Buoyancy of Cosmic Ray Loaded Magnetic Flux Tubes in the Galactic Disk

Roark Habegger[1,*] Ellen Zweibel[1,2]

1: University of Wisconsin – Madison Astronomy Department 2: University of Wisconsin – Madison Physics Department *Presenting Author

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ABSTRACT

Interstellar gas in disk galaxies is vertically supported against gravity by the pressure of thermal gas, magnetic fields, and cosmic rays. When nonthermal pressure support exceeds a threshold, the Parker instability can appear. Like the Rayleigh-Taylor instability, over-dense regions sink, and under-dense regions rise. This produces peaks and valleys in the magnetic field. Gravitational energy provides the free energy necessary to compress the interstellar gas into the valleys [1].

Since cosmic rays are unaffected by the galaxy's gravity, they increase the buoyancy of the ISM. However, the cosmic ray fluid has a finite compressibility, increasing the energy required to form valleys. Linear theory suggests this compressibility dominates buoyancy, suppressing the instability [2,3].

To address this counterintuitive result, we run local simulations of injections of cosmic ray pressure in the galactic disk. This assumes a supernova as the source. If this physically motivated perturbation creates buoyant magnetic flux tubes, then it is likely the Parker instability can develop in the ISM even if instability criteria from linear theory are not met.

CONCLUSIONS

While injection of cosmic rays combined with the streaming instability does de-load magnetic flux tubes, we find the time scale of this mass loss is still too long for dynamical significance. Even with 3D simulations, which make it easier for the tube to rise, it takes on the order of 40 Myr for significant changes. The instability may occur in highly magnetized, star-bursting galaxies. If it appears, the instability drives mixing in the interstellar medium and produces a turbulent magnetic field in the galactic disk. However, these results just add to the similar effects of other physical processes (e.g. radiative cooling and differential rotation). Our results re-affirm the insignificance of the Parker Instability in the dynamical evolution of galactic disks and the interstellar medium of galaxies like the Milky Way [6].

CITATIONS

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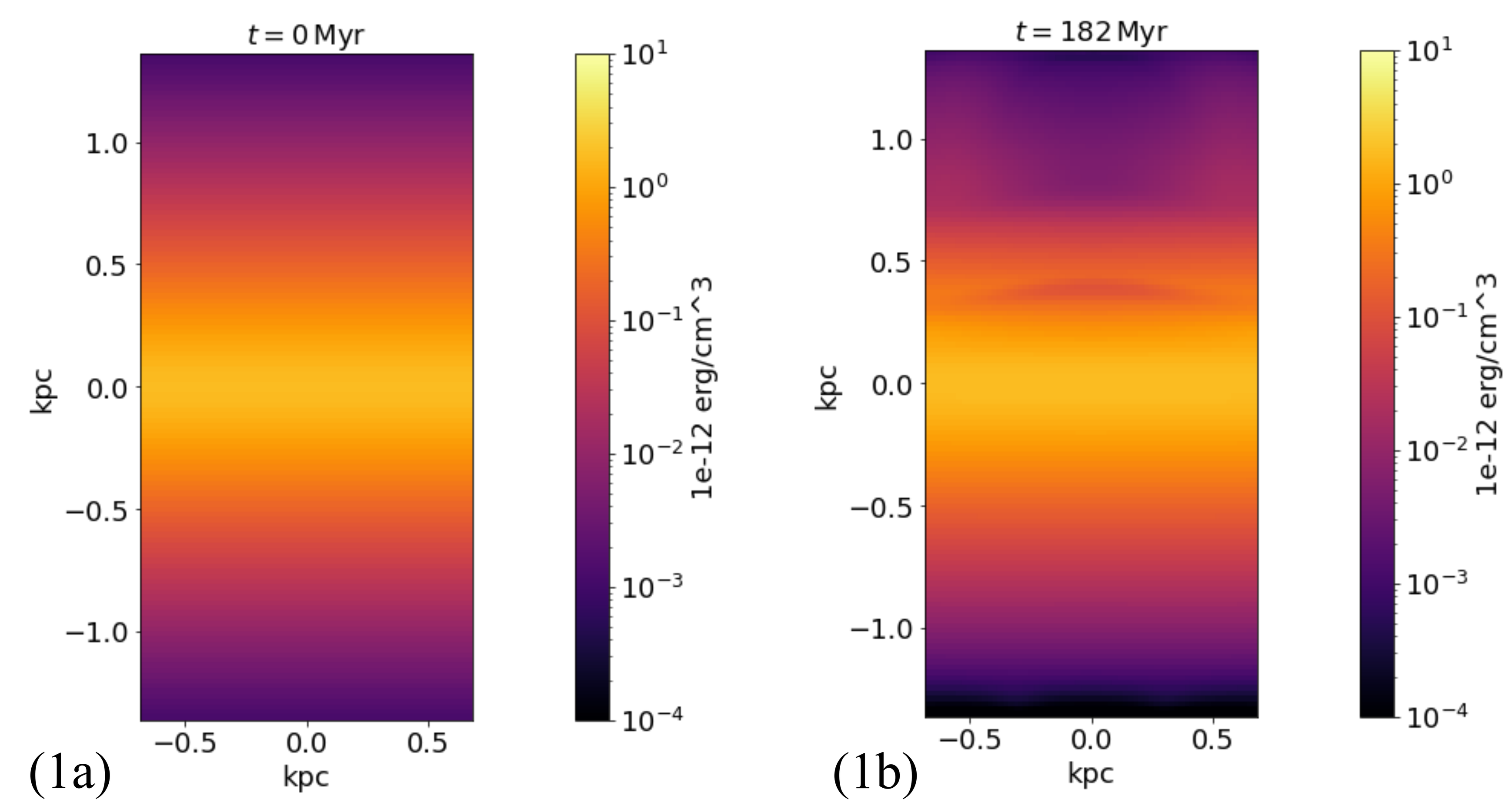

