NUMERICAL MODELS OF MAGNETIZED MOON-FORMING GIANT IMPACTS. P. D. Mullen[1] and C. F. Gammie[1], [1]University of Illinois at Urbana-Champaign, Department of Astronomy, 1002 W Green St, Urbana, IL, 61801 (pmullen2@illinois.edu)

Introduction: In the canonical giant impact hypothesis, a Mars-sized impactor strikes the proto-Earth in an off-centered collision shortly after the formation of the Solar System. This collision sends melted and vaporized debris (originating from both the target and impactor) into orbit about the proto-Earth, forming a Keplerian "protolunar disk". It is from this disk the Moon is thought to have formed. Numerical simulations of giant impacts have been performed using a variety of (1) numerical techniques (e.g., smoothed particle hydrodynamics [1,2,3] and grid-based algorithms [3,4]), (2) equations of state (e.g., Tillotson [5] and M-ANEOS [6]), and (3) impact parameters (e.g., canonical impacts [2] and hit-and-run scenarios [7], to name two). However, prior giant impact simulations have not considered the dynamical importance of any magnetic field the impactor and/or target may have possessed.

If the impactor and/or target possessed a magnetic field, shear from the collision would amplify magnetic field strengths. In the subsequent debris disk, differential rotation would grow field strengths linearly in time due to winding of the magnetic field. Finally, magnetized, differentially rotating disks are subject to the magetorotational instability (MRI) [8]. If the protolunar disk is well coupled to the magnetic field and the MRI is active, magnetic turbulence would yield exponential growth of magnetic field strengths, promote turbulent mixing (thus potentially helping explain the anomalous similarities among Earth and Moon isotopic ratios [9]), and ultimately, drive the early evolution of the protolunar disk [10,11,12].

This work applies numerical simulations to study the amplification of magnetic fields during a canonical giant impact scenario. We seek to determine whether a weak initial magnetic field could be amplified to dynamical significance in the protolunar disk and seed the MRI.

Method: We apply the astrophysical magnetohydrodynamics (MHD) code, Athena++ [13]. Athena++ is a grid-based code, operating in a purely Eulerian framework. For our giant impact simulations, we configure Athena++ to evolve the equations of 3-D MHD with self-gravity [14] using the Tillotson (granite) equation of state. We use a regular Cartesian mesh with linear resolutions of ~176, ~88, and ~44 km.

Our impactor and target are initialized in isentropic, hydrostatic equilibrium, with a total mass, M_T = 1.02 $M_\oplus$, an impactor to total mass ratio, γ = 0.13, an impact angle, ξ=45°, and an impact velocity equal to the mutual escape velocity, v_{esc}.

We seed both the impactor and target with a dipole magnetic field. The strength of the magnetic field is measured at the surface of the impactor/target, at the pole. For the calculations discussed here the impactor and target dipole fields are aligned, with the poles normal to the plane of the collision.

Results: Figure 1 presents a visualization of a magnetized canonical giant impact simulation ~1 h after first contact, for initial dipole strengths of ~1 G.

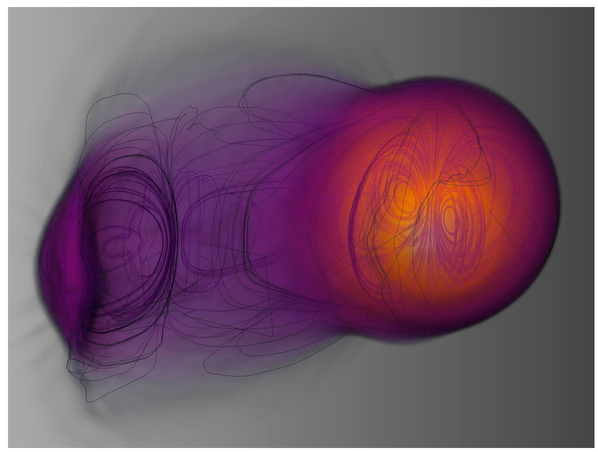

Figure 1: 3-D visualization of a magnetized canonical giant impact simulation using Athena++. Color depicts density (linear scale), while black rods track magnetic field lines.

