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MODELING REVERSALS OF GALACTIC MAGNETIC FIELDS AT LARGE DISTANCES FROM CENTERS OF MILKY-WAY-LIKE GALAXIES USING COMPUTATIONS ON GPUS

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SUMMARY: Nowadays it is strongly believed that in a large number of spiral galaxies there are regular magnetic fields. Their existence is proved by measurements of the Faraday rotation of polarization plane of electromagnetic waves which are received on modern radio telescopes. The theoretical description of magnetic fields generation is connected with the mean field dynamo mechanism. It is based on joint action of the α-effect and differential rotation. At the first stage of evolution, magnetic fields enlarge exponentially with the growth rate described by the largest eigenvalue of the corresponding differential operator. If the field becomes comparable with the equipartition value, the nonlinear terms become more important, and they are connected with saturation of the field growth. The nonlinear system of equations has several stationary points, and some of them are stable. According to the contrast structures theory for a quite small turbulent viscosity and some initial conditions, in different regions there will be magnetic fields of opposite directions, and they will be divided by narrow transition layers. Such features, for example, characterize the magnetic field of the Milky Way. Most of the existing works describe reversals for quite moderate distances from the galaxy center. However, it was shown previously that the magnetic field can principally be generated also in outer parts of galaxies, which are situated at distances of more than 10 kpc from the rotation axis. It is interesting to describe the appearance of reversals in such parts of galaxies. In this work we have studied the dynamo action in outer parts of the Milky-Way-like galaxies. It is shown that it is possible to generate opposite magnetic fields there. We have used random initial conditions to obtain spatial reversals. Because of a large volume of computations, they were carried out by using graphics processing units (GPUs).

Key words. **Galaxies: spiral – Dynamo – Magnetohydrodynamics – Galaxies: magnetic fields – ISM: magnetic fields**

1. INTRODUCTION

Nowadays, the existence of magnetic fields in a number of galaxies has been established quite firmly and is practically beyond any doubt (Beck et al. 1996, Arshakian et al. 2009). In pioneering works (Fermi 1949), there was an estimate that the magnitude of the field has the order of 10^{-6} G, which has been subsequently confirmed by both observations and theoretical estimates. At present, the most effective and recognised method for studying galactic magnetic fields is the measurement of Faraday rotation

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measures, which can use both the galactic (Morris and Berge 1964, Manchester 1972, Beck 2016, Andreasyan et al. 2020) and extragalactic (Oppermann et al. 2012, Horellou et al. 1992, Frick et al. 2016) sources.

From theoretical point of view, the process of galactic magnetic field generation is explained using a dynamo mechanism (Krause and Rädler 1980, Sokoloff 2015). It is connected with the combined action of two main effects. Firstly, there is the α-effect, which is based on helicity of turbulent motions of the interstellar medium, which is asymmetric with respect to the equatorial plane of the galaxy. Secondly, the dynamo is based on differential rotation, which describes the non-uniform large-scale rotation (outer layers rotate more slowly than the inner ones). They compete with turbulent diffusivity, which destroys large-scale structures of the magnetic field (Arshakian et al. 2009). One of the problems is connected with the conjugation of the equations of the $\alpha\Omega$-dynamo and the cascade model of turbulence in the case of spiral galaxies (Stepanov et al. 2008).

In the case of small values of the magnetic field, its generation can be described using a linear model. Thus, it is possible to solve the eigenvalue problem for the corresponding differential operator. The highest eigenvalue will principally characterize the process of exponential growth of the field (Mikhailov 2020). However, as it increases, the nonlinear terms characterising the saturation of this process become more and more significant. From the mathematical point of view, this means that the system of dynamo differential equations has a number of stationary points and some of them will be stable (note that the magnetic field strength in this case will be close to the so-called equipartition level) (Mikhailov 2015). This corresponds to the asymptotic theory of contrast structures which is well-known in mathematical physics (Nefyodov 2010). Regions with different magnetic fields will be divided by narrow transition layers.

