

Alexei Kritsuk, top left

Paolo Padoan, top right

Mike Norman, middle left

Rick Wagner, bottom left

Coherent V-shaped bow shock structures in hypersonic turbulence at Mach 6.

# COOKING STARS AT MACH 6

Simulations open new understanding of hypersonic shock waves that contribute to the birth of stars

**“In space, no one can hear you scream.”**

Although this line from the movie “Alien” packs a dramatic punch, the physics is wrong. Sound travels in space, even in vast regions where the density of matter is extremely low. And if you were inside a molecular cloud — regions where hydrogen is dense and stars are born — you’d experience deafening booms of hypersonic sound waves.

Clouds of gas crashing inward under their own gravity produce sonic booms, and an occasional exploding star would add to the acoustical mayhem. “The place where stars are formed is not in the least quiet,” says University of California, San Diego (UCSD) astrophysicist Alexei Kritsuk.

Kritsuk and UCSD colleagues Michael Norman, Paolo Padoan and Rick Wagner have used a range of TeraGrid computing resources to simulate hypersonic shock waves.

They are especially interested in how these violent phenomena induce turbulence — one of the most important factors in a complex of factors that lead to the birth of new stars. But accurate simulation poses exceptional challenges because, while most turbulence studies deal with “incompressible” flow — having uniform fluid density — the shock waves in molecular clouds produce huge contrasts in density and the turbulence is highly compressible.

In 2007, Kritsuk and colleagues used systems at SDSC and NCSA for a series of simulations of turbulent flow at Mach 6. Their results, reported in the *Astrophysical Journal* (August 2007), showed that well-established characteristics of incompressible turbulent flows do not hold for supersonic compressible turbulence, and they proposed a more general theory that encompasses both flow regimes.

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This year, the researchers extended this work with simulations at PSC (BigBen) and TACC (Ranger). This newer work, involving 1.3-million hours of computing, produced 50 terabytes of data. With analysis still underway (using SDSC's DataStar and PSC's Pople), preliminary results show that the new data confirm the prior studies. Beyond what they tell us about star formation, these studies may shed new understanding on the hypersonic aerodynamics of high-speed aircraft and re-entry space vehicles.

### STIRRED, NOT SHAKEN

The space between stars — the interstellar medium — for the most part contains cold, neutral (no electrical charge) hydrogen atoms. "If you want to create a star," says Kritsuk, "you need to cook up a cloud of the cold, neutral medium, then find a dark space and compress it further, so molecular hydrogen ( $H_2$ ) begins to form, and as it cools to lower temperatures and the densities go up, you will eventually get a collapsing protostellar core."

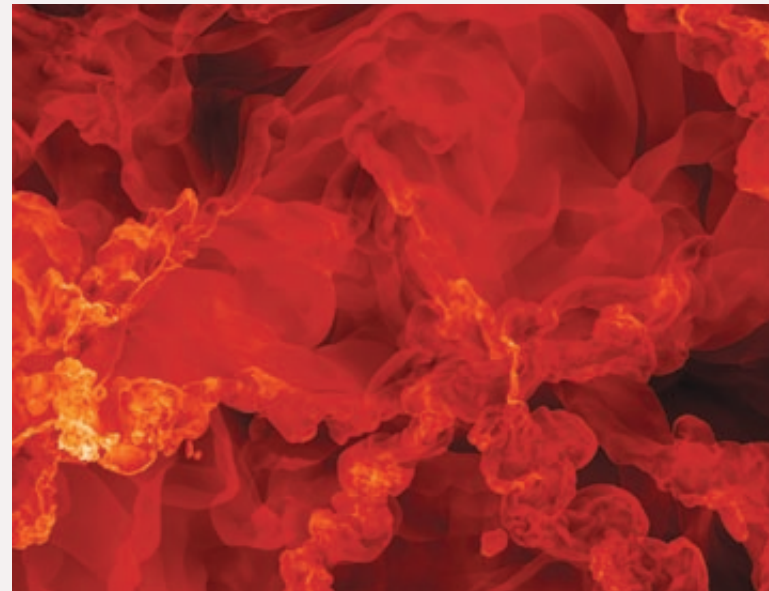
When shock waves occur in these clouds, they push the hydrogen molecules closer together, and at a certain critical density stars begin to form. It sounds simple enough, but much is unknown about these turbulent phenomena and their impact on star formation.

Most of what we know about turbulence is based on geophysical and engineering phenomena: mixing of hot and cold air in the atmosphere to form weather fronts, flow of oil through a pipeline, mixing of gas vapors and air in an engine's combustion chamber. The fluid is at virtually the same density throughout the turbulent region, with only a small amount of variation. Scientists call this uniform state an "incompressible fluid."

Shock waves moving at hypersonic speeds, however, create enormous density variations. One region of a gas cloud can be a million-times denser than a nearby region, and this "compressible" fluid behaves much differently than its incompressible cousin. "If you are sitting on a blob of gas that is a million-times denser than the surrounding medium," says Kritsuk, "you will just fly like a bullet."

To simulate gas clouds with such a density contrast, Kritsuk and his colleagues used ENZO, a program developed at the Laboratory for Computational Astrophysics at UCSD for simulations of cosmological structure. They modeled a cubic volume of space five parsecs (about 98-trillion miles) on a side, filled with hydrogen atoms at an initial density of 500 particles per cubic centimeter and a temperature of 10-degrees Kelvin. In the first round of simulations, they subdivided this volume with a grid ( $512^3$  points) and zoomed in to a finer resolution ( $2048^3$  points)

This graphic shows gas density in a thin slice through the simulation volume, increasing from very low to very high [black through red and yellow to white].



