



Supernovae, supercomputers, and galactic evolution

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The stars in a galaxy emit radiation and solar winds, and they sometimes die in fantastic explosions. Supercomputer simulations are now beginning to assess how those energy releases affect the galaxy's life.

Perhaps the oldest question confronted by humanity is, "Where do we come from?" Philosophers pondered the issue thousands of years ago, and many people continue to ask the question today. For a modern scientist, the problem might be posed as, "How did we get from the Big Bang to the present day?" and the answer would be couched in terms of cosmology, astrophysics, and biology. The first step, at least for an astrophysicist, is to understand how our galaxy, the Milky Way, was formed.

A star is born

Galaxies are tremendously complex systems comprising normal matter, radiation, and dark matter, the nonluminous stuff that for practical purposes interacts only gravitationally. Fluid dynamics is influenced by gravitation, and plasma physics and nuclear physics come together inside stars—two hundred billion of them in a galaxy like the Milky Way. Moreover, galactic processes play out over an enormous range of scales. For example, the diameter of the Milky Way and the gravitationally bound spherical "halo" of dark matter surrounding it is about 200 000 light-years, whereas the diameter of a single star is just a few light-seconds. The complexity means the system is chaotic and nonlinear; the equations that describe it can be solved only numerically. The dynamic range means that numerical solutions push the world's premiere supercomputers to their limits.

Despite the challenges, physicists have arrived at a basic consensus as to how galaxies form (see the article by Tom Abel in *PHYSICS TODAY*, April 2011, page 51). Tiny fluctuations in the density of matter arise in the early universe during an "inflationary" epoch of rapid expansion. Those fluctuations grow as gravity attracts ever more material toward the denser bits. Eventually the dense regions become gravitationally bound. Dark matter, like regular matter, is captured. But since it essentially interacts only gravitationally, it forms an extended halo. On the other hand, as a region becomes more dense, its hydrogen and helium gases can interact with each other and with stray electrons. The photons emitted in those interactions escape and carry away kinetic and thermal energy; the cooled gas is pulled ever more strongly by gravity. The gas has some angular momentum, so it spins faster as it contracts, until its rotation halts further gravitational contraction.

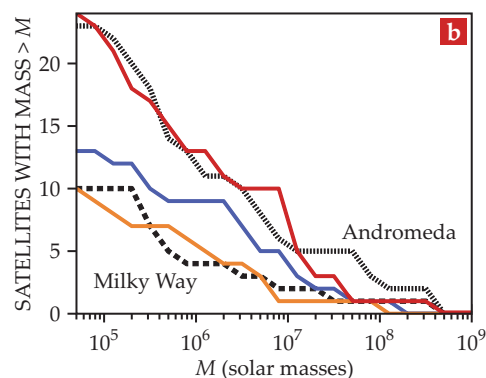
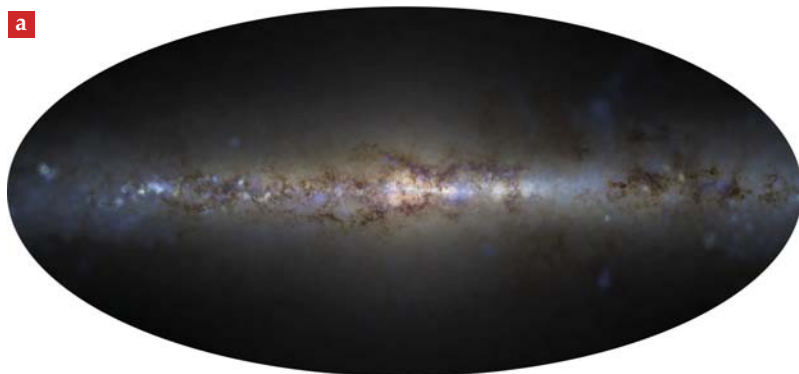
At that point, the galactic disk has formed. Within it, the concentration process repeats: Denser regions of gas pull together under the influence of gravity and continue to accumulate matter. Clumps of material break away, and in time, one of them gets so dense and massive that nuclear fusion ignites. A star is born.

A star is not to be ignored

As always, the devil is in the details. Simulations based on the above picture do a remarkably good job of obtaining the distribution of matter on large scales in the universe; we understand well why galaxies live where they live. But the simulations fail to reproduce the galaxies we actually see. Inevitably, they predict that almost all the normal matter in the universe should end up in stars, whereas only a small amount, perhaps a few percent, actually does. Moreover, they predict that the stars should have formed early in the history of the universe, when it was just a tiny fraction of its present size. However, we know that our sun, for example, formed when the universe was something like 75% of its current size.

By the 1990s astrophysicists realized that influences of the stars themselves simply cannot be ignored. After a star is born, its nuclear furnace emits energy in the form of radiation and stellar winds that can push on and heat up matter. Some of the most massive stars will explode as supernovae, thereby expelling a tremendous amount of energy in a cataclysmic event. In fact, the kinetic energy released by the supernovae that have exploded in the Milky Way is an order of magnitude greater than the gravitational potential energy holding the galaxy's normal matter together.

