's collisions with the Milky Way—one simulation for the lighter mass, and the other for the greater mass.

Both supercomputer simulations revealed that the first impact, which smacked the disk of the Milky Way flat on "like a ghostly belly flop" in the words of Purcell, would have stripped away 80 to 90 percent of the Sagittarius Dwarf's dark matter. Immediately, the collision also set up instabilities (fluctuations in density of stars) in the flat disk of the rotating Milky Way. Our Galaxy rotates faster toward its center than toward its edges, so those instabilities were stretched and sheared, leading to the formation of spiral arms. The simulations also revealed that the impact significantly influenced the tell-tale bar-shaped feature now known to exist at the center of the Milky Way. The impact also gave rise to ring-like structures found at the edges of our Galaxy's circumference (possibly including a visible feature called the Monoceros Ring for the constellation in which it is seen).

The second impact affected the Milky Way less, giving rise to only milder, less dense spiral-creating waves, because the Sagittarius Dwarf had by then lost most of its dark matter mass. Without the dark matter to hold the dwarf galaxy together, its visible stars began to be pulled apart by the Milky Way's huge gravitational field and tidal forces.

Today, long streamers of stars from the dismembered dwarf galaxy arch over and around the Milky Way, and "right now, some small fraction of the dark matter from the Sagittarius Dwarf is raining down onto the Earth," said Purcell. "Meantime, the Sun itself is revolving around the center of the Milky Way Galaxy, in a complex and still-evolving system of multiple spiral arms."

About supercomputer simulations and UC-HiPACC

GreenPlanet is a supercomputer cluster at UC Irvine primarily used to model the interactions of land, atmosphere, and ocean for climate studies. The cluster is owned and operated by the School of Physical Sciences, and is used mostly for parallel computing.

"This excellent work by Purcell and others at UC Irvine is a prime example of what supercomputing brings to computational astronomy," said Joel Primack, director of the University of California High-Performance AstroComputing Center (UC-HiPACC). "Supercomputer simulations allow astronomers to recreate a model of distant, violent events that occurred over billions of years, and observe that model in sped-up time, in order to make predictions that can be tested by actual observations of the real universe—as Purcell was able to do in comparing the spiral arms that might have been produced by Sagittarius Dwarf galaxies of different masses."

The University of California High-Performance AstroComputing Center (UC-HIPACC), based at the University of California at Santa Cruz, is consortium of University of California campuses—including

Irvine—plus three Department of Energy laboratories (Lawrence Berkeley Laboratory, Lawrence Livermore Laboratory, and Los Alamos National Laboratory). UC-HiPACC does not support research, but "one of its missions is to draw attention to the world-class resources for astrocomputing within the University of California system," noted Primack.

Purcell, a former graduate student at UC Irvine, collaborated with his Ph.D. advisor James S. Bullock and graduate students Erik J. Tollerud and Miguel Rocha, all at the University of California at Irvine. The fifth coauthor was Sukanya Chakrabarti at Florida Atlantic University; at the time of the work, she was a UC President's Fellow at the University of California, Berkeley. Bullock is the University of California, Irvine representative to the Council of UC-HiPACC.

Visualizations

Two images from the simulation with explanatory captions appear below.