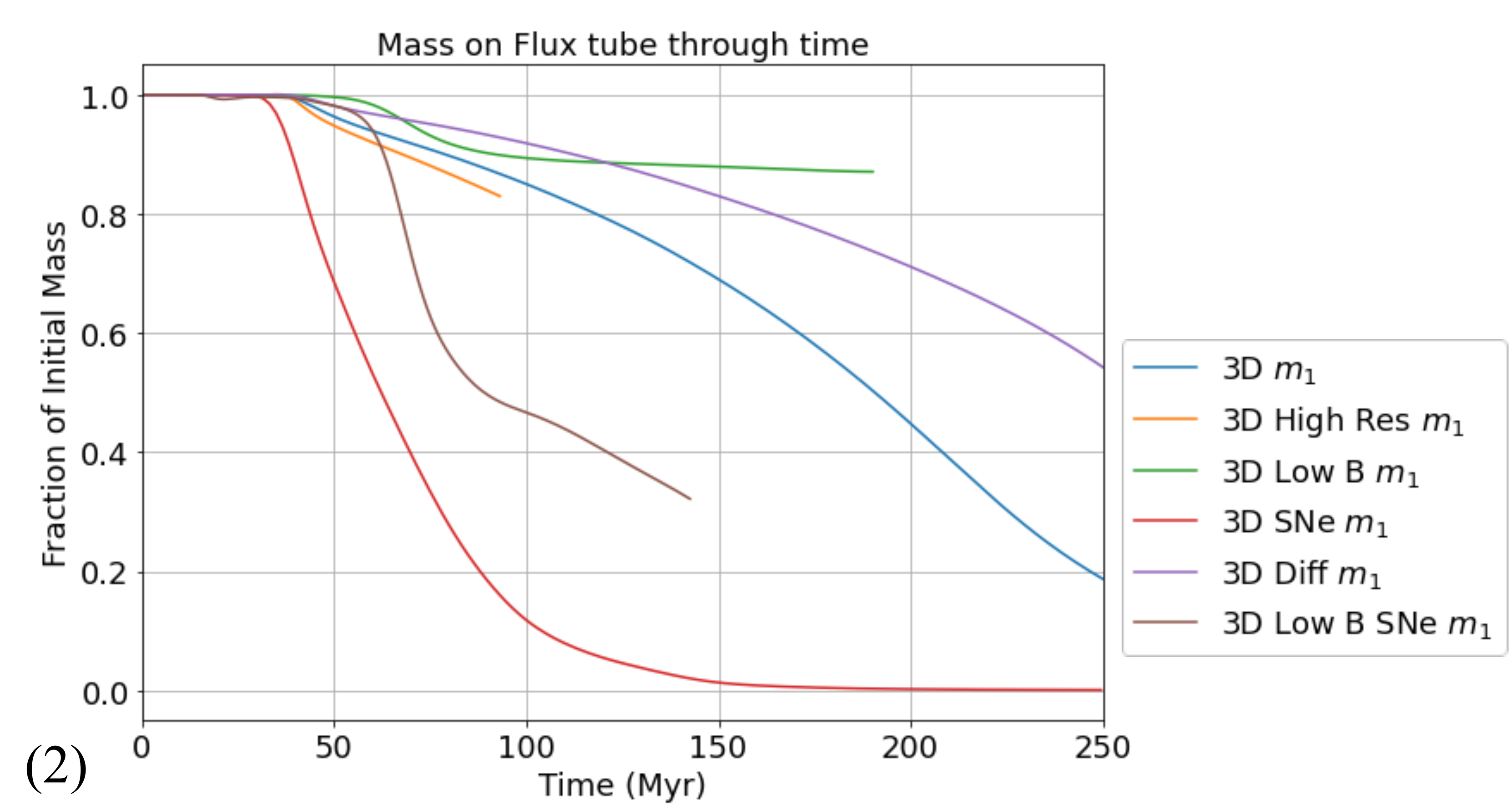

Figure 1: Gas pressure in the xz-plane of simulation. Plot 1a shows the initial condition of exponential stratification from the midplane. Plot 1b shows a later time, when mass has been evacuated as a result of cosmic ray injection. The flux tube has created a bulge in the gas.

Figure 2: Using a scalar dye, we track the original flux tube where the injection occurred. This figure shows the total mass on that tube over time for different simulation parameters. Each case varies from the base case in blue. "High Res" has double resolution. "Low B" has a third of the magnetic field strength. "Sne" had a larger injection of cosmic rays. "Diff" had a higher cosmic ray diffusion rate. "Low B Sne" had a low magnetic field and large perturbation.

Figure 3: Scalar dye in xz-plane for different parameters. Similar to Fig. 1, these plots show the flux tube along which the cosmic rays where injected for various simulations runs. Plot 3a is the base case (blue line in Fig. 2), matching the simulation shown in Fig. 1. Plot 3b was run with a higher diffusion rate. Plot 3c was run with a larger initial cosmic ray injection.

INITIAL CONDITIONS & METHODS

