SIMULATING TWO-FLUID MHD TURBULENCE IN STAR-FORMING MOLECULAR CLOUDS ON THE BLUE WATERS SYSTEM

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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, 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 that regulates star formation. This turbulence, and the nonideal physics it gives rise to, is fundamentally different from single-fluid magnetohydrodynamic (MHD) turbulence. The project aims to study these differences.

RESEARCH CHALLENGE

Our understanding of the star formation process requires advanced observational capabilities. Consequently, NASA has made multi-million-dollar investments in the HAWC+ instrument aboard the 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 multi-year 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 resources [1–3]. The partially ionized fluid in a GMC is best modelled as a neutral fluid and as an ionic fluid that interacts with the magnetic field. Such simulations are extremely CPU-intensive, and only simulations with very limited resolution (512^3 zones) are in hand. At the present resolution, we will be unable to match the observations from HAWC+. With current simulations, NASA's investment in HAWC+ will be in vain because the detailed match between simulations and observations will not be possible. The work on this newly funded grant will rectify this situation.

The most compelling motivation for understanding two-fluid, ambipolar diffusion-mediated turbulence comes from recent observations. Observations of differences in the linewidths between neutral and ionized tracers suggest that the dissipation of turbulence from ambipolar diffusion sets occurs on scales smaller than 0.0018 parsecs in M17 [4]. Fig. 1a from [4] shows observed velocity dispersions as a function of length for the HCN molecule (black) and the HCO^+ ion (red). The dashed lines trace turbulent spectra. The velocity dispersion in the ions is smaller than that of the neutrals (especially on smaller scales), providing evidence for dissipation via ambipolar diffusion on small scales. The dissipation scales found by [4] are consistent with theoretical estimates of Alfvén wave dissipation by ion-neutral drag [5]. Fig. 1b from [2] shows the simulated linewidth-size relationship for ions (red) and neutrals (black) from one of our simulations. We see that the lower envelope of the ion linewidths is indeed lower than that of the neutrals. This is very much in keeping with the observations of [4].

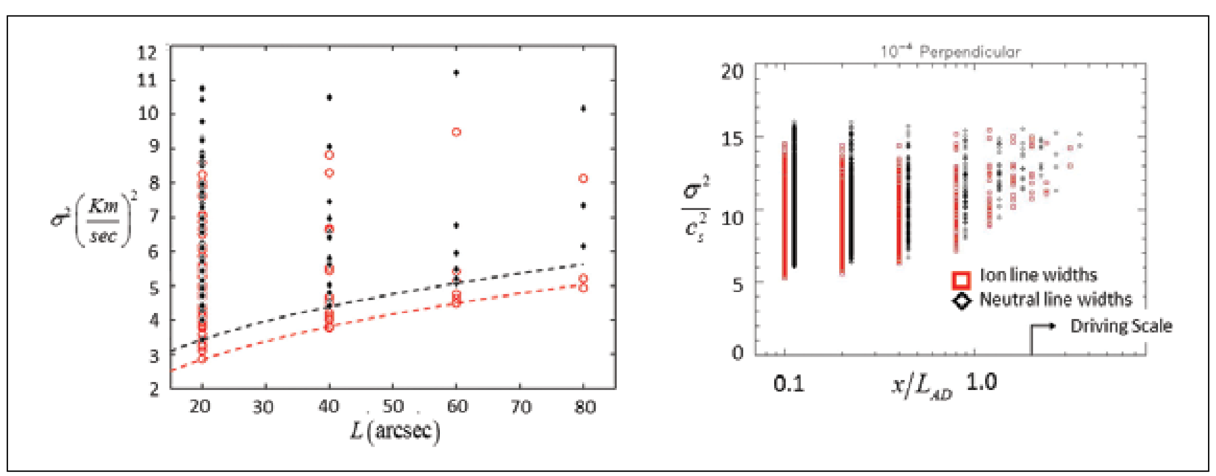

Figure 1a [4]: Observed velocity dispersions as a function of length for the HCN molecule (black) and the HCO^+ ion (red). The velocity dispersion in the ions is lower than that in the neutrals. Figure 1b [2]: Shows simulated linewidth-size relationship from simulations.

