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The galactic dynamo effect due to Parker-shearing instability of magnetic flux tubes

III. The fast dynamo model.

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Abstract. We present a new fast dynamo model for galactic magnetic fields, which is based on the Parker-shearing instability and magnetic reconnection, in the spirit of the model proposed by Parker (1992). We introduce a new scenario of flux tube interactions and estimate the dynamo transport coefficient basing on simple geometrical arguments. The obtained expressions are equivalent to the formally derived helicity α_d and diffusivity η_d in the first paper of this series. The model we propose predicts that the α-effect in galactic discs has opposite sign with respect to that resulting directly from the sign of the Coriolis force. We estimate the rate of magnetic heating due to the reconnection of magnetic flux tubes, which plays an important role in our dynamo model. The corresponding luminosities of the diffuse X-ray emission are consistent with the ROSAT observations of nearby galaxies.

The present considerations synthesize the ideas of Parker with our own results presented in the preceding papers (Hanasz & Lesch 1993, 1997; Hanasz 1997).

Key words: Magnetic fields – Instabilities – Galaxies: magnetic fields – spiral – ISM: kinematics and dynamics of

1. Introduction

The 'classical' galactic dynamo mean field theory based on Kolmogorov turbulence experienced a fundamental criticism by Kulsrud & Anderson (1992) and Vainshtein & Cattaneo (1992). It was argued that the classical mean-field dynamo approach misses the magnetic back reaction on the turbulent flow. Thereby the turbulent diffusion coefficient is reduced as well as the turbulent helicity. The effect of Kolmogorov turbulence on the evolution of a weak large-scale field was found to build up small scale magnetic fields on the equipartition level very quickly and then begins to dissipate by ambipolar diffusion (Kulsrud and Anderson 1992).

Parker (1992) (hereafter P' 92) reviews the application of dynamo theory to galactic magnetic fields, he argues like Vainshtein and Cattaneo (1992) that a weak large scale magnetic field grows to a certain limit, which is very small compared to the equipartition magnetic field. Above this limit the cascade of magnetic energy toward diffusive scales is blocked by the Lorentz force and turbulent diffusivity as well as the α-effect are reduced. However, unlike Kulsrud and Anderson (1992) and Vainshtein and Cattaneo (1992), he does not draw the conclusion that the galactic magnetic field must be of primordial origin. Instead, he argues that the agreement of the predictions of dynamo theory with observations suggests that it is basically sound, so that some other explanation should be found for the relative large values of the turbulent diffusivity that seem to give consistent results.

Parker's model of buoyancy driven galactic dynamo is as follows: Since the interstellar medium is composed of the ionized gas, magnetic field and cosmic rays, the last two weightless components support the heavy gas against vertical gravitation due to the stellar disc. Such a configuration is intrinsically unstable against vertical perturbations of initially azimuthal magnetic field lines. The ionized gas slips down along magnetic field lines forming gas condensations in valleys and the cosmic ray gas tends to escape from the galactic disc together with an amount of the trapping magnetic field. The main effect of cosmic ray gas is to inflate the raised region and form magnetic lobes (see Fig. 2 of P'92). The Ω-shaped loops form and are tightly packed due to the inflation. At the boundary of adjacent lobes the magnetic field lines of opposite direction are pressed together and a fast magnetic reconnec-

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tion starts to rearrange the magnetic field configuration. As a result, close magnetic loops form which are free to rotate since magnetic tension does not counteract rotation. Then, further reconnection fuses many loops to form a large scale poloidal magnetic field and galactic differential rotation forms the azimuthal field. The reconnection at current sheets at the boundary of lobes is supposed to transform an amount of magnetic energy into heat that maintains the $10^6 - 10^7$ K temperature of the halo gas producing the halo X-ray emission. Since the magnetic reconnection is one of the simultaneously working heating processes, the observed X-ray luminosity of the order of 10^{40} erg/s determines an upper limit of magnetic reconnection heat output. Parker postulates that such a process can be described by the conventional $\alpha\omega$-dynamo equations.

The term "fast dynamo" refers to the dynamos for which the generation rate of the mean magnetic field remains finite in the limit of vanishing resistivity. The resistivity is responsible for the dissipation of the small scale magnetic field. In the galactic conditions the Kolmogorov cascade is cut off by viscosity at scales much larger than the resistive scale. Then, in the standard dynamo theory the resistive dissipation is suppressed, which implies that the transition from chaotic to the uniform components of magnetic field becomes infinitely slow. In the Parker's fast galactic dynamo the transition between small and large scale magnetic fields is possible (within a finite time) in the limit of vanishing (i.e. enormously small) resistivity because of the presence of tangential discontinuities in magnetic field.

The magnetic reconnection which takes part in the dissipation process of fast dynamos is supposed to proceed as fast as the Alfven speed v_A divided by logarithm of the Lundquist number $N_L = lv_A/\eta \sim 10^{15} - 10^{20}$.

