3D numerical global simulations of cosmic ray driven dynamo in barred and dwarf irregular galaxies.

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Abstract

In this paper we present our results of three-dimensional global numerical simulations of barred and irregular galaxies including a process of a cosmic-ray driven dynamo in respect to star formation rates. We are looking for the answer which physical mechanism could be liable for magnetic field evolution observed in both types of the mentioned galaxies. Our main goal is to compare our numerical results with observations, so we prepare model of high-frequency (Faraday rotation-free) polarized radio emission maps from the resulted magnetic fields and cosmic rays (CR) both active in our modeled galaxies.

The main result is that CR driven dynamo can amplify weak magnetic fields up to several mG within few Gyr in barred galaxies. Magnetic field structures in model of the barred galaxies are alike the observed in maps of the polarized intensity in these galaxies. Our results also provide new information about the observed polarimetry properties of barred and spiral galaxies: the quadrupole modes of modeled galaxies often present in real barred galaxies, a stochastic nature of magnetic field reversals (present in the Milky Way), the dipole modes of magnetic structures resulted at certain stages of the galactic evolution (e.g. NGC 4631).

In the case of dwarf irregular galaxies despite the adverse conditions (low mass, slow rotation) the dynamo can operate. Observations and numerics show some indication for some dynamo thresholds - needs further deep investigation. SFR/SNR is the key parameter, but to high destroys the rotation: but we need both to operate the large scale dynamo. Possible magnetization of the IGM.

1. Introduction

The radio polarization observations of barred and dwarf galaxies [1, 2] show that the magnetic field in their disks could be dynamically important. In barred and spiral galaxies the radio observations prove that their magnetic fields have two components, random (around 9–15 μG) and regular one (around 5 μG) [1]. The large scale structure of the magnetic field in such galaxies is generally represented by a superposition of modes with different azimuthal and vertical field directions and symmetries. In disks of galaxies the axisymmetric spiral (ASS) mode is the strongest one [3], however the bi-symmetric spiral mode (BSS) or a mixture of both with a preponderance of one of these two shapes is also observed [4]. The vertical symmetry can be the even (quadrupole) or the odd (bipolar). Rotation measure observations show that the ASS magnetic field exists in several galaxies, e.g., in M31 [5], IC 342 [6] or Large Magellanic Cloud (LMC) [7]. The BSS mode has been with no doubt observed only in one galaxy, namely in M81 [6].

In comparison with spiral galaxies dwarf irregulars have very small masses having also irregular distribution of star formation regions, and half order of magnitude slower rotation than spirals [8], but they are most numerous population in the Universe. The radio polarization observations and analysis of 17 dwarf irregulars (12 observed in the Local Group, [9] showed that in general magnetic fields in dwarf galaxies are much weaker than in spiral and barred galaxies. The authors also

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found that the magnetic field strength is proportional to the local star formation rate (SFR). This seems to be consistent with the predictions of the dynamo theory, where the generated magnetic field depends on the energy input. SFR determines the number of supernova explosions which contributes significantly to the turbulent energy. However, there are also some dwarf galaxies (like IC10 or NGC4449) which show strong magnetic field with strength about 10μG [9, 10, 11], similar to observed in grand designed spirals. The 3D MHD calculations of dwarf galaxy were also made by [12] who discussed the influence of supernova explosions onto ISM and the galactic magnetic field without any dynamo action. They also got strong magnetic wind into the galactic halo and further out which could be a source of intergalactic magnetic fields [13].

The strength of the observed magnetic field in barred and spiral galaxies is so strong, that it is necessary to amplify its value very efficiently from the value of the seed fields, which is not higher than 10^{-9}μ G). And because of that the idea of MHD mean field dynamo appeared historically [14, 3]. The main theoretical model of the dynamo process is the mean field dynamo theory [3], which can explain magnetic fields in many contexts: the Earth, the Sun, or stars. In galaxies the mean field dynamo clarifies the generation of the regular large scale magnetic field as a result of the joint action of differential rotation and helical turbulent motions of interstellar gas (the so-called X-effect). However, for galaxies the classical kinematic dynamo gives rather long timescale of the magnetic field amplification, i.e., about 10^9 yr. This timescale is too long to explain strong magnetic fields in high redshift galaxies beyond z = 1 [15]. A faster amplification is possible when the cosmic-ray (CR) driven dynamo [14, 16-20] is applied. This dynamo relies on three principle effects: first, the cosmic-ray energy is continuously supplied by supernovae (Sne) remnants to the galactic disk, which became turbulent due to buoyancy of magnetic field with the help of CRs. Second, the fast turbulent magnetic reconnection [21, 22] allows small scale loops of a magnetic field to merge into large scale coherent structures in the limit of vanishing resistivity. Third, the differential rotation leads to generation of the toroidal magnetic field component from the poloidal one.