Such configurations are also known from astronomical observations and are called the magnetic field reversals. Thus, it is firmly established that the magnetic field in the Milky Way changes its direction twice: this corresponds to distances of about 5 kpc and 7 kpc from the centre (Moss et al. 2012). It is necessary to emphasize that the actually observed configurations repeat the simulation results (Mikhailov and Khasaeva 2019) almost unambiguously. It is also assumed that such reversals may take place in other spiral galaxies such as M31, M33 etc.

At the same time, most of the existing studies of magnetic field reversals are associated with magnetic fields at relatively small distances from the central parts of galaxies (up to 8–10 kpc). Nevertheless, it was previously shown that dynamo-generated magnetic fields can be formed at distances of up to 15–20 kpc from the centre (Moss et al. 2012). The generation is usually possible due to the action of mechanisms that are qualitatively similar to those that explain the evolution of reversals. So, it is important to study the possibility of producing magnetic fields with opposite directions at large distances from the centre of the galaxy.

In present work, we study the generation of magnetic fields at large distances from the centre of the galaxy. From physical point of view, it is reasonable to assume that the initial conditions for a large-scale magnetic field are formed with the help of the so-called small-scale dynamo, which occurs in small domains with magnetic fields of random directions and magnitude (Arshakian et al. 2009). Due to this fact, it is clear that we need to consider stochastic initial conditions for the magnetic field (Kalling et al. 2011, Moss 1995).

These factors (extention of the investigation area, as well as consideration of a large number of parameter values) significantly increase the requirements for computing resources. The use of the graphics processing units (GPUs) together with algorithms that allow parallelization is quite effective here.

2. MAIN EQUATIONS

Generally, the magnetic field evolution in galaxies can be described by the Steenbeck-Krause-Rädler equation (Krause and Rädler 1980):

$$\frac{\partial \vec{B}}{\partial t} = \mathrm{curl}[\vec{v}, \vec{B}] + \mathrm{curl}(\alpha \vec{B}) + \eta \Delta \vec{B}, \qquad (1)$$

where $\vec{v}$ is the large scale velocity of the interstellar medium, α characterises the impact of the α-effect on the magnetic field generation, η is the turbulent diffusivity coefficient, which in our case is considered as a small parameter.

Considering the nonlinear dependence of the α-effect on the field magnitude, one should note that this equation does not have an analytical solution, which means that we must use some simplifications. In spiral galaxies, magnetic field is generated essentially in the equatorial plane of the galactic disk. Moreover, the half-thickness h of the disk has the order of 500 pc, while its radius substantially exceeds its half-thickness and is approximately of 10 to 12 kpc. According to the abovementioned assumptions, we can consider the galaxy as a thin disk in the so-called planar approximation (Moss 1995).

The equations are written in rectangular Cartesian coordinates. This can seem strange for axisymmetric objects but, from computational point of view, this approach is much more convenient to be realized. The angular velocity is described according to the following dependence:

$$\Omega = \Omega(x, y) = \frac{\Omega_0}{\sqrt{1 + \frac{x^2+y^2}{r_0^2}}}, \qquad (2)$$

where Ω_0 is the angular velocity at the rotation axis of the galactic disk, r_0 is the distance, from which the rotation curve can be considered close to flat (the linear velocity does not depend on the distance to the axis), equal to 2 kpc in our case.

There is a number of mathematical models to describe the α-effect. It is believed that the α-effect weakens further from the center of the galaxy at a sufficiently large distance. It can be assumed that the fundamental dependence of the corresponding coefficient on the kinematic parameters in the disk plane is described by the relation $\alpha \sim \frac{\Omega l^2}{h}$, where l is the scale of the turbulent motions, which is approximately 50-100 pc. We will also assume that, due to the nature of the influence of the Coriolis force on the flow, the values will be different for $z > 0$ and $z < 0$. This means that the α-effect is mirror asymmetric (in the simplest case, this can be described by a linear dependence on z (Moss 1995)). In this case, the expression for the alpha effect can be described using this equation:

$$\alpha(x, y, z, B) \cong \frac{\alpha(B)}{\sqrt{1 + \frac{x^2+y^2}{r_0^2}}} \cdot \frac{z}{h}. \tag{3}$$

One should also note that the magnitude of the magnetic field cannot grow infinitely, so we need to introduce a saturation condition for its growth (which causes the dependence of the α-effect on the absolute value of the field B). Also, the α-effect should be asymmetric to the equatorial plane, and should be close to zero in the central area. This can be taken into account by the following law:

$$\alpha(B) = \alpha_0 \left(1 - \frac{B^2}{B_0^2}\right), \tag{4}$$

where B_0 is the equipartition field, in which the field growth saturation occurs, α_0 is the amplitude value of the α-effect parameter.