Our aim is to modify some elements of the Parker scenario and provide some more details according to our detailed studies of the dynamo effect due to the Parker-shearing instability contained in Papers I and II. The key points of the Parker's scenario are based on the following facts:

1. The ascending magnetic flux tubes inflate vigorously and the closely packed magnetic lobes form and reconnect to form closed loops of magnetic field.
2. There are two patterns of reconnection illustrated in Fig. 3 of P'92: (a) at the bases of lobes and (b) at the upper regions of the lobes. The second pattern is suggested to be more likely.
3. In both the patterns reconnection operates on single magnetic flux tubes, otherwise it would not form closed loops.
4. The closed loops are free to rotate because they are disconnected from the surrounding and therefore released from the restoring magnetic tension.

We would like to propose a slightly modified picture following from our calculations of Papers I and II:

1. The magnetic tension limiting cyclonic deformations (i.e. these which provide the helicity α_d) is compensated by two effects: (i) the powerful contribution of cosmic rays in buoyancy, which is free of restoring tension and (ii) the differential forces counteracting the magnetic tension, due to the rotational shear and the density waves. As a result, even open magnetic field lines produce a strong α-effect in the nonlinear regime of the Parker-shearing instability.
2. The related radial displacement amplitudes of magnetic flux tubes are in general comparable to vertical ones and exceed the cosmic ray driven thickening of the lobes. This implies that adjacent magnetic flux tubes are predominantly pressed together by the horizontally twisting Coriolis force.
3. Due to this fact the reconnection should take place in two locations on the flux tube which are maximally displaced in the radial direction due to the Coriolis force.
4. The most likely possibility is such that reconnection operates on some neighboring flux tubes and does not form closed loops from a single flux tube.

The above remarks allow us to propose a geometrically different scenario, which remains still in the spirit of the Parker's model. In the present approach the classical concept of turbulence is replaced by more or less chaotic superposition of unstable Parker modes. The perturbations may be uncorrelated along the mean direction of magnetic field over distances of the order of a few wavelength of the Parker instability. We assume additionally that neighboring flux tubes can be braided and move individually or coherently within bundles.

We shall estimate the heat output from magnetic reconnection in our model and show that this is in a general agreement with the X-ray data which suggest that an amount of diffuse X-ray emissivity of non stellar origin in some nearby spiral galaxies. We shall take NGC 6946, M51 and NGC 1566 as examples.

2. The new dynamo model

2.1. Geometry of flux tube interactions

The pattern of deformation of flux tubes due to the Parker-shearing instability projected on the planes (ϕ, r) and (ϕ, z) is shown in Fig. 1. We show only single periods of perturbation of two distinct azimuthal flux tubes (plus small pieces of two other flux tubes), characterized by the same magnetic flux Φ. Let us suppose for simplicity that the initial height above the galactic midplane is z_0 for both the flux tubes, and the vertical displacement amplitude due to the Parker-shearing instability is Δz. The initial radial separation of the flux tubes is $2\Delta r$ and the radial displacement amplitude is Δr.

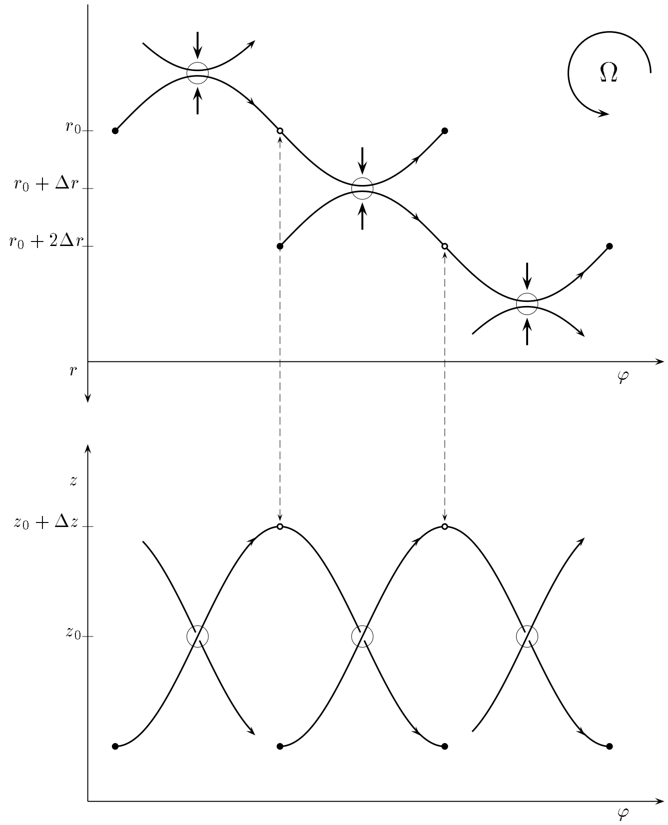

Fig. 1. The horizontal and vertical deformations of two distinct flux tubes. The places of reconnection correspond to the radially most displaced points of the flux tubes and are enclosed by circles.

