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Testing the connection between radio mini-halos and core gas sloshing with MHD simulations

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Abstract. Radio mini-halos are diffuse, steep-spectrum synchrotron sources associated with a fraction of relaxed clusters of galaxies. Observations of some mini-halo sources indicate a correlation between the radio emission and the X-ray signature of gas sloshing, "cold fronts." Some authors have suggested turbulence associated with the sloshing motions may reaccelerate relativistic electrons, resulting in emission associated with the fronts. We present MHD simulations of core gas sloshing in a galaxy cluster, where we measure the turbulence created by these motions and employ passive tracer particles to act as relativistic electrons that may be reaccelerated by such turbulence. Our preliminary results support such a link between sloshing motions and particle reacceleration.

Key words. Galaxies: clusters: general – X-rays: galaxies: clusters

1. Introduction

Many galaxy clusters are sources of diffuse radio emission. One such class of sources found in galaxy clusters are that of radio mini-halos. Mini-halos are diffuse, steep-spectrum synchrotron sources found in the cores of so-called "cool-core" clusters. These sources typically are associated with a central AGN and extend out to approximately the cooling radius of the cluster gas (for a review see Ferrari et al. 2008).

A number of mini-halos have emission that is correlated on the sky with spiral-shaped "cold fronts" seen in the X-ray emission, believed to be the signature of sloshing of the cluster's cool core gas (Markevitch et al. 2003; Ascasibar & Markevitch 2006). Mazzotta & Giacintucci (2008) discovered this correlation in two clusters, and suggested that the correlation resulted from a population of relativistic electrons that was reaccelerated by turbulence generated by the sloshing motions. In order to determine whether or not the reacceleration efficiency resulting from this turbulence is sufficient enough to reaccelerate electrons and produce the corresponding radio emission, we have performed MHD simulations of gas sloshing in a galaxy cluster with tracer particles acting as the relativistic electrons.

2. Simulations

Our simulations have been performed using FLASH 3, an adaptive mesh refinement hydrodynamics code with support for simulations

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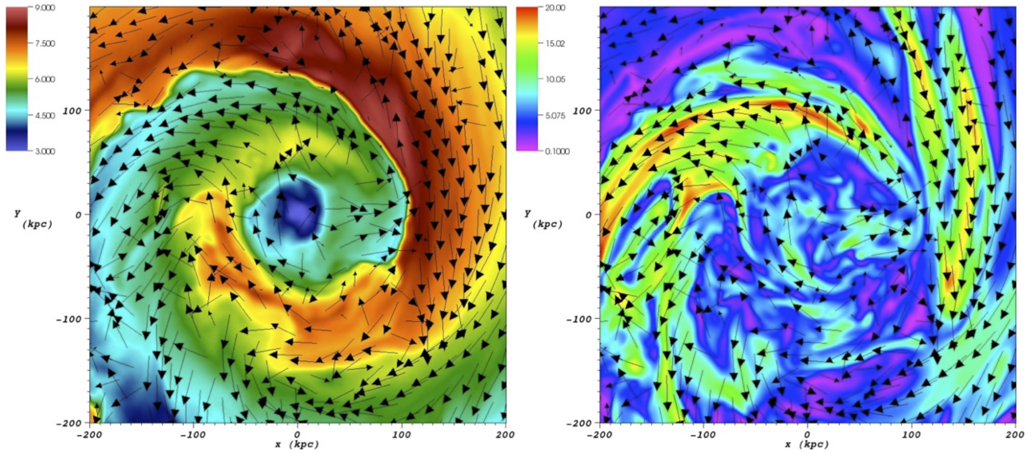

Fig. 1. Slices through the center of the simulation domain of gas sloshing in the center of a galaxy cluster. Left: Temperature (keV), showing prominent spiral-shaped "cold fronts". Right: Magnetic field strength (μG), showing the field amplification near the front surfaces. Vectors show the magnetic field direction. Each panel is 400 kpc on a side.

of magnetized fluids. Our simulations are set up in the manner of Ascasibar & Markevitch (2006) and ZuHone et al. (2010). In this scenario, a large, relaxed cool-core cluster and a small, gasless subcluster are set on a trajectory in which the subcluster will pass by the core. The gravitational force from this subcluster acts on both the gas and dark matter cores of the main cluster, but due to ram pressure the gas core becomes separated from the center of the potential well and begins to "slosh" back and forth in the gravitational potential, forming spiral-shaped cold fronts (see Fig. 1, left panel). The initial magnetic field in our simulations is set up as a tangled field with an average field strength proportional to the gas pressure ($\beta = p/p_B \approx 100$).

