Cosmic-ray driven dynamo in the interstellar medium of irregular galaxies

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1. Abstract

Irregular galaxies usually are smaller and less massive when compared to the spiral, S0 and elliptical counterparts. The radio observations show that the magnetic field in irregular galaxies is present and its value reaches the same level as in spiral galaxies. However the conditions in the medium of irregular galaxy are very unfavorable for amplification of the magnetic field due to slow rotation and low shearing rate.

We investigate the cosmic ray driven dynamo in the interstellar medium of irregular galaxy. We study its efficiency under the conditions of slow rotation and a weak shearing. The star formation is also taken into account in our model and is parametrized by frequency of explosions and modulations of activity. Cosmic rays are injected into the interstellar medium through randomly exploding supernovae.

We find that even slow galactic rotation with a low shearing rate gives an amplification of the magnetic field and that the fast rotation with a low value of the shear enhances the efficiency of the dynamo. Our simulations have shown that a high amount of magnetic energy leaves the simulation box becoming an efficient source of intergalactic magnetic fields.

2. Description of the model

The cosmic ray driven dynamo model consists of following elements (based on Hanasz et al. 2004, 2006, 2009):

- **The cosmic ray component** (CR) is an relativistic gas described by diffusion-advection transport equation and adiabatic equation of state with $\gamma_{cr} = 14/9$.
- **Anisotropic diffusion of CR**. Following Giacalone & Jokipii (1999) and Jokipii (1999), we presume that CR gas diffuse anisotropically along magnetic field lines. In our simulations we use following values 10^3 pc^2 Myr^{-1} and 10^4 pc^2 Myr^{-1} for perpendicular and parallel coeffcients respectively.
- **Localized sources of CR**. In the model we apply the randomly explosions of supernova remnants in the disk volume (see Hanasz & Lesch 2000). Each explosion is also a localized source of CRs. The SNe activity is modulated during the simulation time with the period equal T_p and the activity time T_a.
- **Resistivity of ISM**. In the model we apply the uniform resistivity and neglect the Ohmic heating of gas by resistive dissipation of magnetic fields. We set $\eta = 100$ pc^2 Myr^{-1}.
- **Shearing boundary condition** and **tidal forces**, following the prescription by Hawley, Gammie & Balbus (1995), are implemented to reproduce the differentially rotating disk in the local approximation.
- Realistic **vertical disk gravity** following the model of ISM in Galaxy by Ferrière (1998), however the model has been modified by reducing the contribution of disk and halo masses, by one order of magnitude, to adjust the irregular galaxy environment.

The 3D Cartesian domain size is 0.5 kpc × 1 kpc × 8 kpc in *x, y, z* coordinates corresponding to the radial, azimuthal and vertical directions, respectively. The grid size is 20 pc in each direction. The boundary conditions are sheared periodic in *x*, periodic in *y* and outflow in *z* directions. The domain is placed at the galactocentric radius $R_* = 2$ kpc. The initial state of the system represents the magnetohydrostatic equilibrium with the horizontal, purely azimuthal magnetic field with $p_{mag}/p_{gas} = 10^{-4}$, which corresponds to the mean value of magnetic field in the simulation box of 5 nG.