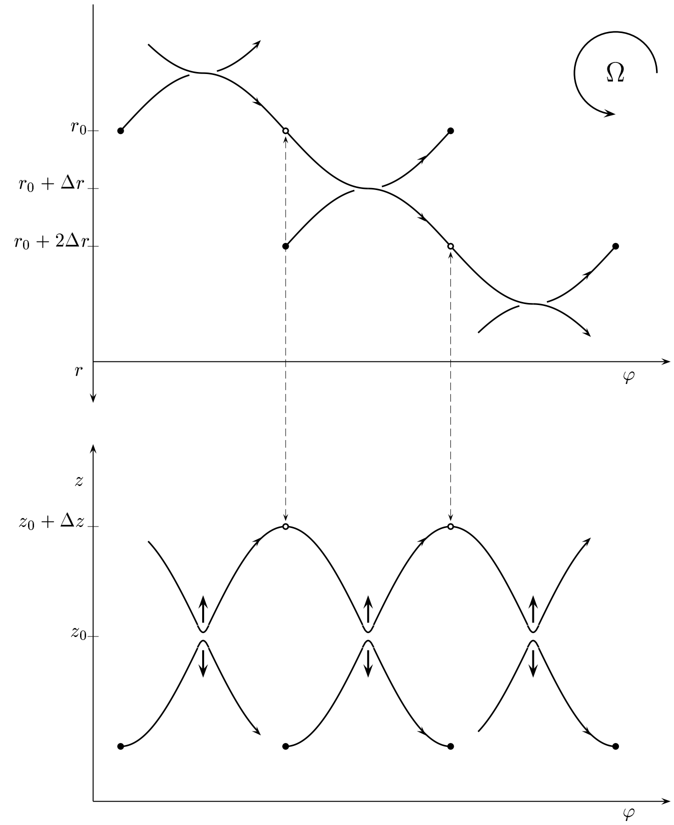

Fig. 2. The final configuration of magnetic flux tubes after reconnection. The flux tubes belong to two families, one remains in the disc and the second is shifted toward the galactic halo. Both of them contain the radial component of magnetic field.

The scenario, we propose is as follows. Due to the action of the Parker-shearing instability the flux tubes undergo cyclonic deformations as shown in Fig. 1. The horizontal deformations press different flux tubes together in places enclosed by circles, which are maximally displaced in the radial direction. The flux tubes form current sheets at their boundary due to the magnetic field gradient and reconnection starts to rearrange and to relax the configuration of magnetic field. The new configuration of magnetic flux tubes, is shown in Fig. 2.

Two new families of flux tubes appear replacing the original azimuthal magnetic field. The first family is formed from the lower parts of the original flux tubes and remains in the galactic disc. The second family formed from the upper parts shifts toward to the galactic halo, since the tops of the flux tubes are typically displaced by the vertical scale height H of ionized gas. Both families acquire a specific amount of radial magnetic field, which can be estimated basing on simple arguments, without invoking the complex techniques of computing the α_d coefficient.

Let us apply the linear approximation (see Paper I) to describe the perturbations on the initially azimuthal magnetic flux tubes in the rectangular reference frame (x, y, z) locally representing the azimuthal, radial and vertical coordinates, respectively. The radial and vertical displacements are

$$y = Y \exp(iks) \exp(\omega_i t), \tag{1}$$

$$z = Z \exp(iks) \exp(\omega_i t), \tag{2}$$

where s determines the position along the flux tube, Y and Z are the initial displacement amplitudes, k and ω_i are the wavenumber and the growth rate, respectively. The corresponding Lagrangian velocities are

$$v_y = \frac{\partial y}{\partial t} = \omega_i z \frac{Y}{Z}, \quad v_z = \frac{\partial z}{\partial t} = \omega_i z, \tag{3}$$

$$\tag{4}$$

Assuming that perturbations on two flux tubes displaced by Δr start to grow simultaneously we can estimate the time interval necessary for a collision of the two flux tubes

$$\Delta t \simeq \frac{\Delta r}{v_y} = \frac{\Delta r}{\omega_i Y/Z \Delta z} \tag{5}$$

If we denote the wavelength of the perturbation by λ, then after reconnection each family of magnetic flux tubes has a component of radial magnetic field

$$\Delta B_r \simeq \frac{4\Delta r}{\lambda} B_\varphi = \frac{2}{\pi} k \Delta r B_\varphi \tag{6}$$

where B_φ is the initial azimuthal magnetic field. The radial magnetic field is generated at the rate

$$\frac{\Delta B_r}{\Delta t} \simeq \frac{2}{\pi} \omega_i k \Delta z \frac{Y}{Z} B_\varphi \tag{7}$$

The coefficient on the rhs. in front of B_φ is quite similar to the analytical expression for α_d (Eqn. (85) in Paper I). Since in the thin disc approximation α_d relates $\partial B_r/\partial t$ with $\partial B_\varphi/\partial z$ we should take into account the assumed stratification of the interstellar medium which according to formulae (18)-(21) of Paper I gives

$$B_\varphi = -2H \frac{\partial B_\varphi}{\partial z} \tag{8}$$

We obtain finally

$$\frac{\Delta B_r}{\Delta t} \simeq \frac{4}{\pi} \omega_i k \Delta z H \frac{Y}{Z} \frac{\partial B_\varphi}{\partial z} \tag{9}$$

For perturbations with the vertical amplitude $\Delta z \sim H$ we obtain the coefficient on the rhs

$$\alpha_d = \frac{4}{\pi} \omega_i k \frac{Y}{Z} H^2 \tag{10}$$

which is consistent with the formula (85) of Paper I with the accuracy to the numerical coefficient of the order of 1.

