SIMULATING TWO-FLUID MHD TURBULENCE AND DYNAMOS IN STAR-FORMING MOLECULAR CLOUDS AND A NEW PARADIGM FOR COMPUTATIONAL ASTROPHYSICS FOR SPHERICAL SYSTEMS

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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 and of itself and has a great impact on several other areas of astrophysics. The consensus is that a predominant amount of star formation in our galaxy takes place in molecular clouds, and more specifically in giant molecular clouds (GMC).

The project aims to study magnetic field evolution in partially ionized plasmas as well as developing and applying a new paradigm for simulating magnetohydrodynamics (MHD) on geodesic meshes that cover the sphere with no coordinate singularities and no loss of accuracy at the poles.

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 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 are theorists who are participating in a multiyear, funded NASA 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 PRAC resources [4,7–10]. At the original resolutions of 512^3 and smaller, the team would have been unable to match the observations from HAWC+. With the new generation of simulations, with a $1,024^3$ zone and upwards resolution, the researchers were able to obtain a well-defined inertial range in two-fluid and dynamo simulations. This ensured that NASA's investment in HAWC+ is being matched by well-resolved simulations.

The most compelling motivation for understanding two-fluid, ambipolar diffusion-mediated turbulence, in fact, 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 the Messier 17 nebula [2].

A breakthrough realization by Xu and Lazarian [7] claimed that magnetic fields would grow in a partially ionized plasma (known as the dynamo problem) at rates that are very different from the growth in a fully ionized plasma. 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 [10]) 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 the research team's highly resolved simulations and the blue curve showing the best fit to a quadratic. The agreement with theory is very good and has 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 the results of this project conform to theory. These results have also been published [10].

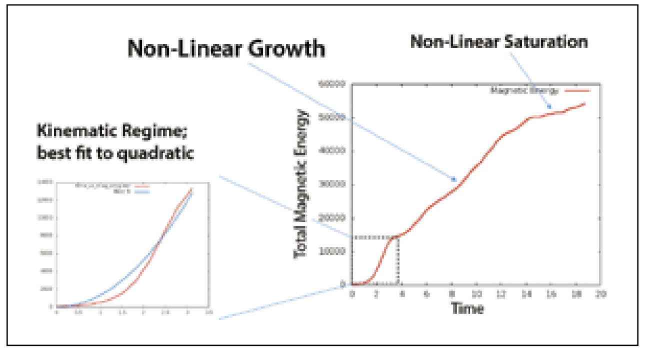

Figure 1: This figure, from [10], shows the evolution of magnetic energy with time in a two-fluid dynamo. The right panel shows magnetic field growth in a partially ionized dynamo. The inset on the left shows the initial growth of magnetic energy with the red curve representing the team's highly resolved simulations and the blue curve showing the best fit to a quadratic.

METHODS & CODES

The core MHD algorithms in the research group's RIEMANN code are based on higher-order Godunov schemes. The team has been on the forefront of the effort to develop high-accuracy schemes for computational astrophysics in general and computational MHD in particular. Two-fluid methods have been described in [3,5,6]. The team has also published its breakthrough work on divergence-free MHD on geodesic meshes [11]. The method made several advances on higher-order-accurate reconstruction, including the reconstruction of divergence-free magnetic fields on isoparametrically mapped meshes.

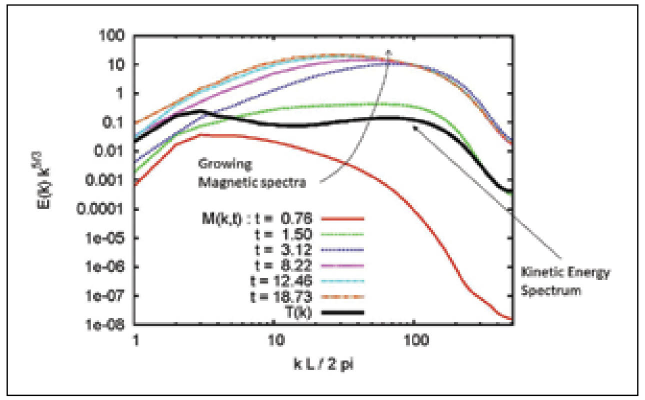

Figure 2: The study of the magnetic energy spectra is also significant. The peak in the magnetic energy spectrum is predicted to evolve with time at a set rate and the results conform to theory.

RESULTS & IMPACT

Several large-scale simulations have been completed or are ongoing on Blue Waters. The key points from these simulations have been documented above and are being readied for publication in 2019. The new work represents a substantial improvement in resolution as well as in the details of input physics and accuracy of the simulation code. In addition, the first results on geodesic mesh MHD have been published [11], showing the petascale scalability on Blue Waters for the new 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 in order to match theory with the observations coming from NASA-funded instruments.

PUBLICATIONS & DATA SETS

S. Xu, S. Garain, D. S. Balsara, and A. Lazarian, "Turbulent dynamo in a weakly ionized medium," *Astrophys. J.*, vol. 872, no. 62, pp. 1–12, 2019.

D. S. Balsara, V. Florinski, S. Garain, S. Subramanyan, and K. F. Gurski, "Efficient, divergence-free high order MHD on 3D spherical meshes with optimal geodesic mapping," *Mon. Notices Royal Astron. Soc.*, vol. 487, p. 1283, 2019.