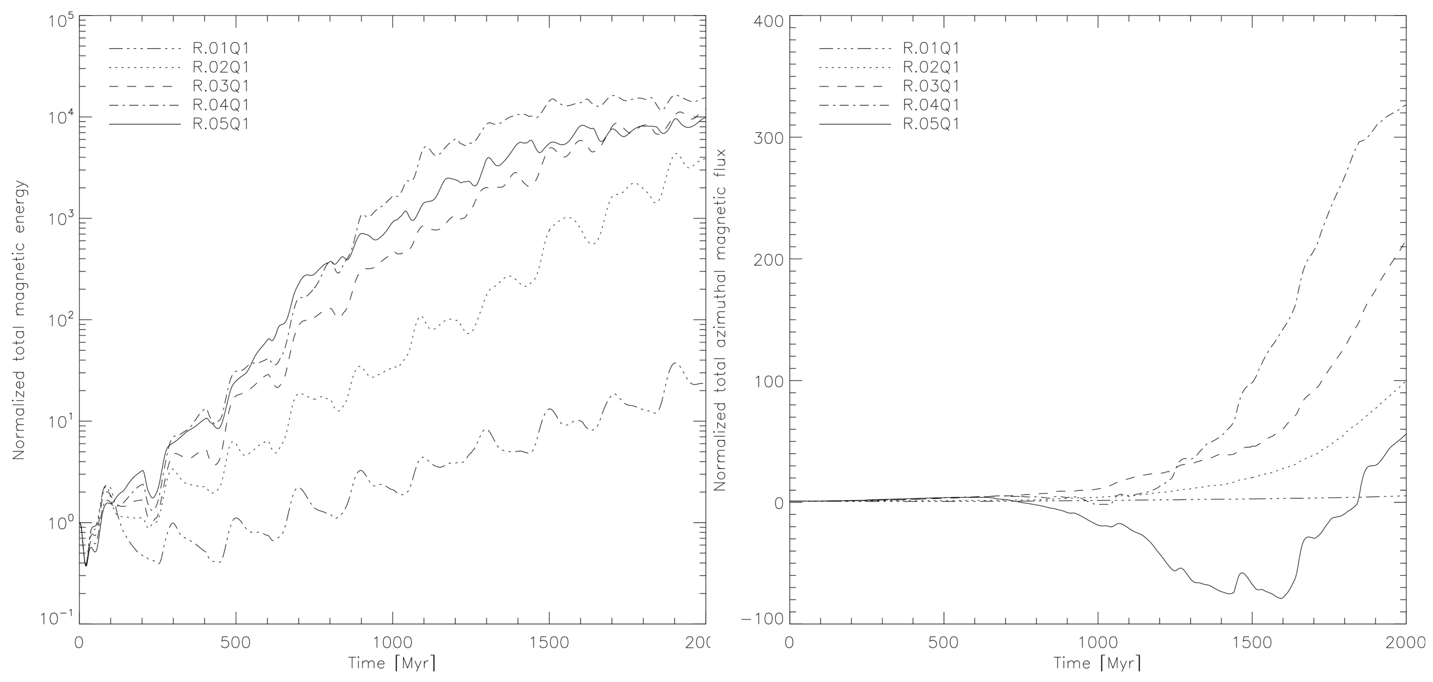
The **model name** consists of combination of four letters: "R", "Q", "SF" and "M" followed by a number. The letter "R" means the angular velocity (rotation), "Q" is the shearing rate, "SF" is the supernova explosion frequency and "M" stands for its modulation during the simulation time, and the numbers determine the value of corresponding quantity. Values of the parameters are given in following units: angular velocity in Myr^{-1} supernova explosion frequency in kpc^{-2} Myr^{-1} and the modulation times in Myr. The experiment named "FIRST", points to an experiment, in which only during the first 50 Myr supernovae are active and after that time CR injection is stopped.

3. Results: Outflow of the magnetic field

To measure the total production rate of magnetic field energy during the simulation time we calculate the outflowing E_B^{out} through the *xy* top and bottom domain boundaries. To estimate the magnetic energy loss we compute the vertical component of Poyting vector S_z. This value is computed in every cell belonging to the top and bottom boundary planes and then are being integrated over the area of boundries and time. The results are following:

- In the cases of experiment in which we find an efficient amplification of magnetic fields the energy loss E_B^{out} is comparable to the energy remaining inside the domain E_B^{end}.
- The ratio E_B^{out}/E_B^{end} varies from 0.03 to 0.96 and it is highly dependent on the supernovae explosion frequency.
- The results show that the outflowing magnetic energy is substantial suggesting, that irregular galaxies due to their weaker gravity can be efficient sources for the intergalactic magnetic fields.