The vertical amplitudes of perturbations of the order of the vertical scale height H imply that the upper family of magnetic flux tubes forms at the base of the galactic halo and is in fact lost for the disc. This can be interpreted as a kind of diffusion of the magnetic field from the disc. The escape rate of magnetic field from the disc to halo can be estimated from the Poynting flux in vertical direction

$$\begin{aligned} S_z &= \frac{c}{4\pi} (\boldsymbol{E} \times \boldsymbol{B})_z \\ &= \frac{1}{4\pi} (v_z B_\varphi - v_\varphi B_z) B_\varphi . \end{aligned} \tag{11}$$

Without going into details we can estimate the Poynting flux through a horizontal boundary between disc and halo

$$S_z \simeq \frac{1}{2} \frac{1}{4\pi} v_z B_\varphi^2 . \tag{12}$$

The additional numerical factor 1/2 in (12) is because only half of wavelength of the flux tube is ascending and transports the magnetic energy through the horizontal plane at the boundary of disc and halo. We express the conservation of magnetic energy as if the other components, i.e. thermal gas and cosmic rays, were absent

$$\frac{\partial}{\partial t} \left(\frac{B^2}{8\pi} V \right) = 2 S_z A_{disc} , \tag{13}$$

where $V = 2A_{disc} \cdot H$ is a volume of a disc with surface area A_{disc} and half widths H. The numerical factor 2 in (13) is because we consider two surfaces at $z = \pm H$ enclosing the disc. With the assumed approximate equipartition of thermal, magnetic and cosmic ray energies, the error we make is at most of the order of 1. The above energy conservation equation leads to the following equation describing loses of magnetic field due to the vertical motions driven by the Parker-shearing instability

$$\frac{\partial \boldsymbol{B}}{\partial t} = \frac{v_z}{2H} \boldsymbol{B} . \tag{14}$$

Taking the relation (8) into account we obtain

$$\frac{\partial \boldsymbol{B}}{\partial t} = 2 v_z H \frac{\partial^2 \boldsymbol{B}}{\partial z^2} , \tag{15}$$

what corresponds to the turbulent diffusion term in the dynamo equation. With the accuracy to a numerical factor of the order of 1 the coefficient on the rhs. of (15) is

$$2 v_z H \sim \omega_i Z(t)^2 = 4 \eta_d \tag{16}$$

if the vertical displacements due to Parker-shearing instability are of the order of the vertical scaleheight H. Thus, basing on the Poynting flux we obtained an effect equivalent to the turbulent diffusion in the dynamo equation.

The above results mean that the presented processes can be described by the conventional dynamo equation, but the physical interpretation of the dynamo transport coefficients is now different from the conventional one.

Following the scenario presented in Figs. 1 and 2 we note that the sign of α-effect is positive for the upper family (halo) and negative for the lower family (disc). This is because the magnetic field lines turned by Coriolis force are advected to the halo and lost from the disc. What remains in disc after reconnection is like rotated opposite to the Coriolis force. This would be a possible explanation of the negative α-effect measured by Brandenburg et al. (1995) in their numerical simulations.

The above properties of our model may be also related to some observational features of galactic magnetic fields. The magnetic field structure is typically a spiral, which is parallel with good accuracy to the optical spiral structure. In typical galaxies like M51 and NGC 6946, representing trailing spirals, gas flows into arms from the direction of inner edges of arms. The rotation of gas is faster than the rotation of spiral pattern inside the corotation radius. For gas streaming from the top of a rising magnetic loop the cyclonic rotation due to the Coriolis force is opposite to the galactic rotation, which implies that the upper family of magnetic field lines tends to acquire a pitch angle of opposite sign with respect to the pitch angle of spiral arms. Compare eg. Fig. 1 of this paper with the picture of M51 in Fig. 1 of Berkhuijsen et al. (1997). The signs of galactic rotations are the same in both cases, but the upper (halo) family of magnetic field lines in our case is transversal with respect to the spirals in the picture of of M51. The problem is more complicated however, because the main effect which determines the pitch angle of magnetic field lines is the differential rotation (see Beck et al. 1996 and references therein). Without taking into account of the α-effect the differential rotation of the trailing spiral provides the same sign of the magnetic pitch angle as the pitch angle of spiral arms. Thus, in our model the α-effect and the differential rotation operate accordingly on the lower (disc) family of magnetic field lines.

The situation in halo is different. The signs of the pitch angle resulting from the differential rotation and the α-effect tend to be opposite. We note that even if on average the effect of differential rotation is dominating, we can probably expect in galactic halos departures from this rule. First of all, it is reasonable to expect that the azimuthal shear is weaker in galactic halos then in discs. Second, in contrast to the differential rotation, the alpha effect may be locally significantly different than its mean value. This is because the α-effect depends essentially on the cosmic ray pressure (see Papers I and II), which is probably highly variable depending on position in the disc and the phase of density wave. A local excess of cosmic rays can easily enhance the α-effect by a factor of 10 or more, together with the substantial increment of the growth rate of the Parker-shearing instability.

