SIMULATING TWO-FLUID MHD TURBULENCE AND DYNAMOS IN STAR-FORMING MOLECULAR CLOUDS

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EXECUTIVE SUMMARY

We are at the threshold of a new data-rich and simulation-rich era in star-formation studies. The question of how stars form is fascinating in itself and has a great impact on several other areas of astrophysics. There is a general consensus that a predominant amount of star formation in our galaxy takes place in molecular clouds and, specifically, in giant molecular clouds (GMC). The molecular cloud material consists of a highly turbulent, very weakly ionized, and strongly magnetized plasma. It is within such a plasma that we observe protostellar cores—the progenitors of the stars that will eventually form. The present project is designed to simulate the two-fluid turbulence and dynamo processes that regulate magnetic field evolution and star formation. This turbulence, and the nonideal physics to which it gives rise, is fundamentally different from single-fluid magnetohydrodynamic (MHD) turbulence. We aim to study these differences.

RESEARCH CHALLENGE

Our understanding of the star formation process has reached the point where advanced observational capabilities are required. Consequently, NASA has made multimillion-dollar investments in the High-resolution Airborne Wideband Camera-plus (HAWC+) instrument aboard the Stratospheric Observatory for Infrared Astronomy (SOFIA) airborne observatory with the specific goal of understanding the turbulent nature of star-forming clouds. At the same time, high-resolution simulations that include the appropriate physics of GMCs are also of critical importance. The PIs of this proposal are theorists who are participating in a multiyear-funded NASA observational proposal to obtain observational data associated with turbulence in the Perseus GMC.

The PIs have also done the leading simulations of two-fluid MHD simulations on a range of XSEDE and Blue Waters PRAC resources ([4]; [7–9]; Xu, et al., 2018a and 2018b). The partially ionized fluid in a GMC is best modeled as a neutral fluid and an ionic fluid that interact with the magnetic field. Such simulations are extremely CPU-intensive and only simulations with very limited resolution (5,123 zones) had been done before this Blue Waters PRAC award. At those resolutions, we would have been unable to match the observations from HAWC+. With our new generation of simulations, with $1{,}024^3$ zones and upwards resolution, we are able to obtain a well-defined inertial range in two-fluid and dynamo simulations. This ensures that NASA's investment in HAWC+ is being matched by well-resolved simulations.

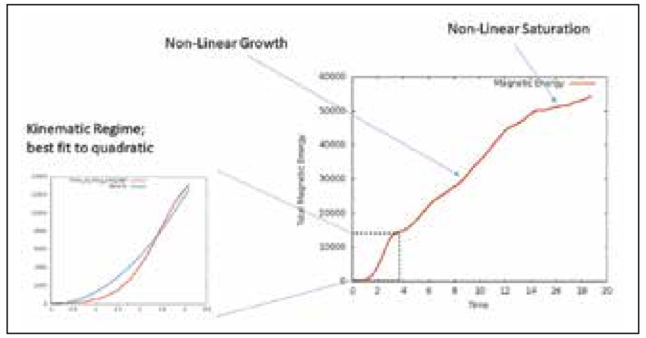

Figure 1: Fig. 1, from Xu, et al. (2018a), shows the evolution of magnetic energy with time in a two-fluid dynamo. The right panel shows magnetic field growth in a partially ionized dynamo. The inset on the left shows the initial growth of magnetic energy, with the red curve representing our highly resolved simulations and the blue curve showing the best fit to a quadratic.

The most compelling motivation for understanding two-fluid, ambipolar diffusion-mediated turbulence comes from recent observations. Differences in the linewidths between neutral and ionized tracers have led to the suggestion that the dissipation of turbulence from ambipolar diffusion sets in on scales smaller than 0.0018 parsecs in M17 [2].

A breakthrough realization by Xu and Lazarian [7] claimed that magnetic fields would grow in a partially ionized plasma at rates that are very different from the growth in a fully ionized plasma. The growth of the magnetic field in a plasma is known as the dynamo problem. Their prediction was that while magnetic fields grow exponentially in a fully ionized plasma, they grow only quadratically in a partially ionized plasma. However, confirmation of the theory requires a highly resolved turbulent flow. Fig. 1 from the first listing under Publications and Data Sets shows the evolution of magnetic energy with time in a two-fluid dynamo. The right panel in Fig. 1 shows magnetic field growth in a partially ionized dynamo. The inset on the left shows the initial growth of magnetic energy with the red curve representing our highly resolved simulations and the blue curve showing the best-fit to a quadratic. The agreement with theory is very good and has

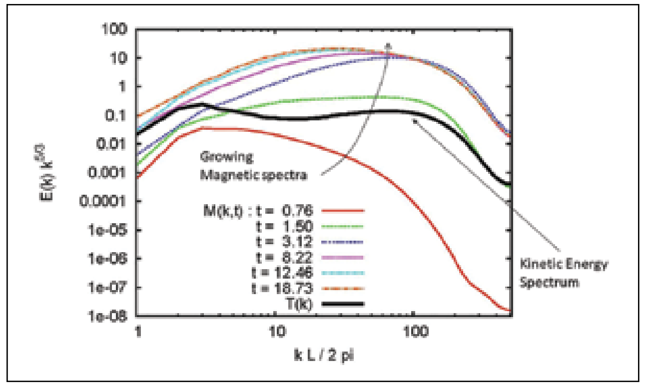

Figure 2: The study of the magnetic energy spectra is also significant. The peak in the magnetic energy spectrum is predicted to evolve with time at a set rate and the results conform to theory.

been documented. The study of the magnetic energy spectra is also significant and is shown in Fig. 2. The peak in the magnetic energy spectrum is predicted to evolve with time at a set rate and our results conform to theory.

METHODS & CODES

The core MHD algorithms in our RIEMANN code are based on higher-order Godunov schemes (conservative numerical schemes for solving partial differential equations). Balsara and his collaborators have been on the forefront of the effort to develop high-accuracy schemes for computational astrophysics in general and computational MHD in particular. We have described two-fluid methods [3], [5], and [6].

RESULTS & IMPACT

We have completed several large-scale simulations while others are still continuing on Blue Waters. The key points from our simulations have been documented above and are being readied for publication. This work will be a substantial improvement on our previous work in terms of resolution as well as in the details of input physics and accuracy of the simulation code.

WHY BLUE WATERS

The simulations reported here are extremely CPU-intensive. The goal of this project is to use the petascale computing power of Blue Waters to push the resolution, accuracy, and fidelity of the simulations much higher so we can match theory with the observations coming from NASA-funded instruments.

PUBLICATIONS & DATA SETS

Xu, S., S. Garain, A. Lazarian, and D.S. Balsara, Turbulent dynamo in a weakly ionized medium—Study of growth rate. *Astrophysical Journal*, in preparation (2018a).

Xu, S., S. Garain, A. Lazarian, and D.S. Balsara, Turbulent dynamo in a weakly ionized medium—Spectral evolution. *Astrophysical Journal*, in preparation (2018b).