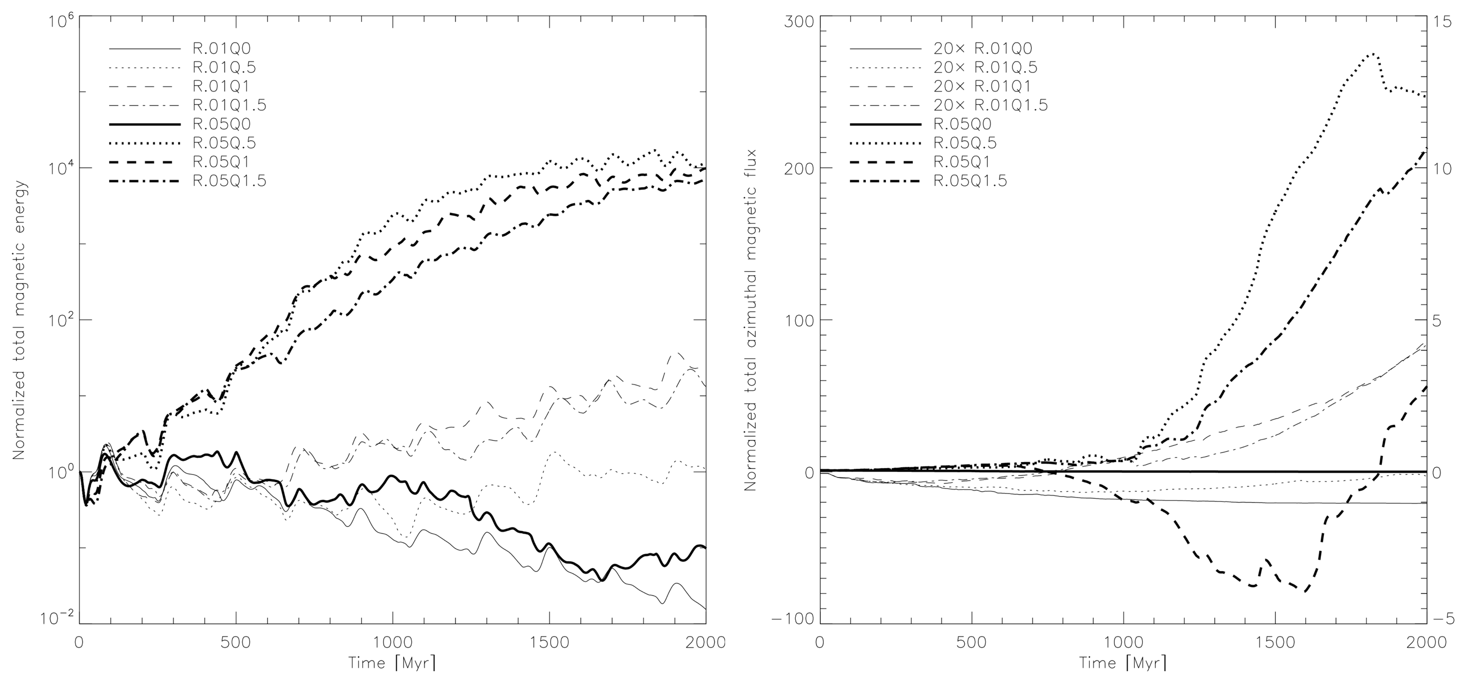
4.1. Results: Dependence on the angular velocity