The field of the large-scale velocity $\vec{v}$ corresponding to rotation of the galaxy around the z axis is determined by the composition of the angular velocity and the corresponding coordinates:

$$v_x = -\Omega y, \tag{5}$$
$$v_y = \Omega x. \tag{6}$$

Generally, the dependence of the magnetic field magnitude on the z-coordinate has a number of variations, but it is known that, in reality, the magnitude of the magnetic induction reaches its maximum in the equatorial plane and vanishes closer to the boundaries of the galactic disk. Practically, the dependence of the magnitude of the magnetic field on the third coordinate can be approximated by the cosine law. Thus, the dependence of the magnetic field on the z-coordinate can be considered as follows (Phillips 2001):

$$\vec{B}(x, y, z) = \tilde{\vec{B}}(x, y) \cos\left(\frac{\pi z}{2h}\right). \tag{7}$$

By introducing the Laplace operator, we can distinguish the second derivative in z:

$$\Delta B_x = -\tilde{B_x}(x, y)\frac{\pi^2}{4h^2}\cos\left(\frac{\pi z}{2h}\right) + \Delta_{xy}\tilde{B_x}, \tag{8}$$
$$\Delta B_y = -\tilde{B_y}(x, y)\frac{\pi^2}{4h^2}\cos\left(\frac{\pi z}{2h}\right) + \Delta_{xy}\tilde{B_y}, \tag{9}$$

where Δ_{xy} is the part of the Laplace operator corresponding to the x- and y-derivatives and it is a combination of the second derivatives of these coordinates. Note that in case of solving the equation in the equatorial plane ($z = 0$), it is enough to find the solution for $\tilde{\vec{B}}(x, y)$.

Thus, the vector equation can be transformed into a system of differential equations that describe the magnetic field of the spiral galaxy in the disk plane (hereon, we will omit tildes above the symbol of the field as, in further considerations, we will not need $B(x, y, z)$ as a function of three spatial variables):

$$\frac{\partial B_x}{\partial t} = \frac{\alpha_0}{h\sqrt{1 + \frac{x^2+y^2}{r_0^2}}}(yB_x - xB_y)\left(1 - \frac{B^2}{B_0^2}\right)$$
$$-\frac{\partial \Omega}{\partial y} yB_y - \Omega B_y - \Omega y\frac{\partial B_y}{\partial y} - \frac{\partial \Omega}{\partial y} xB_x - \Omega x\frac{\partial B_x}{\partial y}$$
$$-B_x(x, y, 0)\frac{\pi^2 \eta}{4h^2} + \eta\Delta_{xy}B_x, \tag{10}$$

$$\frac{\partial B_y}{\partial t} = \frac{\alpha_0}{h\sqrt{1 + \frac{x^2+y^2}{r_0^2}}}(yB_x - xB_y)\left(1 - \frac{B^2}{B_0^2}\right)$$
$$+\frac{\partial \Omega}{\partial x} yB_y + \Omega B_x + \Omega y\frac{\partial B_y}{\partial x} + \frac{\partial \Omega}{\partial x} xB_x + \Omega x\frac{\partial B_x}{\partial x}$$
$$-B_y(x, y, 0)\frac{\pi^2 \eta}{4h^2} + \eta\Delta_{xy}B_y, \tag{11}$$

where η is a small coefficient of turbulent diffusivity.