### Simulating these clouds of molecular hydrogen led to a new fundamental understanding of turbulence.

to get a closer look when the density in a particular area increased by a factor of two or more. In the latest simulation, they used the higher resolution throughout the run to take advantage of the Cray XT3's larger memory capacity and speed-up the calculations.

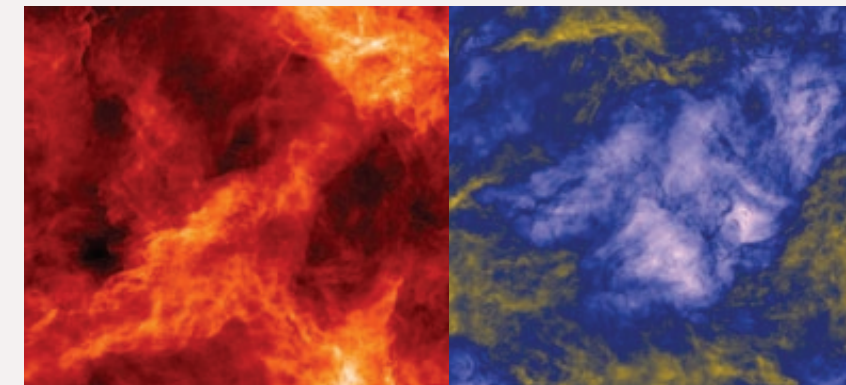
The shock waves produced in these simulations churned cold clouds of molecular hydrogen into compressed regions, and led to a new fundamental understanding of turbulence.

### RESTORING THE FORGOTTEN VARIABLE

In 1941, Russian mathematician Andrei Kolmogorov developed equations that offered a new insight into turbulent flow. In Kolmogorov's view, large vortices or eddies occurred first in a fluid in which turbulence formed, and these large vortices then formed smaller vortices, leading to a conception of turbulent flow as "whirls within whirls."

Velocity and density are both part of Kolmogorov's equation, but for a long time researchers concentrated only on velocity. This made sense, says Kritsuk, because mostly they were concerned with solving

3D projections through the simulation volume represent density of the molecular cloud.



engineering problems. But this concentration also led to a blind spot. "People were working for so many years with incompressible turbulence that they almost completely forgot about density, and what we have done here is put the density variable back in place.

In restoring this forgotten variable, Kritsuk and his colleagues have extended turbulence theory to new levels. "We have shown that if you put density back in place you still get Kolmogorov's law, even for hypersonic flows," says Kritsuk. "When you have density contrasts of a million, it's really important to include density-velocity correlations — and then modeling turbulence becomes simple."

To make things even more simple, Kritsuk is analyzing the 50 terabytes of data using SDSC's DataStar and Pople, PSC's newest system whose shared memory and open multi-processing (OpenMP) architecture allows him to work with the huge  $2048^3$  data-cubes quickly and efficiently. Pople also shares a parallel file-system with BigBen that minimizes file-transfer time.

Besides demonstrating that Kolmogorov's theory applies universally to compressible and incompressible fluids, Kritsuk's work also confirmed that there is order in the apparent chaos of turbulence. Visual representations of the simulation reveal "coherent structures" in the molecular clouds. The most common structural elements are nested bow-shocks having a V-shaped structure, also known as "Mach cones." These cones form when supersonic shock waves coming from opposite directions collide in the molecular cloud. The large V-shaped bows are made up of sequentially smaller V-shaped bows to the current limits of resolution in these simulations, indicating the self-replicating, fractal nature of these structures.

Finally, in confirming that turbulence described by Kolmogorov's equation is universal, covering

situations where the density of a fluid varies by a factor of a million, Kritsuk's group may also help astrophysicists explain another universal phenomenon: the uniform distribution of star masses in molecular clouds — called the "initial mass function."

"You basically have some small fraction of massive stars, then more stars of smaller masses," explains Kritsuk. "The peak of this mass distribution of newly formed stars is roughly one solar mass — the mass of our sun. Then

there are brown dwarfs and such stars having very small masses." Everywhere you look in the universe this distribution is the same.

Kritsuk's collaborator Paolo Padoan and Åke Nordlund of the Niels Bohr Institute, Copenhagen have proposed that supersonic turbulence in dense molecular clouds is the process that underlies the initial mass function, fragmenting the interstellar medium and creating the initial conditions for star formation. Based on his latest simulations, Kritsuk tends to agree. "There are not that many candidates out there. We have high hopes that the universal process we all know — turbulence — will solve the mystery of the initial mass function."

Kritsuk next plans to collaborate with researchers at Purdue University who have a shock tube capable of achieving Mach 6 hypersonic flow — to validate the computational model experimentally. Then he wants to do a second study using BigBen to add magnetic fields to the model of star formation. "Of course, to really model star formation, you need to include magnetic fields," says Kritsuk. "Numerically it's a challenge, and there's a lot of new interesting physics there. Adding the magnetic field components is like opening a Pandora's box." It's a box for which Kritsuk and his colleagues are eager to start prying the lid. (TP)

### MORE INFORMATION

<http://www.psc.edu/science/2008/mach6.html>