It is possible that in some cases the strong α-effect (positive in halo) is related to the rotation of magnetic field lines toward the direction transversal to spiral arms. Then the differential rotation can make the upper (halo) component of magnetic field even more transversal or possibly antiparallel to the magnetic field in the disc. This seems to be observed by Berkhuijsen et al. (1997). It is also possible that the described effects can be responsible for rapid variations and reversals of the magnetic pitch angle. One should remember, however, the halo magnetic field is typically much weaker and has a smaller influence on the radio continuum image of magnetic structure. What is usually observed is the stronger disc magnetic field.

The negative α-effect in the disc corresponds to positive dynamo numbers $D = R_\alpha R_\omega$. The positive dynamo numbers lead to oscillatory solution of the dynamo equation in the thin disc approximation. These solutions propagate as spiral waves in the disc plane and can couple to the density waves (Chiba and Tosa 1990; Hanasz, Lesch and Krause 1991, Hanasz and Chiba 1994, Mestel and Subramanian 1991, Subramanian and Mestel 1993, Moss 1996) if the propagation velocity of the magnetic wave is the same as the propagation velocity of the spiral structure. The coupling by means of the parametric resonance provides an additional growth rate to the dynamo waves. Since, in the standard dynamo models the dynamo numbers of the real galaxies are negative, it has been problematic how the corresponding solutions can couple to density waves in the thin disc approximation. It has been known, however, that in the thick discs the oscillatory solutions exist even for negative dynamo numbers (Starchenko and Shukurov 1989). The present dynamo model provides a new justification for the oscillatory dynamo modes and their coupling to density waves.

In order to close the dynamo cycle we describe next the dissipation process of the small scale components of the field by magnetic reconnection, estimate the heat output and compare it with the observed X-ray luminosity which is a measure for plasma contents in galactic halos.

2.2. Magnetic heating

Most of the interstellar plasma is highly conductive, i.e. the electrical conductivity is very large (details see below) and any relative motion between the conductor and the field induce electric currents. The relation between the field and plasma is given by Ohm's law $\mathbf{j} = \sigma\left(\frac{1}{c}\mathbf{v}\times\mathbf{B}\right)$ which gives for a highly conducting medium (neglecting external electric fields E, with the current density j and the electrical conductivity σ) an infinitely large current density for an infinite conductivity. However, this frozen-in property of the magnetic field changes drastically if field lines with different directions approach each other. The chain of processes which is triggered by antiparallel field lines is called **magnetic reconnection** (e.g. Biskamp 1994).

Magnetic reconnection is a fundamental intrinsic property of agitated magnetized, turbulent plasmas (e.g. Schindler et al. 1991). Whenever, magnetic fields with different field directions encounter each other, the magnetic energy is rapidly dissipated, by accelerating particles and by plasma heating. As mentioned above, outside the forming current sheet the motion of the plasma is ideal, i.e. the magnetic field lines follow the plasma motion as if they were frozen into it, which is provided by the high electrical conductivity. When the oppositely directed field lines following the plasma motion approach, the field gradient steepens and the current density $\frac{c}{4\pi}\nabla\times\mathbf{B}$ increases until strong dissipation sets in. The problem of reconnection is to know how the dissipation of the currents with the density $j = en_{\rm e}v_{\rm d}$ is provided ($n_{\rm e}$ is the electron number density per cm^3 and $v_{\rm d}$ denotes the drift velocity of the electrons relative to the protons). Rapid dissipation follows because of the small thickness of the transition layer from one field to another, providing a thin intense current sheet. The dissipation may be further increased when the current density exceeds a critical current density, i.e when the drift velocity exceeds some thermal velocity of the plasma constituents. If $v_d \geq v_{crit} = v_{thermal}$ plasma instabilities excite plasma waves. The wave-particle interaction replaces the Coulomb interaction, thereby increasing the electron scattering frequency (e.g. Zimmer et al. 1997).

Magnetic reconnection is unavoidable in turbulent plasmas, therefore the encounter of two antiparallel field components in the "magnetic atmosphere" of a galaxy transfers the plasma kinetic energy into heat via compressed, strained, torn or even decomposed magnetic field structures, which heavily dissipate the stored magnetic energy in current sheets via magnetic reconnection.

