MAGNETIZED MODELS OF GIANT IMPACTS

Allocation: Exploratory/30 Knh, 300 Knh
PI: Charles F. Gammie[1]
Co-PI: Patrick Mullen[1]

[1]University of Illinois at Urbana–Champaign

FS

EXECUTIVE SUMMARY

The giant impact hypothesis suggests that about 4.5 billion years ago, a highly energetic, off-centered collision between a Mars-sized body and the proto-Earth formed a massive debris disk about the early Earth. It is from this orbiting disk of debris that the Moon is thought to have coalesced. Numerical simulations of the giant impact require massively parallel, high-resolution, multiphysics simulations. The research team's models, applied to the Blue Waters supercomputer, are unique in that they are the first to address the dynamical importance of any magnetic field the impactor and/or proto-Earth may have possessed. These simulations have found that the natural consequence of a magnetized Moon-forming giant impact is a disk of debris hosting a toroidal magnetic field. A series of high-resolution numerical experiments also demonstrated that magnetic field strengths are amplified by as many as three to four orders of magnitude following the impact and early disk evolution.

RESEARCH CHALLENGE

Shortly after the formation of the solar system, the giant impact hypothesis suggests that a Mars-sized impactor, Theia, struck the proto-Earth in an off-centered collision. This giant impact sent liquid and vaporized silicates into orbit around the proto-Earth, forming a protolunar disk from which the moon is thought to have coalesced. Three-dimensional simulations of this impact have been studied extensively; however, all of them have neglected the potential role of magnetic fields [1,2]. Therefore, the research group employed the Blue Waters supercomputer to study the dynamical importance of magnetic fields in the giant impact and the early evolution of the protolunar disk.

METHODS & CODES

The team applied the astrophysical magnetohydrodynamics code Athena++ [6]. Athena++, written in C++, operates in a purely Eulerian framework and uses a hybrid parallelization model based on OpenMP/MPI. The code employs a task-based execution model: each thread works on whichever tasks are presently available during a given timestep. Athena++ is modular; the included physics (such as magnetic fields, self-gravity, equation of state, diffusion, and the like) in addition to the choice of integrator/reconstruction method and coordinate system, are set as configure options at build time.

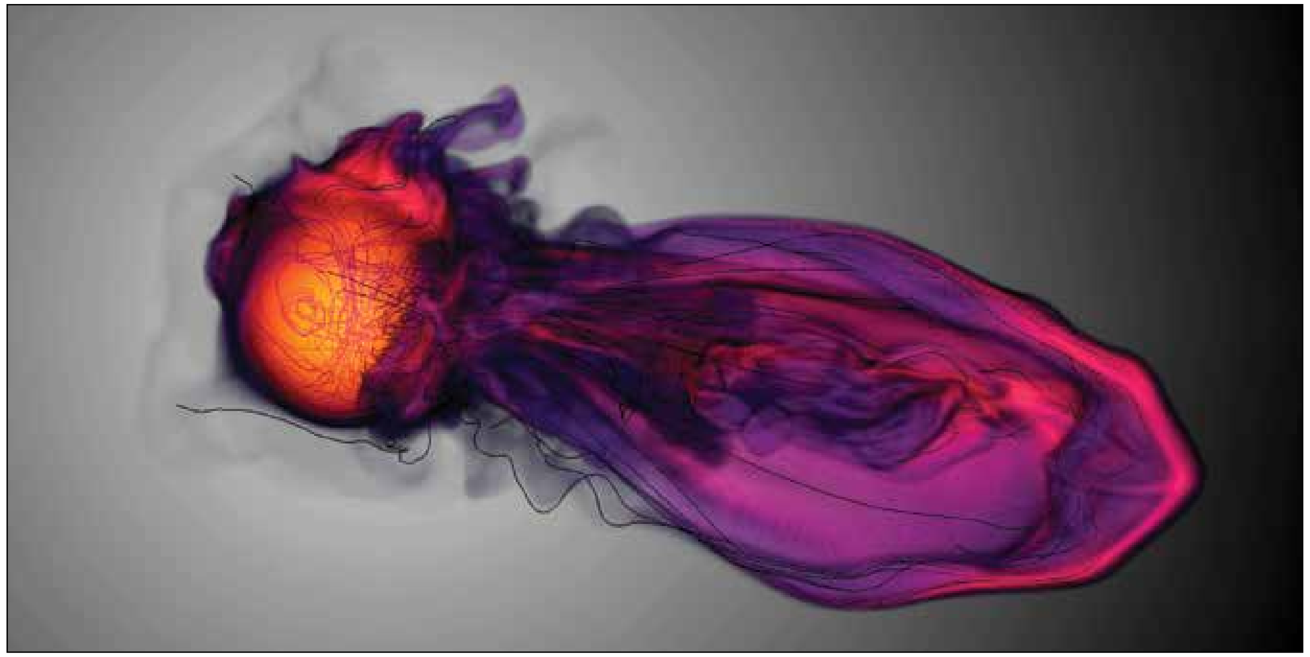

Figure 1: Tidal arm of impact debris ejected approximately one hour after a magnetized Moon-forming giant impact. The log of the composite density is shown in color while black rods show magnetic field lines. Visualization performed with VisIt [3].

RESULTS & IMPACT

The research team's simulations initialize the impactor and proto-Earth with dipole magnetic fields. The Moon-forming giant impact wraps and winds these magnetic field lines into a toroidal configuration in the debris disk. Shear and turbulence in the disk amplify these field strengths by nearly four orders of magnitude in approximately one month after initial contact [4]. Thus, with even a modest initial field strength for the impactor and proto-Earth, these simulations demonstrate that magnetic fields could become dynamically important in a short timescale compared to the lifetime of the protolunar disk. In particular, magnetic fields may drive a fluid instability in the disk that causes turbulence to mix vaporized rock between the protolunar disk and the Earth. Such magnetic turbulence may help explain the isotopic similarities between the Earth and the Moon [4].

WHY BLUE WATERS

A large computational domain is required to contain the giant impact. In addition, a high-resolution is necessary to accurately model dynamically important shocks and capture the onset of turbulence in the disk. Further, long integrations are required to evolve the simulation from initial impact to approximately one month after the formation of the protolunar disk. The Blue Waters supercomputer enables these large-scale, multiphysics simulations in which the team has applied as many as 128 Blue Waters XE nodes to a $1{,}024^3$ (~200-km linear resolution) simulation.

PUBLICATIONS & DATA SETS

P. D. Mullen and C. F. Gammie, "Magnetized models of giant impacts," in preparation, 2019.