Modelling Protogalactic Collapse and Magnetic Field Evolution with FLASH

Chris Orban (UIUC) and Paul Ricker (UIUC)

Introduction

The $\alpha\omega$ dynamo model explains magnetic field structure and amplification in spiral galaxies.

- Field evolution attributed to amplification of toroidal and poloidal magnetic field modes by turbulence and stretching of field lines.
- Radio observations corroborate model.

Problem - the $\alpha\omega$ dynamo only explains the mechanism for amplification. A poorly understood initial "seed" field is needed to start the dynamo engine.[2]

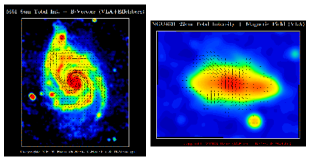

Figure 1. Two radio observations of spiral galaxies. The vectors indicate the direction of the magnetic field lines.
(Images courtesy of the Max-Planck-Institute für Radioastronomie[1])

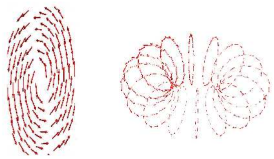

Figure 2. Left: a poloidal field, right: a toroidal field. The $\alpha\omega$ dynamo amplifies these modes. Compare to the field structures seen in Fig. 1.

Biermann Battery

The Biermann battery is a viable candidate for this seed field.

- Shocks cause ions and electrons in a plasma to separate, generating currents, and hence magnetic fields.[3]
- Arises naturally from shocks in protogalactic evolution.
- Can be modeled by a pure hydro simulation when the fields are very weak.
- Magnetic field, **B**, inferred from the gas dynamics, $\omega \equiv \nabla \times v$ and **B** = $\alpha\omega$ where ω is the vorticity, v is the velocity, α is a constant, $\alpha \equiv m_p c / e(1+\chi) \approx 10^{-4}\, G\, s$ and χ is the ionization fraction.[4] We assume χ is constant and $\ll 1$.

The Protogalaxy Model

- A collapsing prolate spheroid of gas. Prolate, oblate and spherical shapes were simulated.
- A dark matter halo simulated by $\sim 10^6$ particles that only interact gravitationally.
- Set in an expanding universe with cosmological parameters, $(\Omega_0 = 1, h = 0.7, \sigma_8 = 0.5)$

Simulations

Tools:

- The Tungsten cluster, a 2900 processor Linux machine, at the National Center for Supercomputing Applications. Used for high resolution protogalactic collapse simulations.
- The Tsoodzil cluster. A Linux machine, 8 Intel Xeon processors, 16 GB of RAM. Used for analysis.
- FLASH, an adaptive mesh refinement (AMR) code for astrophysics.[5] AMR allows the resolution to be increased in more interesting regions of the simulation.

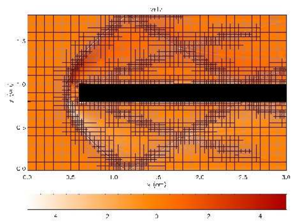

Figure 3. A FLASH simulation of supersonic wind incident on an obstacle. The overlaid blocks reveal how the resolution varies across the simulation. This simulation tests the accuracy of the code in generating vorticity, an important quantity for the protogalaxy simulation.

Analytic Tests:

- An analytic result for the vorticity jump across a shock was used to check accuracy.
- The vorticity jump should follow $\Delta\omega \quad -\dfrac{\delta^2}{1+\delta}\dfrac{\partial v_\perp}{\partial \tau}$, where $\delta \equiv \rho_{\text{post-shock}}/\rho_{\text{pre-shock}}-1$ and ρ is a density. The derivative is along a tangential distance, τ, ahead and behind the shock front.
- A bow shock simulation shows that the vorticity generation is accurate to about 30%

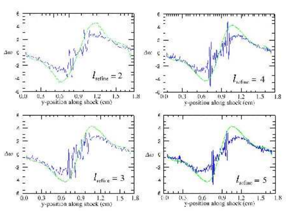

Fig. 4. Comparison of the measured vorticity jump to the analytic values for different levels of refinement for the bow shock.

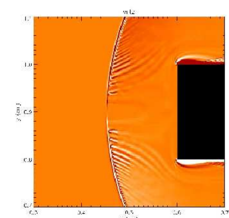

Fig. 5. A closer view of the vorticity for the highest resolution run. Ribbon-like numerical effects decrease accuracy.

Protogalaxy Results

Results from the spherical collapse are presented at 512^3 resolution. The protogalaxy begins to collapse at z = 100 in the simulation. A strong outgoing shock forms at z ~ 12, which is the largest source of vorticity generation.

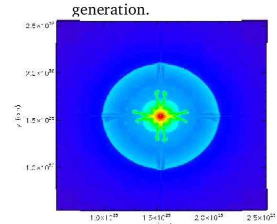

Fig. 6. A log density plot of z = 10.0 There is obvious deviation from spherical symmetry near the center, but otherwise the distribution is nearly spherical.

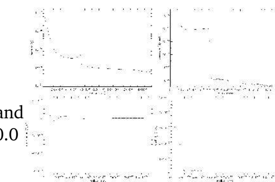

Fig. 7. Radial profiles of the density, pressure, vorticity, and compression $(\nabla \cdot v)$ at z = 10.0

Conclusions

By summing up the vorticity in regions least affected by numerical issues, at z = 10.0 the total vorticity of the protogalaxy is $5.5 \cdot 10^{-17}$Hz. This implies a seed field of $5.5 \cdot 10^{-21}\, G$ which is of the order required to explain the magnetic field strengths of present-day spiral galaxies.

Future Work

- Quantitatively comparing results of the simulation to previous studies with different codes.[4,6]
- Analysis of prolate and oblate simulations.
- Longer term, explore later stages of protogalactic evolution with the radiative cooling and magenetohydrodynamics modules of FLASH.

References

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