In Search of Planetary Pancakes

There aren’t enough stars in the Milky Way. Few of us notice, but it’s a problem. We don’t think about it when we look at the night sky, because there’s 100,000 million stars in our Galaxy, which seems like enough. Still, physicists like Mike Norman want to know why there’s not more.

The problem has to do with molecular clouds, huge gaseous conglomerations of matter — mostly molecular hydrogen (hence the name) along with helium and a trace of other elements. “You can think of molecular clouds as being a stage on the way to star formation,” says Norman, an astrophysicist at the University of California, San Diego. “The more smoothly distributed gas in our Galaxy has to collect, become dense, and it has to cool. And just like hailstones form out of a thunder cloud when conditions are right, stars form out of a molecular cloud.”

But something happens that physics hasn’t yet been able to explain. “Given these big molecular clouds,” says Norman, “which have up to a million solar masses of material — why are they forming stars at such a pitiful rate?”

The question, which astrophysicists have pondered for about 40 years, centers on a calculation called “free-fall time.” Given the force of gravity and the observed density of molecular clouds, they should collapse into stars almost 10 times faster than they do. “You’ve got this enormous reservoir of gas,” says Norman, “and you’d expect it to collapse in a million years and convert a large fraction of its mass to young stars. And it doesn’t. Molecular clouds appear to be at least 10 million years old, and maybe 20 to 30 million years.”

It’s a perturbing gap in understanding, not least of all since the process of how stars form slides across the border from physics into biology. Carbon-based life, the only kind we know, requires planets, and planets are born from the aura of gas and dust swirling around young stars. The processes that underlie star formation and that, at least once anyway, led to a metal-laden planet with an oxygen-rich atmosphere are, in other words, intrinsic to the origins of life.

What holds up molecular clouds? That’s the question in a nutshell. One idea has been that magnetic fields in the swirling, turbulent gas clouds are strong enough to counteract gravity. Or maybe the turbulence itself is enough counterforce, or some combination. Supercomputing offers a means to explore what’s happening and fill-in the gaps between observation and theory, but it’s a monstrously challenging modeling task. “Right off the bat,” says Norman, “you’re confronted with a three-dimensional, magneto-hydrodynamic, self-gravitating medium — a lot of adjectives. This is why it’s an unsolved problem.”

This spring, taking advantage of the prototype Terascale Computing System at PSC, Norman and his colleagues Pakshing Li of the National Center for Supercomputing Applications (NCSA), Mordecai-Mark Low of the American Museum of Natural History and Fabian Heitsch of the Max Planck Institute for Astronomy mounted the most exacting simulation of star formation in a molecular cloud ever attempted. With resolution eight-times greater than heretofore possible, these computations provide clear pictures of gas clumps collapsing into dense, disk-like cores — the progenitors of stars. It’s the first time dense cores with disk-like structure, resembling the pancake-shaped protoplanetary disks observed by the Hubble Space Telescope, have formed in a simulation.

PROPLYDS

A new word was coined in 1994 when the Hubble Space Telescope revealed swirling disks of dust around young stars in the Milky Way. Rice University astronomer Robert O’Dell, who discovered the disks, dubbed them “proplyds,” for protoplanetary disks — the raw material out of which planets form.

Before the Hubble discovery, dust disks had been confirmed around only four stars. O’Dell and his colleague Zheng Wen surveyed 110 stars in the Orion Nebula, only 1,500 light-years from Earth, and found proplyds around more than half. All contain enough mass and necessary ingredients — carbon, silicates and other metals — to make Earth-like planets, and their abundance reinforces the belief that planetary systems are common in the universe.

It’s an important discovery because proplyds, which are much harder to see than stars, have been a missing link in the story of how planets form, bridging the gap between molecular clouds and stars. “This gap is now starting to be filled observationally,” says Norman, who did his Ph.D. thesis 20 years ago on star formation, “but it’s never been filled in computationally, because there’s such a vast range of scales that need to be encompassed — from interstellar distributed regions to protostellar concentrations, and we haven’t had the computational capability.”
Density of the molecular cloud as simulated (increasing from dark blue to red) at one plane through the cubic grid. The simulation first establishes the molecular cloud as a turbulent medium. Then gravity is switched on. By 4.25 freefall times, the end of the simulation, 12 disk-like cores have formed. Grid resolution is insufficient to resolve further evolution of these cores.