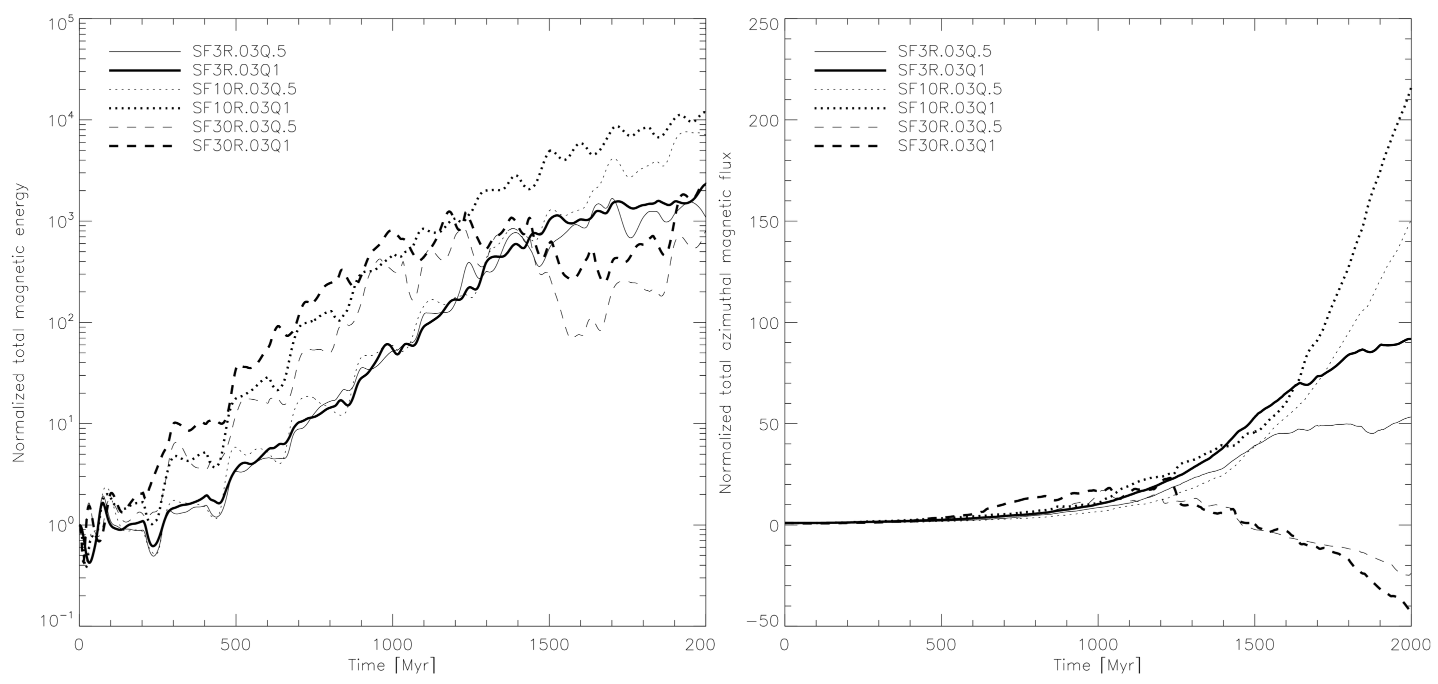
- Exponential of E_B growth in all cases.
- Models with higher rotation saturates after 1200 Myr.
- Higher angular velocity gives higher amplification of total azimuthal flux.
- Model R.01Q1 does not enhance azimuthal flux at all.

4.2. Results: Dependence on the shearing rate

- Shear: $q = -d\ln\Omega/d\ln R$.
- The evolution of E_B and B_φ in all cases follows the evolution of model R.05Q1 (see 4.1).
- The model R.01Q.5 sustains the initial magnetic field only.
- In the case of models with no shear (R.01Q0, R.05Q0) the initial magnetic field decays.

