The Dust Between Us and the Big Bang

PI: David C. Collins (Florida State University)

We are requesting 4477 SUs on Frontera in order to perform several studies of the interstellar medium (ISM). This is part of an effort to observe gravitational waves from the big bang, imprinted in the cosmic microwave background (CMB). These observations are hampered by the dust and plasma in our own galaxy, which outshines the CMB. We will simulate the plasma in the ISM in two ways to characterize its observational properties. One study will be high resolution simulations of plasma turbulence, and the other suite will be simulations of isolated galaxies.

1 Background

Gravitational waves generated at the beginning of the Universe leave an imprint in the polarization of the cosmic microwave background (CMB). The CMB is the oldest light observable in the Universe, and gives us a snapshot of its very early stages. Observing the polarization of the CMB will give us a measurement of gravitational waves that were produced at the formation of the Universe. Unfortunately, the dusty plasma in our own Milky Way also produces polarized light that is brighter than the primordial signal. Our simulations will study the polarization properties of the light from the plasma in Milky Way type galaxies. Understanding this polarization is essential for its removal from future measurements of the CMB.

The Planck satellite measured the polarization of the whole sky. Polarization, having direction on the sky, needs two quantities for its description. The most useful option are the parity-even E-mode and parity-odd B-mode. The only source of $B-$ mode polarization in the CMB are gravitational waves. So searching for $B-$modes in the CMB will prove quite profitable. However, the dusty, magnetized plasma and synchrotron electrons in our own galaxy produce $B-$mode polarization. So this must be understood so it can be removed.

The Planck satellite measured the E- and B-mode signals over the entire sky. They found that both are relatively uniform power-laws in wavenumber, with power spectra given by powerlaws

$$C_\ell^{EE} = A^{EE} k^{\alpha^{EE}}, \tag{1}$$

for $E-$mode and a similar expression for $B-$mode. They found that the slopes are roughly equal, $\alpha^{EE} \sim \alpha^{BB} \sim -2.5$, and the $B-$mode have roughly half the power of the $E-$mode.

We have shown (Stalpes et al 2023, in prep) that the slopes of the polarization are directly related to the Mach number, $\mathcal{M} = v/c_s$, the ratio of r.m.s velocity to sound speed, and Alfvén mach number, $\mathcal{M}_{\rm A} = v/v_A$, where v_A is the speed of magnetic disturbances. Increasing $\mathcal{M}$ makes for more filamentary structure in the cloud, and slopes in line with what Planck observed. We ran a suite of $\mathcal{M}$= ($\frac{1}{2}$,1,2,3,4,5,6) and $\mathcal{M}_{\rm A}$=($\frac{1}{2}$,1,2). After interpolating, we predict that the observed values of α^{EE} and α^{BB} are best matched by plasma with $\mathcal{M}$=4.7 and $\mathcal{M}_{\rm A}$=1.5. The study presented in Stalpes et al were run at a modest resolution of 512^3.

Another curious finding in the Planck data is a correlation between the total signal, $T-$mode, which is parity-even, and the parity-odd $B-$mode. In principle, these should be uncorrelated, but the Planck satellite measured a non-zero correlation at the 5% level. The results from Stalpes et al (2023) show that turbulence alone can account for such a correlation only at the 2% level at best, and these were relatively low resolution studies. It is entirely likely that the TB correlation comes from large scale features in the dust and magnetic field morphology. To properly reproduce the large scale magnetic field, we will simulate an entire Milky Way sized galaxy as well as the circumgalactic medium (CGM) that surrounds it. The dust that we are interested in, as well as the star formation and explosions that determine the energetics of the galaxy, all happen in a thin disk, roughly 100pc thick and 20,000pc across. Plasma is ejected from the disk by supernovae, and expelled into the CGM, where it cools and falls back to the disk. This baryon cycling dictates the star formation activity in the galaxy and impacts the magnetic field strength and morphology throughout the system. All of these pieces are important for a complete picture of the polarized sky.

We propose two suites of simulations. The first is a continuation of the moderate resolution turbulent boxes presented in Stalpes et al (2023). In that study, we predict that a Mach number of 4.7 and an Alfvén Mach number of 1.5 reproduce the sky. We will perform two simulations at 2048^3. These simulations will test our prediction, and provide high quality datasets that reproduce the salient features of the sky that can be used to test foreground removal algorithms algorithms and ISM models. While these simulations are quite large, the excellent scaling and our years of experience guarantee success. The second suite of simulations is a set of three isolated galaxies that will simultaneously provide high resolution on the mid plane, and properly resolve the environment and boundary conditions of the galaxy. These will be used initially to test CMB foreground models, and will also have many applications beyond the CMB. These galaxies will be a stack of nine fixed resolution levels at roughly 512^3 per level.

The code we will use is Enzo (Bryan et al. 2014; Collins et al. 2010), an open source code that has been used for a number of astrophysics applications (Abel et al. 2002; Correa Magnus et al. 2023). Enzo is an adaptive mesh refinement (AMR) code that dynamically adds resolution elements as the system requires it, using the strategy of Berger & Colella (1989) and **?**. We will use the constrained transport (CT) module (Collins et al. 2010; Gardiner & Stone 2005) that conserves the divergence of the field to machine precision. It uses FFT-based gravity for the root grid and multigrid relaxation for gravity on fine grids. The base MHD solver is a higher order Godunov method.

There are three primary systems in the code that contribute to the performance. The MHD method is entirely local, and thus scales extremely well. The main gravity solver is based on Fourier transforms, and thus scales like $N \ln N$. To perform the gravity solve, the cube is rearanged into pencils for the FFT. Between the $\ln N$ and rearangement, the gravity solver scales less perfectly than the hydro. The third system is the AMR overhead, which includes communication between the different grids and the memory needs of the metadata. This is heavily dependent on the layout of the grid patches, and can become quite demanding. We mitigate the overhead by forcing the grid patches to be of uniform size and relatively large.