Magnetic reconnection corresponds to the dissipation of electric currents and the dissipation (or heating) rate Q (in $\mathrm{erg\ cm^{-3}s^{-1}}$) is

$$Q = \frac{j^2}{\sigma} \tag{17}$$

With the advent of plasma turbulence

$$\sigma = 2 \cdot 10^7 \left[\frac{T}{1\ \mathrm{K}}\right]^{3/2} \mathrm{s}^{-1} \tag{18}$$

Dissipation is equivalent to either increased current density and/or reduced electrical conductivity σ

$$\sigma = \frac{\omega_{\mathrm{pe}}^2}{4\pi\nu_{\mathrm{coll}}}. \tag{19}$$

where

$$\nu_{\mathrm{coll}} \approx \nu_{\mathrm{LH}} \approx 4 \cdot 10^5 \left[\frac{B}{1\mathrm{G}}\right] \mathrm{s}^{-1} \tag{20}$$

is the collision frequency driven by lower hybrid waves with frequency ν_{LH}, which has the lowest threshold velocity for the critical current of the order of the thermal velocity of the ions (e.g. Papadopoulos 1979).

$$\omega_{\mathrm{pe}} \sim 5.6 \cdot 10^4 \sqrt{\frac{n_{\mathrm{e}}}{1\ \mathrm{cm}^{-3}}} \mathrm{s}^{-1} \tag{21}$$

is the electron plasma frequency. The conductivity and the anomaleous resistive diffusion coefficient are respectively

$$\sigma \approx 0.6 \cdot 10^6 \left[\frac{n_{\mathrm{e}}}{0.01\ \mathrm{cm}^{-3}}\right] \left[\frac{B}{10\mu\mathrm{G}}\right]^{-1} \mathrm{s}^{-1}, \tag{22}$$

$$\eta = \frac{c^2}{4\pi\sigma} \approx 1.3 \cdot 10^{14} \left[\frac{n_{\mathrm{e}}}{0.01\ \mathrm{cm}^{-3}}\right]^{-1} \left[\frac{B}{10\mu\mathrm{G}}\right] \frac{\mathrm{cm}^2}{\mathrm{s}}. \tag{23}$$

The Lundquist number (the magnetic Reynolds number with respect to v_A) is

$$N_L = \frac{L v_A}{\eta} \approx 5 \cdot 10^{12} \left[\frac{L}{10\ \mathrm{pc}}\right] \left[\frac{n_{\mathrm{e}}}{0.01\ \mathrm{cm}^{-3}}\right]^{1/2} \tag{24}$$

where L is the assumed typical diameter of colliding flux tubes.

The obtained value of $N_L \sim 5 \cdot 10^{12}$ suggests that the Parker-Sweet reconnection pattern with the inflow speeds of the order of $v_{in} \sim v_A/\sqrt{N_L}$ would be very inefficient and not applicable to galactic conditions. Even incorporation of the anomaleous resistivity does not help very much to depart from the limit of large Lundquist numbers. The Petschek's model, on the other hand appeared to be not valid in the astophysically relevant range of small η. It can be used however, as a phenomenological approach assuming an anomaleous resistivity enhancement in the diffusion region, such that $R_M \equiv v_{in}L/\eta = MN_L\mathcal{O}(1)$, but again, even with the anomaleous resistivity the last condition is not fulfilled.

Fortunately, the numerical simulations (see eg. Biskamp 1994) of the reconnection process lead to the reconnection rates sufficiently large and independent of resistivity in the small resistivity limit. This is accomplished by a nonstationary behaviour in the reconnection region due to the tearing instability which subsequently leads to small-scale turbulence and formation of many small-scale secondary current sheets with short life times. Finally it seems that the resulting reconnection rate is not much different than $\sim v_A/\ln N_L$ applied by Parker in his "fast dynamo" model.

We give a qualitative estimate of magnetic energy conversion into heat via magnetic reconnection and rough estimates of the heating process. The details of the plasma processes involved have been generally discussed by Lesch (1991) and for the case of the halo of the Milky Way by Zimmer et al. (1997). We ask what magnetic field strength B_{eq} is necessary to heat up a plasma to X-ray temperatures of several 10^6K and compare the values with the observed ones in the halo of the Milky Way (e.g. Kazes et al. 1991) of about $10\,\mu$G. In Fig. 3 the magnetic field

$$B_{\mathrm{eq}} = \sqrt{8\pi n_{\mathrm{e}} k_{\mathrm{B}} T_{\mathrm{e}}} \tag{25}$$

is computed for a temperature of $2 \cdot 10^6$K and a density range from 0.1 cm^{-3} down to 10^{-3} cm^{-3}. We obtain $3\mu\mathrm{G} \leq B_{\mathrm{eq}} \leq 30\mu\mathrm{G}$.

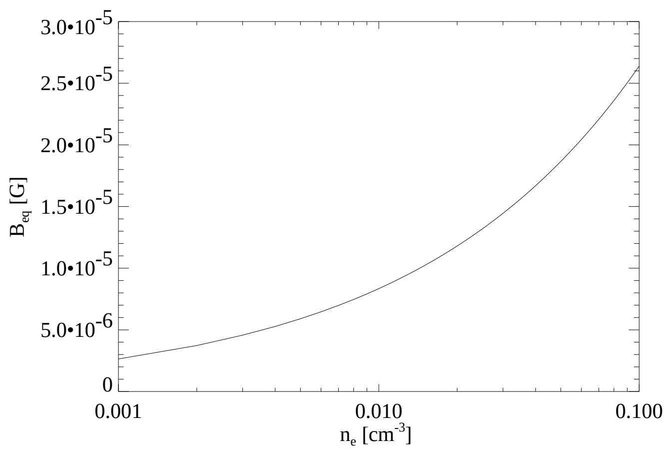

Fig. 3. Magnetic field strength B_{eq} equivalent to the temperature $2 \cdot 10^6$ K vs. the number density.