For the relativistic electrons, we employ a simple model, assuming they are passive tracer particles advected along with the fluid motions. Each particle is given an initial energy and carries with it the properties of the local fluid. With this information, we derive the evolution of the particle energy along its trajectories by taking into account the relevant physical properties.

We assume that electrons are reaccelerated via transit-time damping (TTD) of magnetosonic turbulent modes (Cassano & Brunetti 2005; Brunetti & Lazarian 2007, 2010). We determine the turbulent velocity field in our simulation by a process of filtering (Dolag et al. 2005; Vazza et al. 2006, 2009). The velocity field is assumed to be a sum of a"bulk" component and a "turbulent" component. For each position the local turbulent velocity is calculated by quadratically interpolating the mean velocity from surrounding boxes of width ~20 kpc and then subtracting this mean value from the total velocity. The turbulent reacceleration coefficient for the electrons then may be determined using the TTD formalism. Figure 2 shows the resulting turbulent velocity has a power spectrum that is close to Kolmogorov (left panel) and is strongest in the region of the sloshing motions (right panel). We take into account radiative (synchrotron and inverse Compton) and Coulomb losses to calculate the evolution of the particle energy, with the physical parameters determined from the properties of the magnetized fluid. With the updated particle energies, we can then compute the associated synchrotron emissivities that may be projected along a line of sight to produce a map of radio emission.

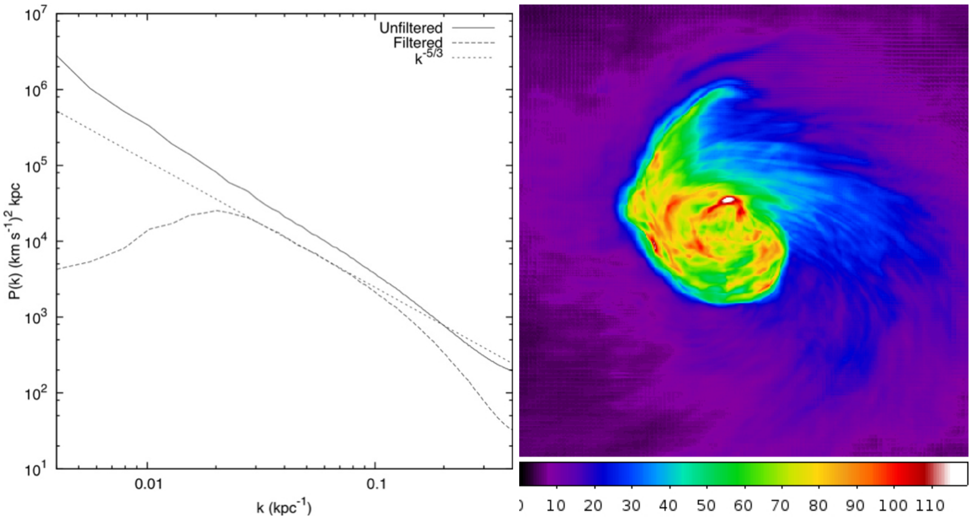

Fig. 2. The turbulent velocity structure of the sloshing gas. Left: The power spectrum of the velocity field. Solid line indicates the unfiltered power spectrum, dashed line the filtered power spectrum. The dotted line shows what would be expected for a Kolmogorov spectrum for comparison. Right: Mass-weighted, projected turbulent velocity of the gas in units of km s^{-1}. The most significant turbulence is contained within the envelope of the cold fronts. The panel is 400 kpc on a side.

