FROM DUST TO DUST

A unique supercomputer provides a glimpse of how galaxies evolve

By IVARS PETERSON

The images lack the flash and action of a video game. Nonetheless, the patterns weaving across the screen have a mesmerizing effect. Strands and filaments in speckled shades of red, orange and yellow float against a background of blue pinpoints. Lumps accumulate, then disappear. Bubbles collapse, then form again.

This "galaxy in a box," a remarkable computer simulation, suggests how a galaxy evolves, as marked by the ebb and flow of interstellar dust and gas against a background of stars forming and dying. In this simulation, minutes of computer time stretch into billions of years on a galactic time scale.

By matching such computer models with astronomical observations, scientists hope to determine the fundamental factors affecting galactic evolution. Already, the results of simulations show that a wide range of initial conditions produce plausible patterns of star formation and destruction within a galaxy.

What makes the galaxy-in-a-box simulation possible is the use of a one-of-a-kind, experimental supercomputer that combines the power of 576 individual processors, each one roughly as capable as the original Cray-1 supercomputer. But even with such a machine, it takes careful programming, tremendous attention to detail and a number of mathematical tricks to get the right images on a screen quickly enough so that scientists don't need to wait hours or even years for results.

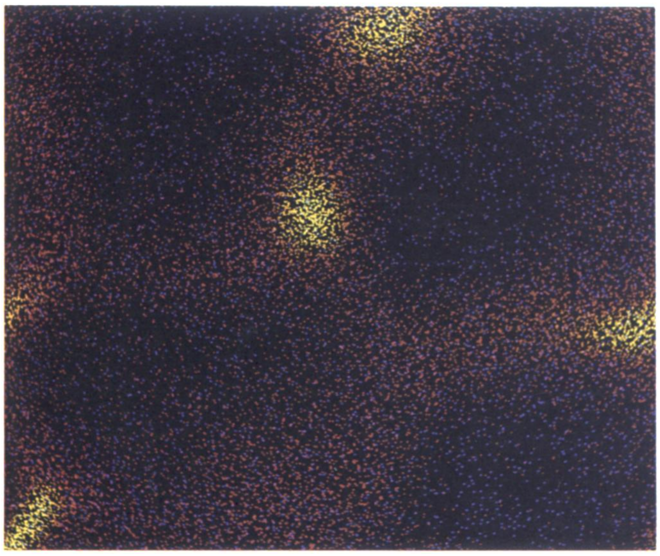
Developed over the last three years, the galaxy-in-a-box simulation represents the joint efforts of astrophysicist Kevin H. Prendergast and mathematicians David V. Chudnovsky and Gregory V. Chudnovsky, all from Columbia University in New York City, and M.M. (Monty) Denneau of the IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y., who designed and built the GF11 supercomputer.

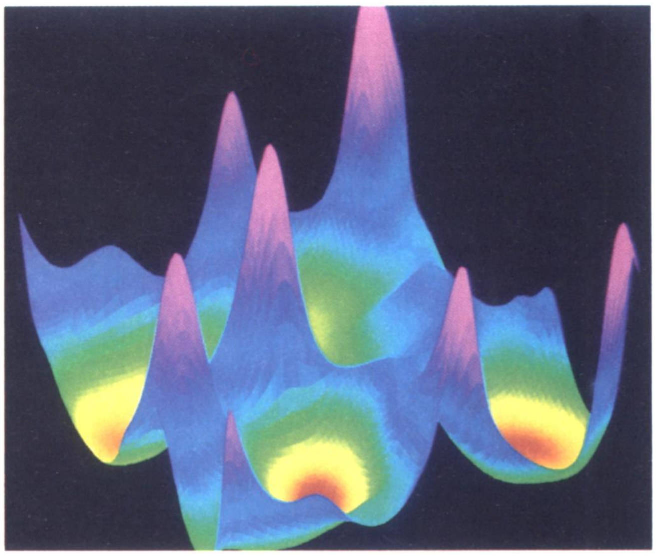
Stars condense out of clouds of coalescing gas. During their lifetimes, fueled by internal nuclear engines, they slowly evaporate, or lose mass, by returning gas to the interstellar medium. Massive stars end their lives in supernova explosions, leaving behind small remnants in the form of neutron stars or black holes and scattering the bulk of their mass as dust and gas. Eventually, this ejected material gets recycled, becoming part of another generation of stars.

This picture of the birth and death of individual stars emerges from a combination of physical theory and observations of nearby astronomical objects, especially of regions where stars now appear to be forming. Missing is the bigger picture of how entire galaxies, consisting of billions of stars, form and evolve.