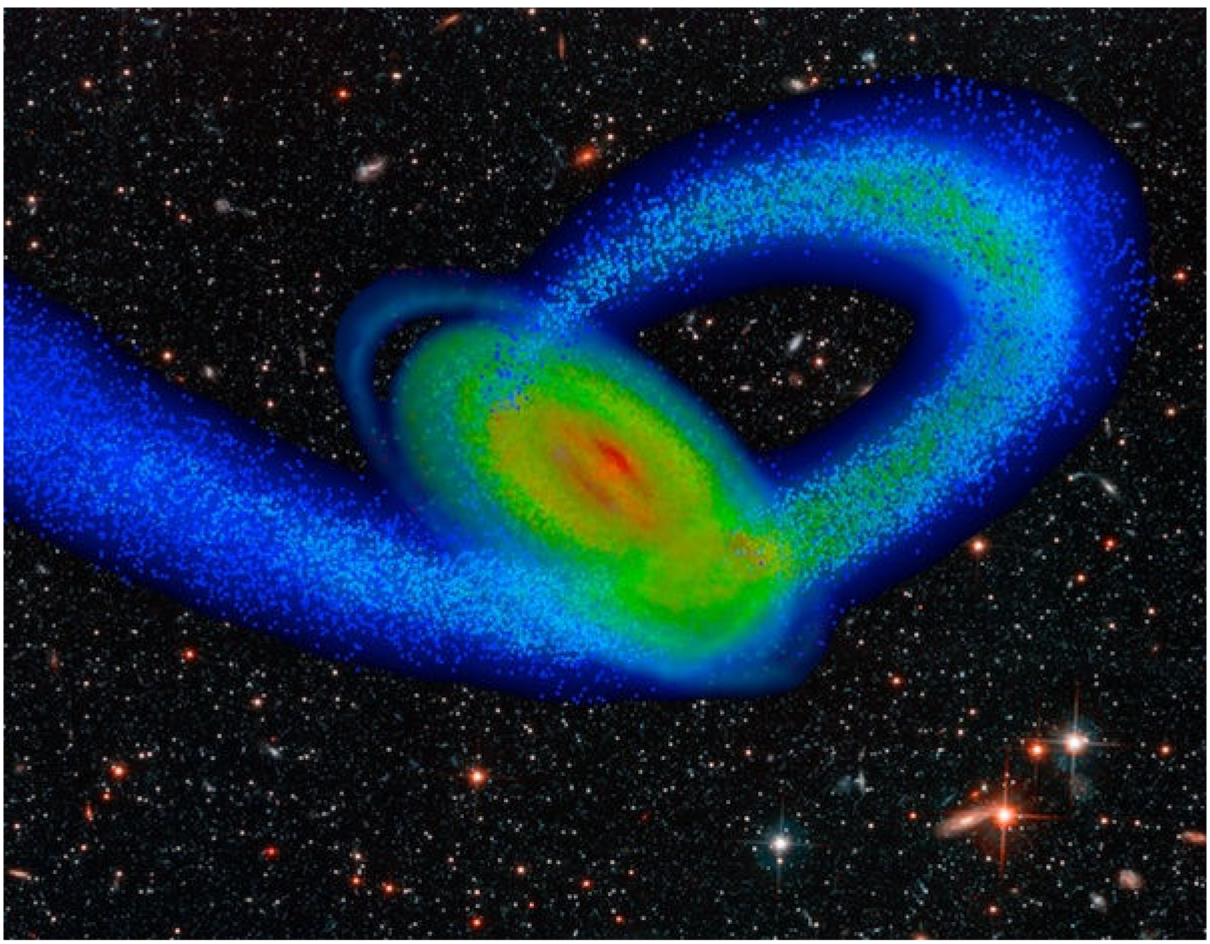

Figure 1 – Incoming third impact of the Sagittarius Dwarf galaxy (blue stream of stars) with our Milky Way Galaxy (multicolored disk) was simulated by supercomputer and rendered by Erik J. Tollerud against a background of galaxies seen in the Hubble Deep Field. Note the simulated disk's ring-like spiral extensions in the outer Milky Way (upper left), which strongly resemble actual streams found at low latitudes with respect to the disk plane, in the nearby region of the Milky Way viewed from the Earth in the opposite direction from the center of the Galaxy.

According to a paper by Chris W. Purcell and coauthors, just published in the British journal *Nature,* those spiral arms began to emerge after the initial impact of the Sagittarius Dwarf galaxy nearly two billion years ago; they have been amplified until the present day, into the many spiral arms observed in our Milky Way.