In present paper we check how our model working effectively in spiral galaxies [16-19] works in two different galaxies: the barred galaxies and to dwarf irregulars one. From this reason in the present numerical experiment we study the problem how model input parameters observed in barred galaxies and dwarf irregulars (smaller gravitational potential, slow rotation and small shear) would influence the magnetic field in them. We are trying to reproduce observations of dwarf irregulars presented in Chyży et al. (2011) [9] in the global model of the irregular galaxy, because of some positive indications were found in the local model [13].

2. Problem description

Our model of cosmic-ray driven dynamo solve the MHD equations together with the diffusion convection equation of the cosmic-ray gas [23]. Cosmic-ray fluid is coupled with the thermal gas via the extra pressure term in the equation of motion. Supernovae are injected into the cosmic-ray fluid (10% of the kinetic energy of SN explosion) in random position weighted according to the local thermal gas density. In the case of barred galaxy we make five experiments with the same value of magnetic diffusion coefficients $3x10^{25}$ cm^2/sec and other physical parameters as the total mass of a model galaxy 1.75 M^{11}_{sun}. The size of a galaxy is 30kpc x 30kpc x 8kpc with resolution of 512×512×123. The size of the bar is 6kpc× 3kpc× 3kpc. The only parameter we changed is the star formation rate with values present in Table 1.

Table 1: Overview of the obtained parameters characterizing barred galaxy models.

Model	f_{SN} [yr^{-1}]	τ [Myr]	M_{lost} [$M_\odot yr^{-1}$]	$maxB^{bar}_{\varphi}$ [μG]	$maxB^{arms}_{\varphi}$ [μG]	B_{mean} [μG]
S25	1/25	230	4.7	88.8	$4.7\ 10^{-2}$	3.7
S50	1/50	194	3.2	85.1	2.1	6.4
S100	1/100	326	1.7	71.3	5.9	7.1
S200	1/200	300	1.1	53.4	9.5	10.2
S300	1/300	360	0.6	59.3	8.6	7.9

Initial conditions of the irregular galaxy model are set to hydrodynamic equilibrium and with no magnetic field. In the first 1Gyr of simulation with the every tenth SN explosion a small magnetic dipole is injected. The key parameters of the model are: total mass (the rotation which have maximum around 50 km/s), size of the galaxy, frequency and modulation of SN explosions. In model of the presented dwarf galaxy we apply the following input parameters: size of the numerical domain is 8×8×4 kpc in x, y, and z direction, with resolution of 256 × 256 × 128, respectively, the mass of stellar thin disk is 600× 10^6 $M_\odot$ and the halo is 7. 4×10^9 $M_\odot$, the magnetic diffusion is 9×10^{24} cm^2/s, and in the end the assumed mass of the gas is 500×10^{6} $M_{\odot}$. The magnetized explosions occurs only for the first t_{mag}=0.6Gyr, and then they are stopped. The SNe explosion frequency is f_{SN}= $3x10^{3}kpc^{-2}Gyr^{-1}$ and is modulated with period 0.2Gyr. The SNe are active only for the first 0.04Gyr of each period.

3. Results

The total magnetic energy grows efficiently for each experiment in time with e-folding time shown in the Tab. 1 (from 230 Myr to 360 Myr). The fastest growth was obtained for the highest star formation rate (1/25 yr)(Fig.1 bottom right). We also obtained that the value of the magnetic field intensity in the modeled bar and the magnetic spiral arms are similar to the observed values. The highest values are obtained for the highest SN rates (see Table 1). For almost all experiments we obtained quadrupole symmetry (s25, s50, s200). Only for one experiment s100 (Fig.1 right middle top panel) we got dipole mode for azimuthal component of magnetic field (similar to e.g. NGC 4631). All experiments also show that stochastic reversals are present in all maps at each time step of azimuthal magnetic field component gray plots. Such character of magnetic field topology is observed for instance in our Milky Way. The polarization maps of modeled magnetic fields (Fig.1 bottom left bottom) prove that in the face-on map we obtain shifting of the magnetic arms into the inter-arm regions reaffirming our earlier results [24]. The last result presented here is the edge-on map of our model galaxy (Fig.1 bottom left top) which is alike the observed edge-on polarization maps not only for the barred but also for the spiral galaxies.