First Hour. Figure 2 presents a slice through the midplane of the collision for the same simulation, 600 s after first contact. At our highest linear resolution of ~44 km, we have begun to resolve the Kelvin-Helmholtz instability (KHI) at the shear interface between the two impacting planetary bodies. Within the first hour, we find that shear and the KHI amplify magnetic energies, moreover, we find that magnetic field amplification is *not converged* at the linear resolutions studied thus far. At ~1 h, the total magnetic energy in the simulation domain, E_B, has been amplified to ~1.03 $E_{B,0}$, ~1.25 $E_{B,0}$, and ~1.59 $E_{B,0}$, in the ~176, ~88, and ~44 km linear resolution calculations, respectively (where $E_{B,0}$ is the total magnetic energy in the initial condition).

Disk Phase. The largest amplification of magnetic energies occurs in the disk phase, following the initial collision. Beyond ~15 h, the debris has wrapped into a differentially rotating Keplerian disk. We find that the natural consequence of a magnetized Moon-forming giant impact is a protolunar disk hosting a nearly toroidal (azimuthal) magnetic field, as seen in Figure 3. Our simulations demonstrate that once in the disk phase, field strengths grow linearly in time, due to the aforementioned winding of the field. Altogether, we find that at a linear resolution of ~176 km, magnetic energies are amplified by nearly ~3 orders of magnitude at ~3 d post-impact, due to shear from the collision, the Kelvin-Helmholtz instability, and winding from differential rotation.

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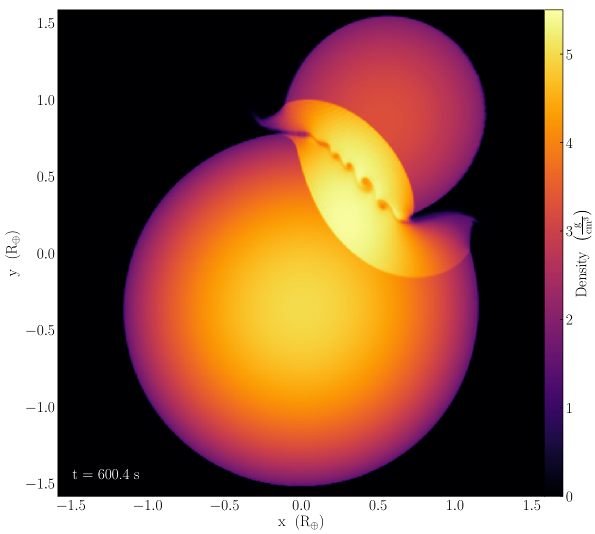

Figure 2: Density slice (linear scale) through the midplane of the collision in a magnetized canonical giant impact simulation with a linear resolution of ~44 km. At the interface of the proto-Earth and impactor, vortices from the Kelvin-Helmholtz instability are observed. Two shocks are clearly visible, one propagating forward through the proto-Earth, one propagating backward through the impactor.

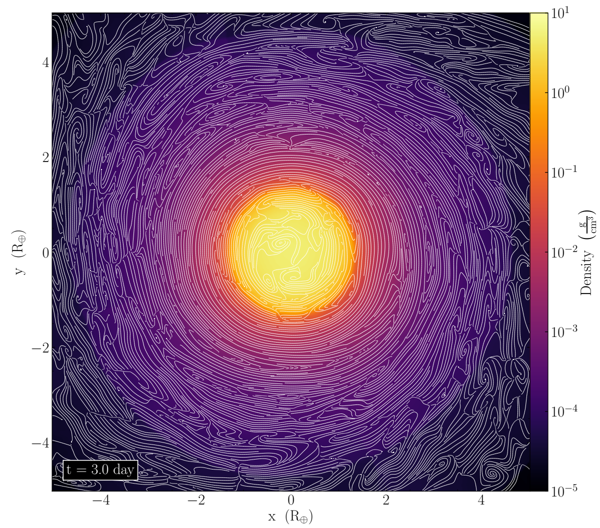

Figure 3: Slice through the midplane of the protolunar disk ~3 d post-impact in a magnetized canonical giant impact simulation with a linear resolution of ~176 km. Color depicts density (log scale); white streamlines track the x and y components of the magnetic field.

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