Next, we calculate the magnetic heating rate

$$Q = \frac{B^2}{8\pi}\epsilon v_{rec} A \tag{26}$$

where A is the surface area of the interface of two flux tubes, $v_{rec} = V_A / \ln(N_L)$ is the reconnection rate and ϵ is the efficiency of magnetic energy conversion into heat. Let us suppose that $\epsilon = 1/2$. If the flux tube diameter is D of the order of 10 pc, then the surface area at the interface of two flux tubes is of the order of $A = 100$ pc^2. We assume here that the typical configuration of colliding flux tubes is similar to that presented in Fig. 1, where the collision regions are marked with circles. We can estimate the heat released by a single reconnection event i.e. by the complete reconnection of two flux tubes with the cross section area $A \sim 100$ pc^2 and the magnetic field $B \sim 10\mu$G. Following our estimation of $N_L \sim 5 \cdot 10^{12}$ one obtains $\ln(N_L) \sim 30$. The heating rate during the single reconnection event is

$$Q_1 = 1.2{\cdot}10^{33} \left[\frac{B}{10\mu\mathrm{G}}\right]^3 \left[\frac{n_e}{0.01\ \mathrm{cm}^{-3}}\right]^{-\frac{1}{2}} \left[\frac{A}{100\ \mathrm{pc}^2}\right] \mathrm{erg/s} \tag{27}$$

The duration of the reconnection event is

$$\begin{aligned} t_{rec} &= \frac{D}{v_{rec}} \\ &= 1.5 \left[\frac{D}{10\ \mathrm{pc}}\right] \left[\frac{B}{10\mu\mathrm{G}}\right]^{-1} \left[\frac{n_e}{0.01 cm^{-3}}\right]^{\frac{1}{2}}\ \mathrm{Myr} \end{aligned} \tag{28}$$

The estimated reconnection times can be confronted with observations. Since the magnetic field in the arms of NGC 6946 is turbulent in arms and uniform in the interarm regions (Beck and Hoernes, 1996) the time available for the postulated uniformization process, sketched in Figs. 1 and 2, is as short as the quarter of rotation period. We note that the described process eliminates the irregularities introduced by the Parker-shearing instability. In the final state the major part of the nonuniform magnetic field is replaced by the new radial magnetic field component.

The mentioned quarter of the rotation period is approximately the time which elapses between the passages of subsequent maximum and minimum of density corresponding to the spiral density wave. This estimation can be done more precisely, however we can assume a typical galactic rotation period $t_{rot} \sim 200$ Myr, which leads to a rough limitation

$$t_{rec} \leq 50\ \mathrm{Myr}, \tag{29}$$

if the magnetic arms in between the optical arms are to be formed. Since the reconnection is supposed to undergo in the upper layers of the galactic thin disc we can assume electron densities down to $n_e \sim 10^{-2}$ cm^{-3}, so the reconnection times for single flux tube can be of the order of a few Myr. This means that we can consider flux tubes much thicker than the assumed diameter 10 pc, or alternatively domains containing many coherently moving flux tubes. The above limitation on the reconnection time seems to allow for the domain size transversal to the mean magnetic field up to 100 pc. This appears to be consistent with the typically adopted space scale of the interstellar turbulence. It is important to notice that the reconnection time is proportional to square root of density, which implies that reconnection goes faster for higher heights over the galactic symmetry plane. If the reconnection is not sufficiently efficient at a specific height, the rising buoyant motion makes it easier and easier. Summarising, we can say that magnetic reconnection is able to remove irregularities of magnetic field up to the scale of 100 pc in between the passages of subsequent arm and interarm region.

This conclusion supports the galactic dynamo model proposed in the Paper I, which represents a cyclic process related to the density wave cycle. In that model the magnitude of differential force (dependent on the phase of density wave) controls the magnitude of the α-effect. Additionally, from Paper I we know that both the growth rate of the Parker-shearing instability and the α-effect are strongly dependent on the cosmic ray pressure. The cosmic rays are accelerated in the supernova remnants in the rate dependent again on the phase of the density wave. Due to this fact the instability is the most vigorous in arms, making the magnetic field nonuniform. Then reconnection takes place and a huge amount of cosmic rays decouples from the disc together with the upper family of magnetic field lines. The lower family of magnetic field lines which remains in the interarm regions of the disc is after reconnection less populated by cosmic rays, more stable and in consequence more uniform than the magnetic field in arms.