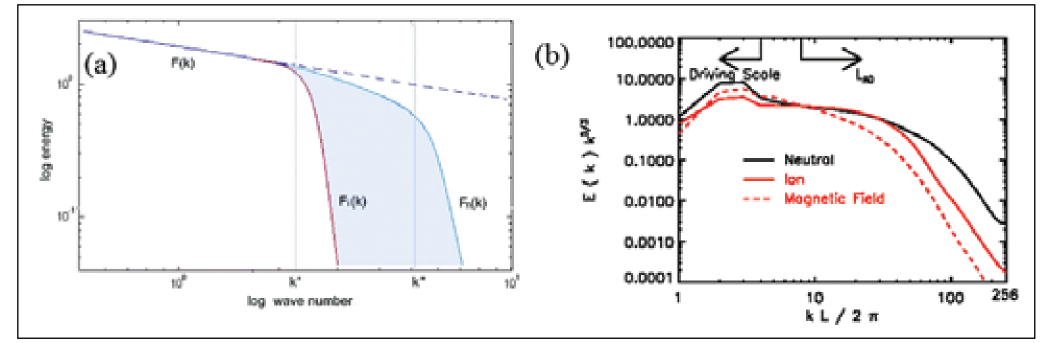

Figure 2a [4]: Shows the scaled power spectrum in the ions (subscript i) and neutrals (subscript n) needed for understanding Fig. 1. Figure 2b: Shows the velocity spectrum of the neutrals (solid black line), velocity spectrum in the ions (solid red line), and magnetic spectrum (dashed red line) from our simulations.

Li and Houde [4] have already made the connection between their data and our theory. The theory posits that on length scales that are smaller than the ambipolar diffusion length scale (shown here as L_{AD}), the MHD waves in the ions differ strongly from hydrodynamic waves in the neutrals because of the dominance of ion-neutral drag. Such MHD waves have a strongly preferred velocity fluctuation that is orthogonal to the mean field. Consequently, we see strong differences between ion and neutral linewidths when the line of sight is orthogonal to the magnetic field.

Fig. 2a from [4] sketches their scenario. It realizes that the velocity spectrum in the ions is damped on the ambipolar diffusion dissipation scales, while the velocity spectrum of the neutrals continues undamped. As a result, the linewidths in the neutrals are systematically wider than that in the ions on a range of length scales shown in Fig. 1. Other researchers [1–3] carried out two-fluid simulations and evaluated the velocity spectra in the ions and neutrals, shown in Fig. 2b. The scaled velocity spectrum of the neutrals is shown by the black solid line. This clearly lies above the scaled velocity spectrum of the ions on length scales that are dominated by ambipolar diffusion. The linewidth-size relations and simulated linewidths in the ions and neutrals were also found to be consistent with the conjecture of Li and Houde [4].

Such simulations are extremely CPU-intensive, and only simulations with very limited resolution are in hand. At the present resolution we will certainly be unable to match the observations from HAWC+. The goal of this newly funded project is to use the petascale computing power of Blue Waters to push the resolution, accuracy, and fidelity of the simulations much higher so that we can match the theory with the observations coming from NASA-funded instruments.

METHODS & CODES

The core MHD algorithms in our RIEMANN code are based on higher-order Godunov schemes. 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. Two-fluid methods have been described in [6–8].

RESULTS & IMPACT

This project is newly funded and is in its initial stages where large-scale simulations have been planned and are ongoing on Blue Waters. Several papers have been published by our group using lower-resolution simulations [1–3]. The new 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 simulation code.

WHY BLUE WATERS

Balsara's group has also simulated at petascale on Blue Waters via the Great Lakes Consortium for Petascale Computation. We are, therefore, extremely familiar with the Blue Waters system. The PIs are also funded via NSF grant DMS-1622457 to develop computational capabilities for turbulent simulations in computational astrophysics. This newly funded proposal will provide us with the impetus for developing petascale-ready simulation tools for astrophysical turbulence and making them freely available to the greater astrophysics community.

PUBLICATIONS AND DATA SETS

Meyer, C., D.S. Balsara, B. Burkhart, and A. Lazarian, Observational Diagnostics for Two-Fluid Turbulence in Molecular Clouds as Suggested by Simulations. *Monthly Notices of the Royal Astronomical Society*, 439 (2014), pp. 2197–2210.

Burkhart, B., et al., Alfvénic Turbulence Beyond the Ambipolar Diffusion Scale, *The Astrophysical Journal*, 805 (2015), pp. 118–126.