In a number of cases, the galactic magnetic field is generated in such a way that it can have the opposite direction in different parts of the disk. This happens due to the occurrence of an axisymmetric transition layer, which is commonly known as a reversal. Generation of the magnetic field reversals within the galactic disk was investigated earlier (Mikhailov 2020). It has also been shown (Mikhailov et al. 2014) that magnetic fields can reach large distances from the center. It is especially interesting if the generation of magnetic field reversals is even possible at such large distances.

As for the boundary conditions, according to general theoretical considerations it would be reasonable to assume that $B_x \to 0$ and $B_y \to 0$ at

$r = \sqrt{x^2 + y^2} \to \infty$. However, such conditions are difficult to implement from the computational point of view. Therefore, in such problems (Moss et al. 2012), it is common to use the conditions $B_r|_{r=R} = B_\phi|_{r=R} = 0$, where R is some value significantly exceeding the dimensions of the region of our interest (for example, values of about 20 kpc).

The result of evolution of the magnetic field and possibility of the reversals existence depends mainly on the initial conditions. Usually, when solving such problems numerically, the deterministic initial field values are used. For example, to obtain a field with reversals, it is sufficient to consider sinusoidal initial conditions. However, in reality, the initial conditions for a large-scale field form from values of the magnetic field in turbulent cells (the so-called small-scale field), whose directions and magnitudes are random (Moss 1995). Thus, the solution obtained using random initial values of the field describes the actual reality with better accuracy. Previously, it was shown that under some random initial conditions one can obtain a magnetic field with reversals as a result of evolution, (Phillips 2001). Our aim is to determine whether reversals associated with random initial conditions can occur at distances from the center that exceed the average dimensions of the galaxy.

Here, the initial conditions in the form of Gaussian wavelets are used (a similar approach was used in the previous work of (Moss and Sokoloff 2013)):

$$\vec{B} = \sum_{n=0}^{K} \vec{B}_n e^{-\frac{(\vec{r}-\vec{r}_n)^2}{2\sigma^2}}. \qquad (12)$$

3. NUMERICAL SOLUTIONS

Eqs. (10) - (11) were solved numerically using the explicit numerical method implemented on the C++ language and adopted for parallel calculations. We have a quite large object, and it is necessary to study a large number of random realizations of initial conditions. So, the requirements for computational resources are quite high. This problem can be solved by using graphic processors. CUDA is a hardware-software architecture that allows parallel computing using graphic processing units (GPUs) from NVIDIA. Despite the significantly lower clock frequency of processor cores (typical GPU frequency usually does not exceed 2.5 GHz) and a simpler architecture, a large number of cores, about several thousands, allows efficient calculations that is enough for using parallel methods. When choosing appropriate algorithms, the acceleration of calculations compared to the single-threaded mode can reach a hundred times or more (Kalling et al. 2011, Grechkin-Pogrebnyakov et al. 2015).

For calculations and performance testing, we used the following graphic cards:
1) GeForce GTX 660 clocked at 1.033GHz with 960 stream processors (cores),
2) Titan Black clocked at 980 GHz with 2880 cores.

The computational procedure was modified in such a way that solutions of the equations describing the magnetic field evolution in case of no-z approximation were found in parallel on each time layer. Typical computation times for the same problem for a given CPU and different GPUs, and for different rectangular grids are shown in Table 1. A 200x200 grid was used to obtain the solution presented in Figs. 1 - 8. The colored zones represented in Figs. 1 - 3 and Figs. 5 - 7 show the field values from different ranges. The black lines show the limits of these regions.

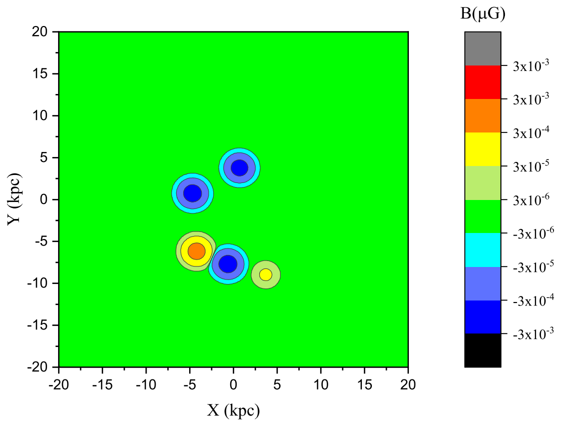

Fig. 1: Initial azimuthal field in the case of reversal occurrence. The colors correspond to the scale on the right, picturing the value of the field induction in each point of the galaxy. Red and blue zones are connected with "positive" or "negative" direction of the field vectors, as indicated on the scale. The circles represent the zones with the field values in a certain range. This applies also to the further figures picturing the field.