Advances in computer power, in computational algorithms, and in theories of stellar evolution have inspired a new generation of galaxy-formation simulations, including those of the Illustris and EAGLE projects and our own collaboration, the FIRE (Feedback in Realistic Environments) project. Our international collaboration comprises 16 institutions. Experts in supernova explosions come together with experts in gravitational dynamics, because the interactions between those processes are so critical. We are now able to simulate a galaxy like our own Milky Way over the whole of cosmic time, with a billion or so resolution elements for each time step (see panel a of the figure). Such resolution is short of that needed to model individual



REALISTIC GALAXIES with few satellites. **(a)** This Milky Way-mass galaxy, simulated by the FIRE (Feedback in Realistic Environments) project, includes filamentary molecular cloud complexes and young star clusters. **(b)** The plotted lines show the number of satellite galaxies whose mass M in stars (as opposed to dark matter) is greater than that given on the horizontal axis. The differences in the colored curves representing three FIRE simulations of Milky Way-mass galaxies reflect statistical variations. For comparison, the black curves show observations for the Milky Way (coarse dashes) and Andromeda (fine dashes), which has a similar mass. Unlike simulations that ignore effects of supernova explosions, the FIRE runs give a realistic population of satellites.

stars, but it's close. And it allows us to resolve key scales so that we can track, for example, the bubbles of hot gas generated when a supernova explodes and violently shocks the gas around it.

In the new generation of models, the above star-is-born story is just the beginning. Once the first stars form, they influence the larger-scale medium. Radiation, stellar winds, and kinetic energy from supernova explosions heat gas and sweep it out of large swathes of the galaxy. If a sufficient number of stars are formed, gas will be rapidly expelled from the galaxy, launched out in galactic superwinds with speeds of hundreds or thousands of kilometers per second. Such superwinds have been observed in many star-forming systems, and now models are able to follow, on galactic scales, the generation and impacts of those winds.

When feedback effects from stars are included, galaxy formation emerges as a competition between gravity pulling gas together and violent explosions blowing it apart. It is not an accident that the energy released by supernova explosions in the Milky Way is a reasonably small multiple of the gravitational potential energy of the stars in our galaxy. If fewer stars had formed, their energetic input would have been unable to stave off gravity; the result would be further collapse and additional star formation. If more had formed, they would have blown away material needed for the next generation of star formation. This realization has led to a new class of equilibrium models of galaxy formation wherein feedback loops regulate the cosmic cycle of inflow, star formation, and galactic outflow.

Stars as terminators

In recent work, we and other groups have shown that stellar feedback resolves one of many outstanding mysteries of galaxy formation, the so-called missing satellites problem. (See the article by Jeremiah Ostriker and Thorsten Naab in *PHYSICS TODAY*, August 2012, page 43.) In short, the simple models that ignored feedback predicted that the Milky Way would be orbited by a swarm of thousands of small, luminous galaxies called dwarf galaxies. In fact, only a couple dozen such systems are seen. Theorists speculated that dwarf galaxies, with their relatively small gravitational binding energy, would be

profoundly altered by feedback processes. For the smallest dwarfs, a single supernova explosion might be enough to terminate star formation forever; the tiny galaxies would be mostly dark. The new simulations of Milky Way-mass galaxies, with their resolution and physics sufficient to capture the evolution of the dwarf satellites and their stars, demonstrate that, indeed, stars shut down their own siblings' formation (see panel b of the figure).

Much work remains to be done. Galaxies smaller or larger than the Milky Way present their own challenges. For example, theory suggests that in the most massive galaxies, the dominant source of feedback energy comes not from stars but rather from matter falling into the supermassive black holes at the galactic centers. Limitations in modelers' understanding of the basic radiation and plasma physics mean that our treatment of radiation-matter coupling, magnetic fields, and cosmic rays is either oversimplified or nonexistent. Such entities almost certainly will present a rich, new phenomenology to explore, and once they are properly accounted for, the story of galaxy evolution might change again. But without a doubt, feedback is here to stay and the small and large scales of the universe will remain inextricably linked.

Additional resources

- P. F. Hopkins et al., "Galaxies on FIRE (Feedback in Realistic Environments): Stellar feedback explains cosmologically inefficient star formation," *Mon. Not. R. Astron. Soc.* **445**, 581 (2014).
- M. Vogelsberger et al., "Properties of galaxies reproduced by a hydrodynamic simulation," *Nature* **509**, 177 (2014).
- R. A. Crain et al., "The EAGLE simulations of galaxy formation: Calibration of subgrid physics and model variations," *Mon. Not. R. Astron. Soc.* **450**, 1937 (2015).
- A. R. Wetzel et al., "Reconciling dwarf galaxies with Λ CDM cosmology: Simulating a realistic population of satellites around a Milky Way-mass galaxy," *Astrophys. J. Lett.* **827**, L23 (2016).
- Phil Hopkins' Research Group, "Animations," www.tapir.caltech.edu/~ph Hopkins/Site/animations.

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