We use ideal MHD and then Chemistry

2 Simulations

Here we describe and motivate the physical layout of the simulations.

2.1 Turbulence

The turbulence simulations begin with uniform density and magnetic field, and add kinetic energy at each step in a way that the kinetic energy in the box stays constant. Energy is added at the large scale, and the nonlinear dynamics of the MHD equations carry that energy to smaller scales until it is ultimately dissipated. The cascade is what we are interested in, as it gives

3 Request Details

The request is outlined in Table 1. The total request is found as

$$SU = t_{wall} N_N \tag{2}$$

$$t_{wall} = \frac{N_Z N_U}{\zeta} \frac{1}{N_C}. \tag{3}$$

For the *turbulence* simulations, $N_Z = 2048^3$. For the galaxy simulations, N_Z will be computed from the grid layout. We construct each level in grid patches of 32^3 zones each. Consistent patch size allows us to optimize the memory usage of the simulation. The finest level is a thin pancake of $100 \times 100 \times 1$ grids. The galaxy will be resolved to 6.25 pc for the entire disk to the dust scale height of $\pm$100pc and a radius of 10kpc. Resolution increases

Table 1: The request broken down by simulation. For the *turbulence* simulations, the duration, T and time step, Δt, are determined by $\mathcal{M}$ and $\mathcal{M}_{\mathrm{A}}$. For the *galaxy* simulations, the AMR structure will be constructed in layers of grids with 32^3 zones each centered on the midplane of the galaxy. The outer box, level 0, is 8.2×10^5pc on a side, and the finest level has a resolution of 6.25 pc. For all simulations, the number of updates for each level is $T/\Delta t$. The total cost $SU = N_Z * T/\Delta t/\zeta/N_C * N_N$, and The total disk is $N_Z * N_F * 8$ bytes, where N_F is the number of fields. For the *turbulence* simulations, $N_C = 32,768$, $N_N = 586$, $N_F = 20$, and $\zeta = 4 \times 10^5$. For the *galaxy* simulations, $N_C = 512$, $N_N = 32$ $N_F = 27$, and $\zeta = 10^4$. Details can be found in the main text.

suite	$(\mathcal{M}, \mathcal{M}_{\mathrm{A}})$		T	Δt	N_Z	SU
turbulence	(4.7, 1.5)		0.53	1.1×10^{-6}	2048^3	5.3×10^4
turbulence	(8, 1.5)		0.31	6.6×10^{-7}	2048^3	5.0×10^4
				Turbulence: Disk	1.3×10^4Gb	SU:1.0×10^5
Suite	Level	grid layout	T[Gyr]	Δt[Gyr]	N_Z	SU
galaxy	8	$100 \times 100 \times 1$	2	2.1×10^{-3}	$(689)^3$	5.5×10^5
galaxy	7	$54 \times 54 \times 3$	2	4.1×10^{-3}	$(659)^3$	2.4×10^5
galaxy	6	$30 \times 30 \times 11$	2	8.3×10^{-3}	$(687)^3$	1.4×10^5
galaxy	5	$16 \times 16 \times 16$	2	1.7×10^{-2}	$(512)^3$	2.8×10^4
galaxy	4	$16 \times 16 \times 16$	2	3.3×10^{-2}	$(512)^3$	1.4×10^4
galaxy	3	$16 \times 16 \times 16$	2	6.6×10^{-2}	$(512)^3$	7.0×10^3
galaxy	2	$16 \times 16 \times 16$	2	1.3×10^{-1}	$(512)^3$	3.5×10^3
galaxy	1	$16 \times 16 \times 16$	2	2.7×10^{-1}	$(512)^3$	1.8×10^3
galaxy	0	$16 \times 16 \times 16$	2	5.3×10^{-1}	$(512)^3$	8.8×10^2
				One Galaxy: Disk	7.0×10^3Gb	SU:9.8×10^5
				Three Galaxies: Disk	2.1×10^4Gb	SU:2.9×10^6
				Total: Disk	3.4×10^4Gb	SU:3.0×10^6

by a factor of 2 each level. The next two levels increase the aspect ratio of the refined region ($54 \times 54 \times 3$ and $30 \times 30 \times 11$ grids, respectively), and the remaining levels are $16 \times 16 \times 16$ grids.

References

Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93

Berger, M. J. & Colella, P. 1989, J. Comput. Phys, 82, 64

Bryan, G. L., Norman, M. L., O'Shea, B. W., Abel, T., Wise, J. H., Turk, M. J., Reynolds, D. R., Collins, D. C., Wang, P., Skillman, S. W., Smith, B., Harkness, R. P., Bordner, J., Kim, J.-h., Kuhlen, M., Xu, H., Goldbaum, N., Hummels, C., Kritsuk, A. G., Tasker, E., Skory, S., Simpson, C. M., Hahn, O., Oishi, J. S., So, G. C., Zhao, F., Cen, R., Li, Y., & Enzo Collaboration. 2014, ApJS, 211, 19

Collins, D. C., Xu, H., Norman, M. L., Li, H., & Li, S. 2010, ApJS, 186, 308

Correa Magnus, L., Smith, B. D., Khochfar, S., O'Shea, B. W., Wise, J. H., Norman, M. L., & Turk, M. J. 2023, arXiv e-prints, arXiv:2307.03521

Gardiner, T. A. & Stone, J. M. 2005, J. Comput. Phys, 205, 509