To enable comparison, all calculations described in Table 1 were recorded for the same step of the numerical scheme Δt. At the same time, it should be taken into account that for some grids it is unnecessarily small (and in reality, the stability of the scheme can be achieved even with a larger step).

Here and below, the solution of the problem will be presented for the following values of dynamo coefficients: $\alpha_0 = 1\ \frac{\text{km}}{\text{s}}$, $\Omega_0 = 30\ \frac{\text{km}}{\text{s·kpc}}$, $\eta = 0.3\ \frac{\text{kpc·km}}{\text{s}}$, $r_0 = 2$ kpc, $B_0 = 3\ \mu$G (Arshakian et al. 2009, Mikhailov et al. 2014).

Typical initial conditions are shown in Fig. 1. The calculation results for the magnetic field in this case are shown in Figs. 2 - 3. It can be seen that stable contrast structures are gradually generated. It is also important that the magnetic field in a galaxy is measured in 10^{-6} G.

The dependence of the magnetic field on one of the coordinates is of particular interest. Its example is shown in Fig. 4. It can be noted that the magnetic field shows a clearly visible reversal: the magnetic

Table 1: Typical computation times for a CPU and several GPUs

CPU/GPU model	Time(100x100) [s]	Time(200x200) [s]	Time(400x400) [s]	Time(800x800) [s]
CPU Intel i7 7700HQ-	2382	8658	32238	112481
GPU GTX 660	81	334	975	3710
GPU Titan Black	34	139	237	854

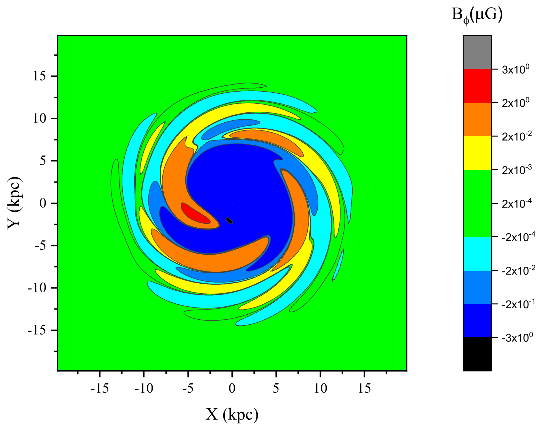

Fig. 2: A large-scale azimuthal field structure in the case of reversal occurrence (t = 5 Gyr).

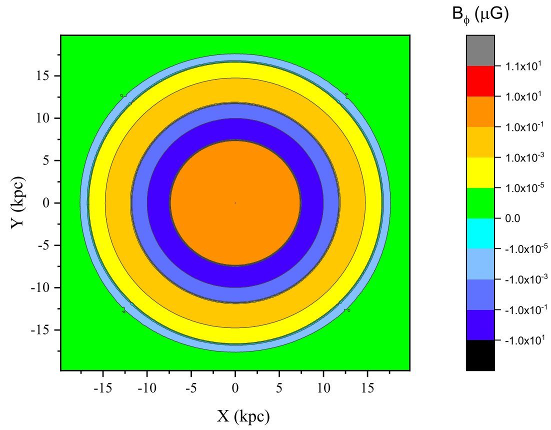

Fig. 3: A large-scale azimuthal field structure in the case of reversal occurrence (t = 15 Gyr).

field in the outer region has a direction opposite to that in the central parts. Also, these results are close to what was obtained within the framework of the axisymmetric model under deterministic initial conditions in the case of the main part of the galaxy.