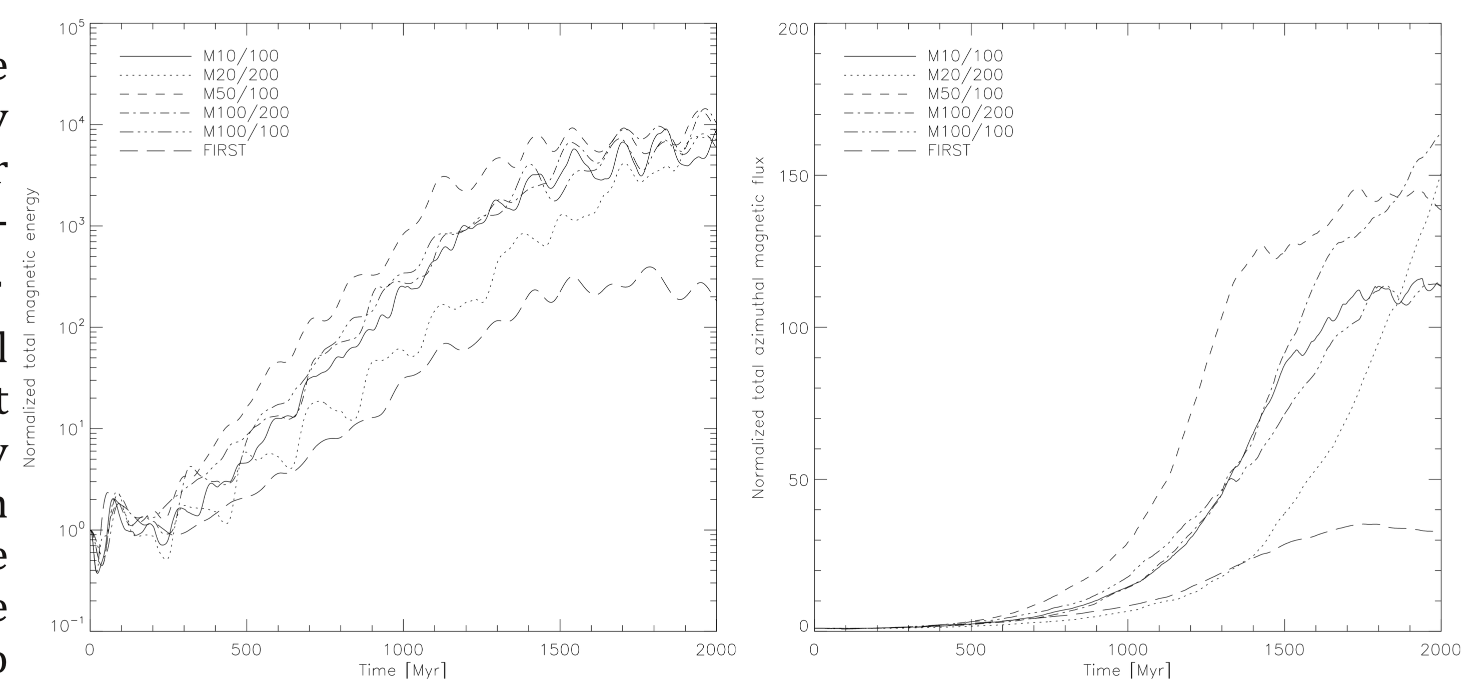


4.3. Results: Dependence on the SNe activity – frequency and modulation



- E_B evolution for all models is similar only in the case of the B_φ we observe differences between the models.
- Results suggest that the dynamo requires higher frequencies of supernovae explosions to create more regular field, however, if the explosions occur too frequently the process is suppressed.

- Shorter times of the stopped SNe activity period give the faster growth of B_φ. The saturation occurs earlier as well.
- In the case of the model FIRST we found that after about 8 galaxy revolutions the growth of E_B and B_φ stops. The azimuthal flux after the saturation starts to decay gently.



5. Conlusions

- In the presence of slow rotation and weak shear in irregular galaxies the amplification of total magnetic field energy is still possible.
- The shear is necessary for magnetic field amplification, but the amplification itself depends weakly on the shearing rate.
- Higher angular velocity gives higher efficiency of the CR-driven dynamo process.
- The efficiency of the dynamo process increases with the SNe activity, but excessive SNe activity damps the amplification.
- Shorter phase of stopped SNe activity gives faster growth and earlier saturation time in the evolution of azimuthal magnetic flux.
- For a high SNe activity and fast rotation the azimuthal flux reverses its direction because of turbulence overlapping.
- Due to a shallow gravitation in an irregular galaxy the outflow of magnetic field from the disk is high suggesting that they may magnetize the intergalactic medium as predicted by Kronberg et al. (1999) and Bertone et al. (2006).

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