We produce 3D simulations with the magnetohydrodynamic code Athena++ combined with a cosmic ray module implemented by Jiang and Oh [4]. The simulations are initialized with a magneto-hydro-static equilibrium in the vertical direction according to equation 1 with a hyperbolic tangent gravitational acceleration [5]. This solution includes gas pressure, magnetic pressure, and cosmic ray pressure.

We start the simulation with a localized injection (~50 pc radius) of cosmic rays one scale height above the midplane of the simulation. This injection mimics the resultant production of cosmic rays in the shock front of a supernova explosion. We also place a scalar dye uniformly along a magnetic flux tube which passes through the injection region (see Fig. 3).

The cosmic ray module includes a streaming term, allowing us to include the impact of the kinetic scale streaming instability associated with cosmic rays [4]. Specifically, the cosmic ray fluid flows along the magnetic field lines at the local Alfven speed. This flow gives additional physical significance to a magnetic flux tube.

The vertical boundary condition is a 'diode' or vacuum state. The horizontal boundary condition parallel to the initial magnetic field is outflow. The horizontal boundary condition perpendicular to the initial magnetic field is periodic.

$$\frac{d}{dz}\left[P_g + P_B + P_{cr}\right] = \rho g_z \quad (1)$$

$$g_z \propto -\tanh\left(\frac{z}{H}\right) \quad (2)$$