It is important to note that solutions corresponding to reversals are not always generated. Thus, Figs. 5 - 8 show an example when random initial conditions lead to a field that has the same direction in all parts of the disk.

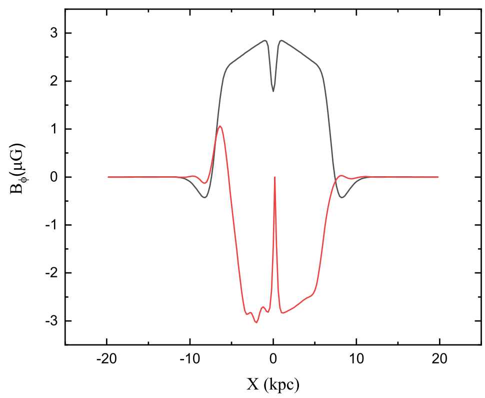

Fig. 4: The dependence of the field value on the x-coordinate (y=0): t = 5 Gyr (red) and t = 15 Gyr (black).

4. CONCLUSION

In our study, it was shown that magnetic field reversals in spiral galaxies can be formed as a result of evolution from stochastic initial conditions for the field. We should mention that, from the fundamental point of view, the results in the inner parts of the galaxy repeat those obtained for the reversal structure in earlier studies (Mikhailov and Khasaeva 2019, Mikhailov 2021). Our modelling methods partly replicate those methods used in some classic works (Subramanian and Mestel 1993, Moss 1995). There are other approaches of modelling galactic fields (Ntormousi et al. 2020), which give principally the same results for the fields without reversals. However, in the present work we have obtained corresponding results using stochastic initial conditions. In addition, it is important to note that, in the present work, the values of the distance from the center exceeding the average radius of the galaxy were considered, and the boundary of the galactic disk was not indicated by strict conditions, but can still be easily recognized according to the computational results. Moreover, as shown in Fig. 2, the reversals of the galactic magnetic field can reach large distances from the center, exceeding the classical radial values of the galaxy, though the absolute values of the field in this case rapidly decrease. The expansion of the computational zone required the use of parallel computing on graphic cards, which significantly accelerated (by about 30 times) the solution process, and also made it possible to sort out a wide range of random initial conditions, from which reversals of the galactic magnetic field would be generated.

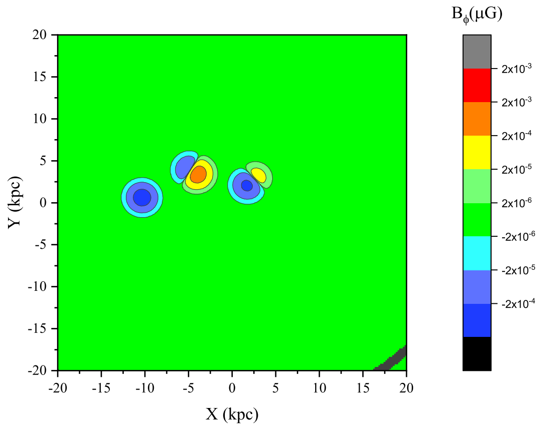

Fig. 5: The initial azimuthal field in a non-reversal case.

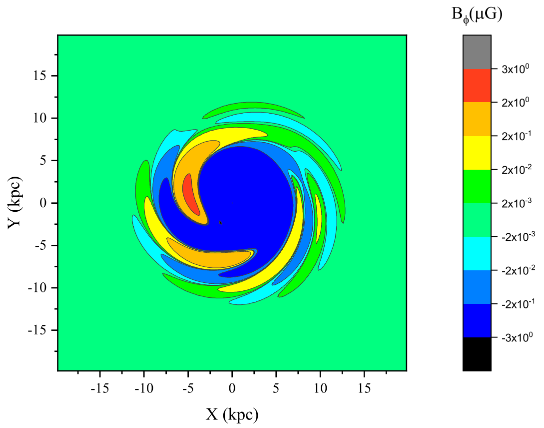

Fig. 6: Large-scale azimuthal field structure in non-reversal case (t = 5 Gyr).