The Columbia-IBM collaboration attempts to construct a realistic computer model of galactic evolution embodying what is known about the interaction of stars and interstellar gas. The model incorporates Newton's laws of motion, star formation and evaporation, the effects of stellar winds and starlight in heating up and pushing around interstellar gas, and the cooling of interstellar gas by the emission of infrared radiation.

The initial computer model developed by Prendergast and his collaborators illustrates star and gas interactions in two dimensions, on a square grid consisting of 100 rows of 100 cells each. That grid represents a slice through a portion of a galaxy about 1,000 light-years across. On this scale, stars are too numerous to be pictured individually, and the stars and gas are treated computationally as two separate but intermingled fluids – not unlike computer simulations in hydrodynamics showing the mixing of two different liquids. For each cell at every time step, the computer calculates the new gas and star densities, taking into





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This frame from a two-dimensional, "galaxy-in-a-box" simulation (left) shows a statistical sampling of stars (blue dots) and the density of interstellar matter (ranging from red at low densities to yellow at high). The landscape plot (right) is an alternative method of showing the density distribution of interstellar matter.

account the effects of star formation, mass loss, and stellar heating and radiative cooling.

On a typical supercomputer, such computations would take days. But Denneau's GF11 supercomputer is special. The hardware fills a room. A massive air cooling system, running 2,000 fans and using 250,000 watts of electricity, controls the temperature. A vast, rapid switching network, requiring 200 miles of cable, handles communication between processors, allowing the linking of any particular processor with any other. An equivalent telephone switching network could handle all of the telephone calls made in New York City.

For the Chudnovsky brothers, programming such a machine posed a special challenge. They needed to find efficient ways of parceling out the galaxy-in-a-box calculations among the GF11 supercomputer's processors. By carefully dividing up the task among a specified number of processors, they could significantly speed up the calculations.

The mathematicians also had to streamline their computer program to use the computer's processors as efficiently as possible. In several instances, that step required the use of a sophisticated computer algebra program known as Scratchpad II to transform algebraic expressions and equations into forms that better fit the computer's modes of operation.

"We developed custom-designed programs for utilizing the peak performance of the machine," David Chudnovsky says. "Properly programmed, the GF11 is capable of performing the world's fastest scientific calculations."

As an example of the GF11's high performance, a quarter of the machine can simultaneously run 150 independent, two-dimensional galaxy-in-a-box cases, calculating at an effective rate of 3 billion arithmetic operations on real (decimal) numbers per second. Simulating 2 billion years of galactic evolution requires approximately an hour of computer time.

Writing programs for such a unique machine as the GF11 has its advantages and disadvantages, says Gregory Chudnovsky. There are no publications or experts to consult for advice, "but it's also fun to drive a machine that no one else has ever driven," he says.

The resulting simulations show physical processes at work in a representative piece of a galaxy under a given set of physical conditions. For each computer run and test case, the researchers vary the rules governing star formation and gas heating and cooling.

"The real game is to see if you can find simple rules that give you interesting results," Prendergast says. To be worthwhile and credible, such simulations must produce results that agree with observations of the form, color, light distribution and internal motions of real galaxies.

Test cases reveal the growth of foamlike structures made up of cold gas clouds and the formation of hot bubbles and filaments. When the gas density in a region gets high enough, stars begin to form. That process, in turn, lowers the gas density. Starlight and stellar winds heat and disrupt surrounding clouds, generating gigantic, expanding bubbles of hot gas. Filaments of cold, dense gas develop at boundaries wherever one growing bubble impinges on a neighboring bubble. As the cycle proceeds, these filamentary gas clouds cool and grow more dense, star formation begins, and clouds of leftover gas and dust are disrupted again.

The researchers have found they get the same general patterns for a wide variety of initial conditions. "It doesn't seem to matter what you specify in detail," Prendergast says. "Eventually, we'll be able to settle on parameters for star formation and gas cooling that seem to give the most realistic images." Those results will be useful in formulating more sophisticated, three-dimensional computer models incorporating the effects of gravity and encompassing an entire galaxy.

Work on the three-dimensional version of the galaxy-in-a-box simulation is almost completed. Computing what happens to stars and gas in a galactic cube, 100 cells on a side, turns out to be comparatively straightforward. The hard part is figuring out what to do with the massive amounts of data produced. "The main issue we're really struggling with is: What can you see?" Gregory Chudnovsky says. "You can do the computations in three dimensions, but how do you view the data?"

The researchers want to tailor their output to the needs and preferences of astronomers. Ideally, astronomers would like to "fly" through a simulated, three-dimensional galaxy, observing the skyscape from a variety of viewpoints as it evolves. But it would take several supercomputers as powerful as the GF11 just to manage the production of the graphic images.

"It's a pretty messy problem in visualization," David Chudnovsky says. "Of course we can do [two-dimensional] slices, but we are working very hard on creating some effects that will allow us to construct [see-through] three-dimensional structures." □