THE MOST EXACTING SIMULATION OF STAR FORMATION YET ATTEMPTED REVEALS THE DISK-LIKE PROGENITORS OF PLANETS.
O’Dell’s observations include identifying features — frisbee-like spin of the disk material and jets of gas shooting out from the centers like the axis of a top — that provide a profile, in effect a picture of what to look for with simulations, which can add detail and physical understanding to the observations. “It’s the picture we’ve had for years as a mental construct,” says Norman. “As gas collapses out of the molecular cloud into a dense core, it conserves angular momentum, so that the core spins up into a disk around the forming star.” With simulations at PSC, Norman evolved that picture further than has been possible till now.

RESOLUTION, RESOLUTION, RESOLUTION

Within the last two years, a series of simulations took aim at identifying the processes that hold up star-formation in molecular clouds. Using several SGI Origin 2000 systems, Mac Low, Heitsch and Dutch astrophysicist Ralf Klessen simulated gravitational collapse in turbulent molecular clouds using astrophysics modeling software called ZEUS, developed by Norman and his students at NCSA’s Laboratory for Computational Astrophysics.

Essentially, these simulations put a supersonic turbulent medium with a magnetic field and gravity into a three-dimensional box. ZEUS sets the cloud into motion, governed by the known physics, and the simulation proceeds in time to see what happens. These large-scale Origin 2000 simulations indicate, first, that the turbulence of molecular clouds dissipates too rapidly to support them against gravitational collapse.

What about magnetic fields? “Turbulence decays rapidly,” explains Norman, “but we think magnetic fields in molecular clouds don’t dissipate. Like a lump under a rug, if you push on it here, it goes over there. Maybe in some parts of the molecular cloud the magnetic field is weak. Couldn’t this be the way in which dense cores form?”

Heitsch, Klessen and Mac Low’s most recent simulations looked at this question. Can pockets of gas form that become gravitationally unstable and collapse to form dense cores? The answer appears to be yes. The simulations showed cores beginning to form, but the 3D box — a cubic grid with 256 points in each dimension — lacked resolution to track the collapse far enough to see disk-like structure.

With this immediate background, Norman realized that the “friendly user” testing period on the prototype Terascale Computing System presented an opportunity. Preliminary runs using a new massively parallel implementation of ZEUS showed that the TCS ran three times faster per processor than the Origin system, with sustained per-processor performance of 500-600 million arithmetic operations per second. This performance, with full-system runs of 256 processors, made it feasible to double the grid-size — 512 points in each dimension, a total of 134 million gridpoints, an eight-fold improvement in the ability to see structural detail.

After a total running time of about 450 hours, the molecular cloud collapsed into 35 dense cores. Twelve of them show disk-like structure. Analysis of these 12 disk-like cores shows a magnetic field perpendicular to the disk plane that sweeps into a corkscrew at the spin axis on both sides of the disk, fitting with the proplyd picture of gas jets shooting out from the center. “The magnetic fields are bipolar,” says Norman, “torqued into this helical structure that’s often invoked, but never before produced in a self-consistent simulation.”

It’s the largest star-formation simulation ever done, and the results confirm that resolution can make all the difference in representing complex physical reality. Unlike proplyds, the disk-like cores in the simulation, says Norman, represent only the genesis of star formation. “Proplyds are an end-point of the collapse of these cores to form new stars in protoplanetary systems, and our simulations don’t go that far. Because of limited resolution, we have to stop well before proplyd disks are formed. But if you’re going to make a star with a centrifugally supported disk of material around it, you’re going to have to start with a collapsing core with some angular momentum. This is what we found.”

For “Star Cores” the sequel, to see if these early-stage disk-like cores evolve further along the pathway to proplyds, stay tuned. With the full-scale Terascale Computing System, Norman plans to again double the resolution in each dimension, to 1,024 grid points. “The history of science is based on smart people attacking simple problems,” he says, “leaving the hard problems for the next generation. The great thing about supercomputing is you can attack the hard problems.”

More information: http://www.psc.edu/science/norman.html
MAGNETIC FIELD LINES AND ROTATIONAL VELOCITY FOR CORE FIVE

Magnetic field lines (left) indicate twisting from disk-like core rotation, with lighter color showing stronger magnetic field. For the velocity field (below), vector length corresponds to magnitude and color represents density.