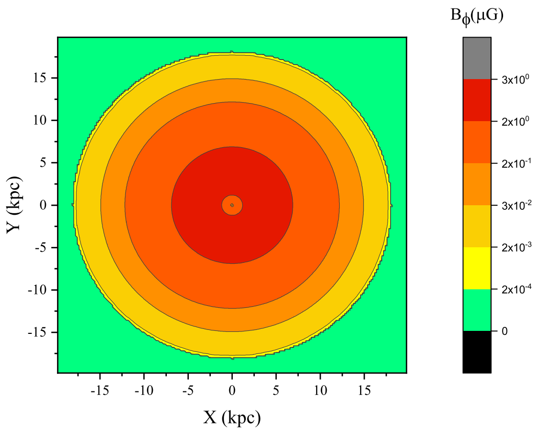

Fig. 7: The large-scale azimuthal field structure in a non-reversal case (t = 15 Gyr).

The acceleration that the GPU GTX 660 provides us is quite sufficient for the present study. It was also found that in problems similar to the present one it is convenient to use Cartesian coordinates to solve them numerically.

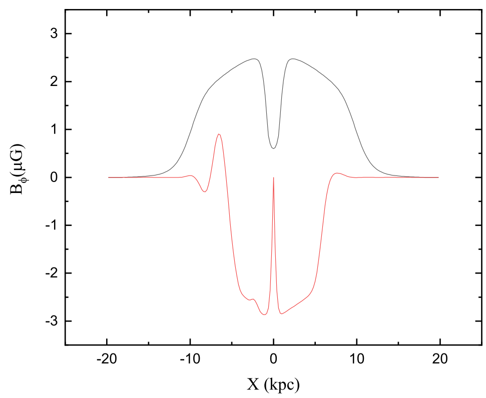

Fig. 8: The dependence of the field value on the x-coordinate (y=0) in the non-reversal cases: t = 5 Gyr (red) and t = 15 Gyr (black).

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МОДЕЛИРАЊЕ ОБРТАЊА ГАЛАКТИЧКИХ МАГНЕТНИХ ПОЉА НА ВЕЛИКИМ УДАЉЕНОСТИМА ОД ЦЕНТРА ГАЛАКСИЈА СЛИЧНИХ МЛЕЧНОМ ПУТУ КОРИШЋЕЊЕМ GPU РАЧУНАЊА

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Оригинални научни рад

У данашње време влада уверење да у великом броју спиралних галаксија постоје регуларна магнетна поља. Њихово постојање је доказано мерењем Фарадејеве ротације равни поларизације електромагнетних таласа, које детектујемо савременим радио-телескопима. Теоријски опис настанка магнетних поља повезан је са механизмом динама средњег поља (поље на великој скали). Тај механизам заснива се на заједничком дејству α-ефекта и диференцијалне ротације. У првој фази еволуције магнетна поља експоненцијално расту, са стопом раста која је описана највећом сопственом вредношћу одговарајућег диференцијалног оператора. Када јачина поља постане упоредива са вредношћу еквипартиције, нелинеарни чланови постају значајнији, и они су повезани са засићењем раста јачине поља. Нелинеарни систем једначина има неколико стационарних тачака, од којих су неке стабилне. Према теорији контрастних структура, за веома малу турбулентну вискозност и одређене почетне услове у различитим регионима, доћи ће до формирања магнетних поља супротног смера, која ће бити подељена уским прелазним слојевима. Такве особине, на пример, карактеришу магнетно поље Млечног пута. Већина постојећих радова описује обртања поља за умерене удаљености од центра галаксије. Међутим, претходно је показано да се магнетно поље може генерисати и у спољним деловима галаксија, које су смештене на удаљеностима већим од 10 kpc од осе ротације. Занимљиво је описати појаву обртања магнетног поља у тим деловима галаксија. У овом раду смо проучили дејство динама у спољним деловима галаксија сличних Млечном путу. Показано је да је могуће генерисати супротна магнетна поља у тим областима. Користили смо насумичне почетне услове да бисмо добили просторна обртања магнетног поља. Због великог обима прорачуна, они су спроведени коришћењем графичких процесора (GPU).