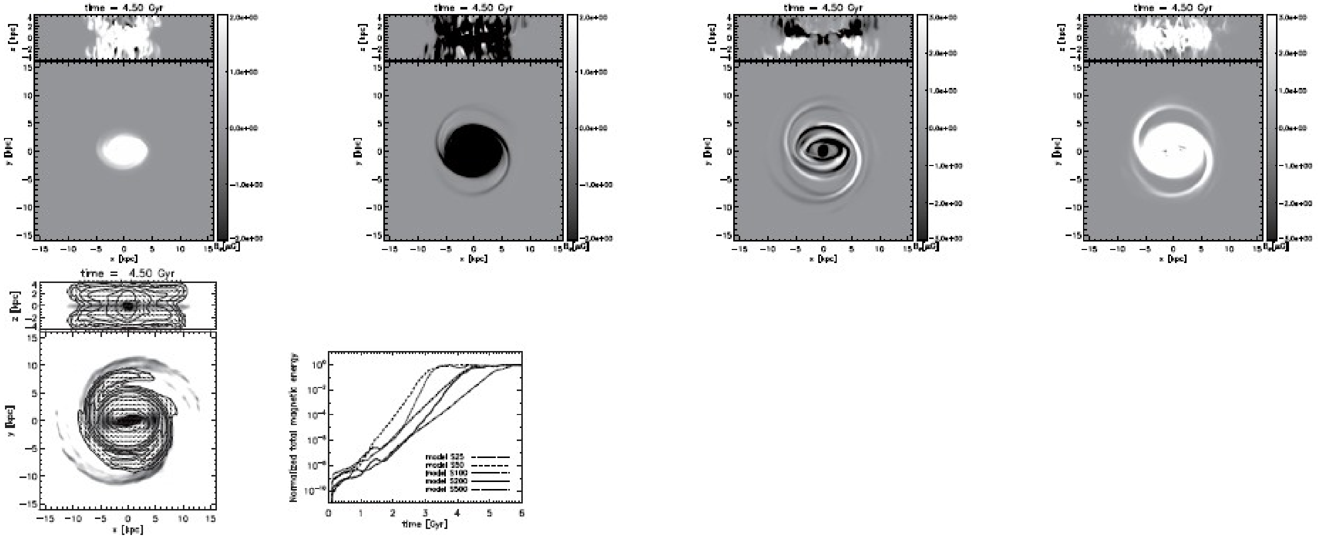

Figure 1: Top panels: the distribution of the toroidal magnetic field in vertical and horizontal slices through the disk center for the following models: S25, S50, S100, s200 (dark color represents regions with the positive toroidal magnetic field, white with negative, while unmagnetized regions of the volume are gray) Bottom panels: Left: Face-on and edge-on polarization maps for selected time step for the model S50, right: the total magnetic field energy in time for the same model.

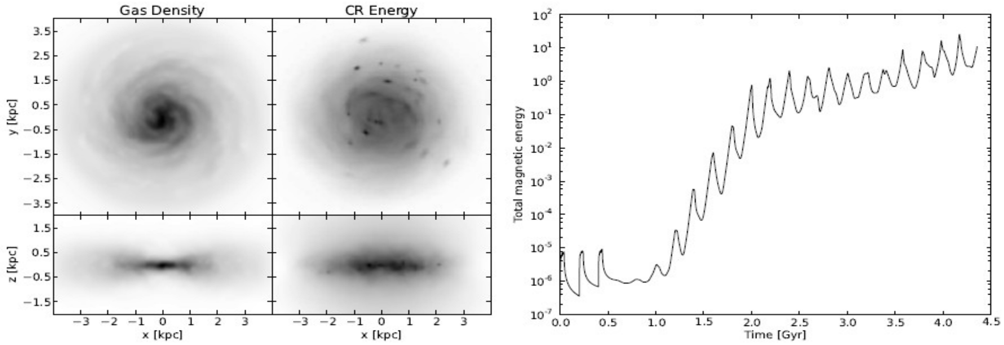

Figure 2: A sample view of dwarf galaxy model. In the left and middle left maps we present xy (top) and xz (bottom) cuts of the gas and the cosmic ray energy densities. In the right plot we show the evolution of the total magnetic energy in time**.**

A sample view of the model of irregular dwarf galaxy is presented in Fig. 2. In Fig. 2 left we present one time step from the time evolution of the gas energy density and the energy density of cosmic-rays. They prove that we have similar behavior of them as the observed quantities. In Fig. 2 (right plot) the evolution of total magnetic field is shown for a model of the dwarf galaxy. The magnetic field is injected in SNe (the first three peaks) and then is exponentially amplified by the cosmic-ray driven dynamo. After 2 Gyr the dynamo starts to saturate.

4. Conclusions

We made numerical experiments of the model of the cosmic-ray driven dynamo for barred galaxies in dependence on the star formation rate and we found that:

- we reaffirm the explanation found in our earlier simulations providing why the magnetic arms are present in inter-arm regions in the barred galaxies,
- the quadrupole modes of modeled galaxies often present in real barred galaxies,
- the dipole modes of magnetic structures resulted at certain stages of the galactic evolution (e.g. NGC 4631),
- the rapid exponential increase of the total magnetic energy and azimuthal flux to the observed worth,
- a stochastic nature of magnetic field reversals (present in the Milky Way).

We also made numerical calculations of the model of the cosmic-ray driven dynamo for dwarf irregular galaxies in dependence on the star formation rate and we found that:

- it is possible to obtain growth of the total magnetic energy to the values observed in dwarfs even for slow galactic rotation and low shearing rate, however fast rotation enhances the efficiency of the dynamo,
- we obtained the distribution of the energy density of gas and the cosmic-rays is similar to observations.

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