3. Results

Two effects contribute to the association of the radio emission with the sloshing cold fronts. Strong shear flows are associated with the cold front surfaces, and these flows stretch and amplify magnetic field lines parallel to these surfaces (Keshet et al. 2010). Our simulations show that the degree of amplification of the magnetic energy along a cold front can be an order of magnitude or more above the initial field energy (ZuHone et al. 2011, in preparation; also see Fig. 1, right panel).

Our most intriguing results come from the integration of electron energies along the trajectories of our tracer particles. Beginning with a spherical distribution of particles with radius r = 200 kpc, and with the number density proportional to the local gas density, we assign electron energies to each tracer particle from an initial power-law distribution, set up shortly after the sloshing period begins. After evolving the particle energies along the trajectories of the tracer particles for approximately 400 Myr, we find that most of the electrons have cooled below the threshold for synchrotron emission, with the exception of those associated with the envelope of the sloshing motions. Figure 3 shows mock observations of X-ray surface brightness and projected "spectroscopic-like" temperature with radio contours overlaid. There is a clear correspondence with the region associated with the cold fronts and the radio emission from the mini-halo. This is also the region where the turbulent motions are strongest (see Fig. 2, right panel). If the electrons are assumed to simply cool without reacceleration, we do not see such emission.

4. Conclusions

We have performed MHD simulations of gas sloshing in clusters of galaxies, with the aim of determining whether or not the correlation between radio mini-halo emission and sloshing cold fronts in some clusters can be explained by the reacceleration of relativistic electrons by turbulence associated with the sloshing motions. Our initial results are very promising, indicating that the combined effects

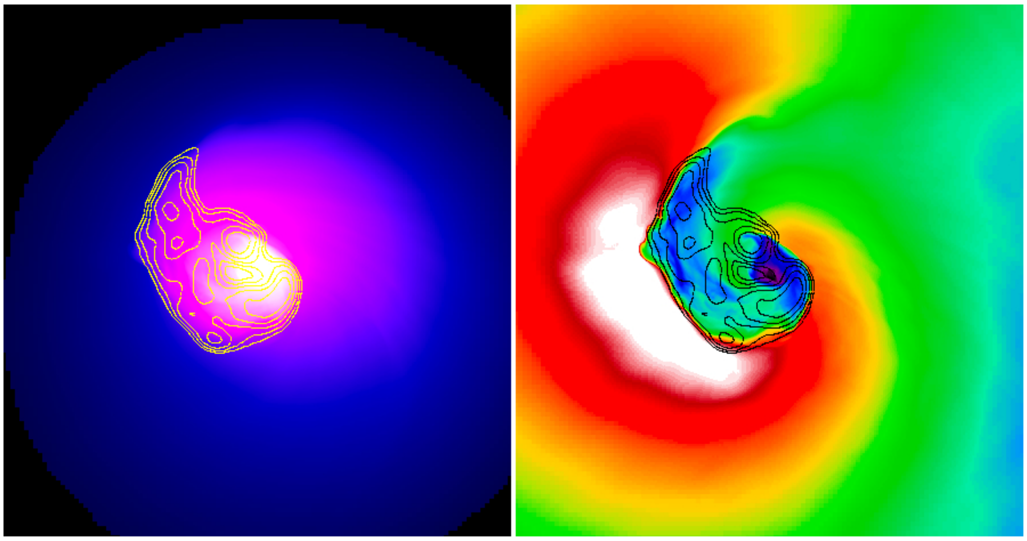

Fig. 3. Mock X-ray images of a sloshing gas core with mock 300 MHz radio contours overlaid, projected along the z-axis of the simulation. Left: X-ray surface brightness in the 0.5-7.0 keV band. Right: "Spectroscopic-like" projected temperature. Contours begin at 0.5 mJy/beam and are spaced by a factor of $\sqrt{2}$. Each frame is 400 kpc on a side.

of the amplified magnetic field and the turbulence associated with the sloshing motions reaccelerates a population of relativistic electrons within the envelope of the cold fronts which emit synchrotron radiation from these regions. In our procedure we assume a population of seed electrons diffused in the sloshing region. Although we do not model the injection process of these particles, several mechanisms may provide an efficient source of fresh electrons to reaccelerate in cluster cool-cores (see discussion in Cassano et al. 2008). Further work will also detail differences in prediction with other models for mini-halos.

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