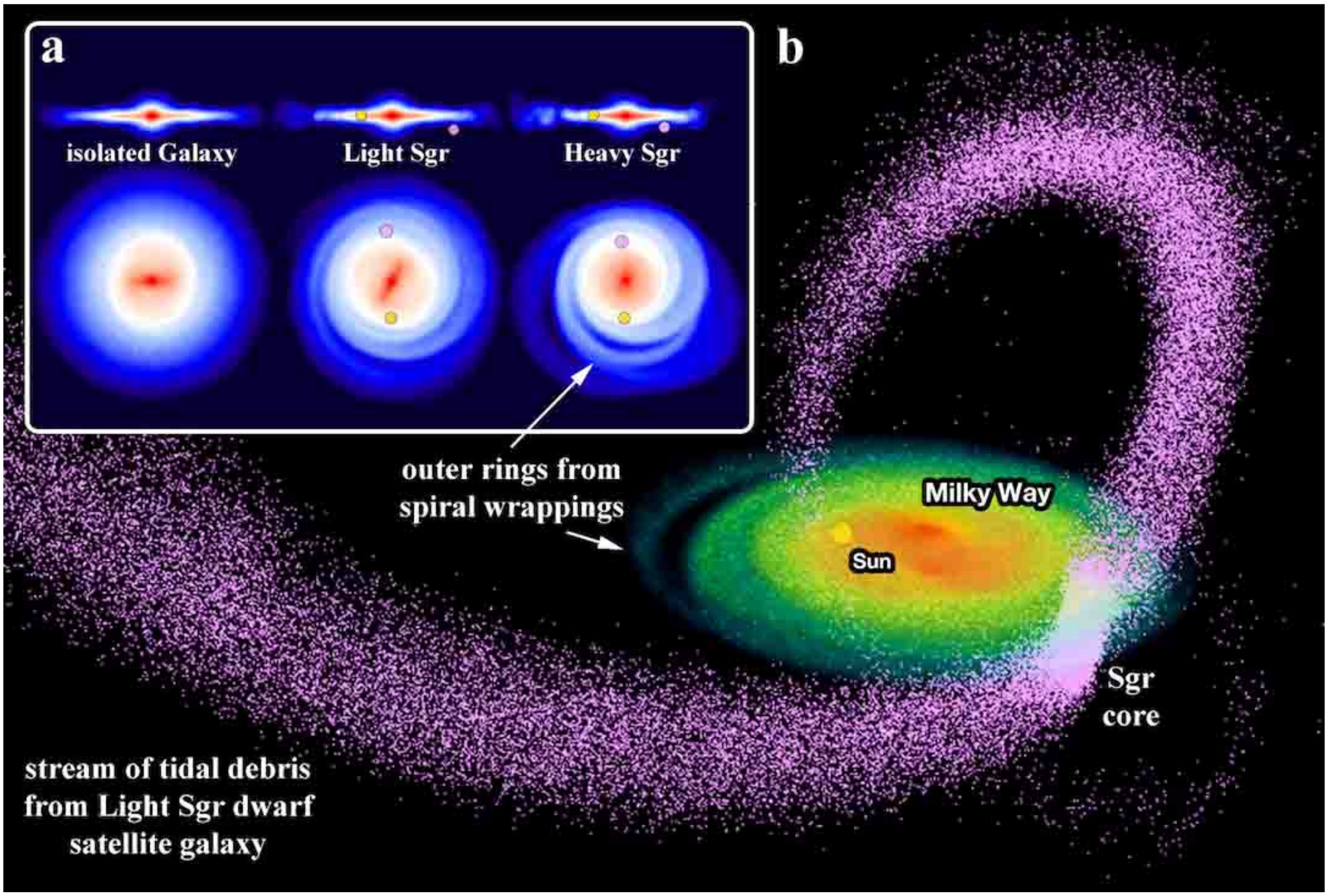

Figure 2: Computer simulations visualized the disk of the Milky Way Galaxy for three cases: no impact with a dwarf galaxy, impact with a Sagittarius Dwarf galaxy of lower mass (Light Sgr), and impact with a Sagittarius Dwarf galaxy of higher mass (Heavy Sgr). Our Milky Way Galaxy is shown both edge-on and face-on in the inset panels, and the sun's location is marked as a yellow dot and the present location of the Sagittarius dwarf's remnant core is marked as a pink dot, as shown after more than two billion years of isolated evolution. Shown in the background is a global rendering of the 'Light Sgr' tidal debris and the Milky Way disk.

Links

The full reference to the *Nature* Letter is: "The Sagittarius impact as an architect of spirality and outer rings in the Milky Way," by Chris W. Purcell, James S. Bullock, Erik J. Tollerud, Miguel Rocha, and Sukanya Chakrabarti, *Nature* 477: 301–303, 15 September 2011. The full text is available online from http://www.nature.com/nature/journal/v477/n7364/full/nature10417.html and from http://arxiv.org/abs/1109.2918 and http://xxx.lanl.gov/abs/1109.2918 .

Both Figure 1 and Figure 2 (in both 72-dpi low resolution and 300-dpi high resolution) are available on the University of California High-Performance AstroComputing Center website at http://hipacc.ucsc.edu/html/MilkyWayImpact.html, along with two movies illustrating how the impact of the Sagittarius Dwarf could have given rise to spiral structure in the Milky Way.

Slides from Purcell's presentation on this work at the 2011 Galaxy Workshop at the University of California Santa Cruz on August 11, 2011, sponsored by UC-HiPACC, appear at http://hipacc.ucsc.edu/Lecture%20Slides/GalaxyWorkshopSlides/purcell_santacruz2011.pdf .

The UC Irvine press release appears at http://today.uci.edu/news/2011/09/nr_milkyway_110914.php .

More information about the missions and work of the University of California High-Performance AstroComputing Center (UC-HiPACC) is at http://hipacc.ucsc.edu .

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