Validation and initial testing of 3D neutron star magneto-thermal code

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Purpose and description

The primary purpose of this collaborative visit was to continue development, validation, and initial testing of our 3D neutron star numerical code. Discussions were anticipated in the following areas: how fundamental timescales and numerical stability change when migrating from 2D to 3D, what selections of initial and boundary conditions would be appropriate for a first batch of simulations, how future simulations will more realistically include dynamical evolution of the NS core, and ultimately how we map the local physics onto our new staggered numerical grid in 3D.

Main results

First, we have developed a field-advance algorithm which is certainly compatible with Ohmic evolution of the magnetic field, and probably also for Hall evolution in the low-magnetization limit. Final estimates for numerical error and critical magnetization parameter are pending. Analysis of the performance of this field-advance scheme will determine what future modifications are necessary for accurately capturing high-magnetization Hall dynamics in 3D.

Second, in 3D spherical coordinates the numerical singularity at the pole presents a well-known, unique problem. Following our discussions, we are confident that for our purposes this challenge may be naturally supassed with a clever arrangement of variables on the staggered 3D grid. Such an arrangement also naturally enforces appropriate polar boundary conditions.

We have also extended pre-existing initial magnetic field prescriptions into 3D, now permitting localized magnetic structure to be prescribed in the azimuthal direction. This code update is important for initial studies of azimuthally-propagating wavemodes, and thus for constraints on e.g. courant conditions.

We have also paid specific attention to the various boundary conditions required for our 3D simulations. Specificially to the outer boundary (NS surface-magnetosphere interface), as the inclusion of azimuthal variation must now be handled by extensions to our existing method of spectral decomposition.

Discussions involving both Dr. Pons' group in Alicante and Dr. Cerdá-Durán's group in Valencia covered many aspects of theory & coupling of our current 2D code with cutting-edge magnetospheric models.

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Finally, we have made significant progress in representing and diagnosing physics in the NS core. Using our most recent and 'realistic' simulations, we have determined that the entire core becomes superconducting within a few years. For our purposes we may thus assume proton superconductivity is always activated in our simulations, which normally span up to a few megayears. We have also addressed and solved disparities between the form of the core induction equation when subject to myriad driving forces. We know correctly compute the superconducting electric field and monitor the most important quantities, both inside of the superconducting matter and at the crust-core interface where understanding magnetic energy transport is crucial.

In closing, most of the practical coding concerns have been addressed and partially implemented for the first series of simulations. This advance would have required much more time in the absence of the STSM funding.

Future collaboration

Dr. Pons is an original author of this code, as well as an expert in observational and theoretical NS physics. He is a major asset in our research path (led by Dr. Nanda Rea), and we expect this collaboration to continue to grow over the next 24 months.

Foreseen publications

Publications concerning both 2D and 3D studies will have benefitted from this STSM. Of course, the first few papers to present results from 3D simulations will have found the greatest benefit. Additionally, now in 2D we have a much more robust set of algorithms implemented to simulate and monitor critical processes in the NS core and at the core-crust interface, and this will positively impact current drafts based on 2D physics.

Host confirmation