The total energy released during the 1 reconnection event is

$$\begin{aligned} E_1 &= Q_1\ t_{rec} = \frac{B^2}{8\pi}\epsilon D^3 \\ &= 5.4 \cdot 10^{46} \left[\frac{B}{10\mu\mathrm{G}}\right]^2 \left[\frac{D}{10\ \mathrm{pc}}\right]^3\ \mathrm{erg} \end{aligned} \tag{30}$$

The number of reconnection events can be estimated as follows. Let us suppose that the galactic disc radius is 20 kpc and the disc full thickness is 500 pc. If the flux tube volume filling factor is close to 1 as we assumed in Paper I then the disc could contain $\sim 2000 \cdot 50 = 10^5$ ringlike flux tubes with the typical diameter 10 pc. In fact we do not assume that the flux tubes are rings going around the entire disc since there are pitch angles up to 30 degrees. The above picture is convenient, however, for the current order of magnitude estimations. The average length of flux tubes is $L = 2\pi \cdot 10$ kpc $= 60$ kpc. Depending on the amount of cosmic rays the typical wavelengths of the Parker instability is $\lambda = 0.1 - 1$ kpc. The upper limit is for the equipartition of the energies of cosmic ray gas and the magnetic field, and the lower limit is for the significant excess of cosmic rays, what has been discussed in the Papers I and II. Then the full range of the azimuthal angle φ corresponds on average to 60-600 spatial periods of the waves associated to the Parker-shearing instability. The dynamo model described in the Section 2 requires one reconnection event per spatial period of undulations. The fulfillment of this condition would ensure the maximal efficiency of the generation of magnetic field, however some smaller numbers of reconnection events would be more realistic. Let us fix our attention on the maximal value. From our estimations it follows that the assumed disc contains

$$N = 6 \cdot (10^6 - 10^7) \cdot \left[\frac{D}{10\ \mathrm{pc}}\right]^{-2} \tag{31}$$

spatial periods of the instability and as many reconnection events should take place within $T_{rot}/2$ assuming that the onset of the Parker-shearing instability is triggered by the enhanced production of cosmic rays by supernovae in spiral arms. This assumption implies that the reconnecting loops of magnetic field are formed once in between arms. As it has been already mentioned, we imagine that the cosmic rays are first injected by supernova explosions, then they are raised by the Parker-shearing instability and finally they are disconnected by the magnetic reconnection. The next sequence of the three above processes can be triggered only by the next spiral arm. The total heating rate of the galactic disc coming from reconnection is then

$$\begin{aligned} Q_{tot} &= \frac{2NE_1}{t_{rot}} \\ &= (10^{38} - 10^{39}) \left[\frac{B}{10\mu\mathrm{G}}\right]^2 \left[\frac{D}{10\ \mathrm{pc}}\right] \left[\frac{t_{rot}}{200\ \mathrm{Myr}}\right]\ \mathrm{erg/s} \end{aligned} \tag{32}$$

Let us note that the above heating rate results from dissipation of a fraction of the total (as well as turbulent) magnetic energy of the disc

$$f = \frac{\epsilon D^3}{\lambda D^2} E_{m\,tot} = \frac{D}{\lambda} E_{m\,tot}, \tag{33}$$

which is 1 to 10 % for the current choice of parameters. This implies that only a small fraction of the energy of the nonuniform component of magnetic field is converted to the heat. However, the process described in the Figs. 1 and 2 efficiently removes the irregularities of magnetic field. The remaining part of vanishing turbulent magnetic energy is first used to built the new configuration of magnetic field and then partially expelled from the disc together with the upper family of magnetic field lines. For this reason the term relaxation is more proper for the described process than the dissipation. On the other hand, the dynamo models which require the full dissipation of the small scale component would produce one to two orders of magnitude larger heating rates. Since the results of Beck and Hoernes (1996) allow to estimate the uniformization time, the amount of turbulent magnetic energy, which decays between arm and interarm regions within that time, the rate of such relaxation or dissipation processes can be compared with observations of the diffuse X-ray emissivity of galaxies (see the next sections of the paper). Such comparison can serve as a test of currents dynamo models.

Since the heating is associated with temperatures $3 \cdot 10^6$ K we expect the heat conversion to the X-ray luminosity via cooling processes. The cooling process of a very hot plasma with temperature more than 10^7 K is thermal bremstrahlung or free-free emission. Gas at lower temperatures cools mainly by electron impact excitation of electronic levels of the neutral and ionized particles. Dalgarno and McCray (1972) derived the interstellar cooling function $\mathcal{L}$ which is at its maximum of the order of 10^{-21} ergs^{-1} cm^3 (at about 10^4K) and about $2 \cdot 10^{-23}$ ergs^{-1} cm^3 at temperatures above 10^6K. We can compare the magnetic heating time with the cooling time. The heating time is

$$t_{heat} \equiv \frac{nk_BT}{q}, \tag{34}$$

where

$$q \equiv Q_1/D^3 \tag{35}$$

is the heating rate per unit volume in the reconnection region of the volume D^3. After substitutions we obtain

$$t_{heat} = 1 \left[\frac{n_e}{0.01\ \mathrm{cm}^{-3}}\right]\left[\frac{T}{10^6\ \mathrm{K}}\right]\left[\frac{D}{10\ \mathrm{pc}}\right]\left[\frac{B}{10\mu\mathrm{G}}\right]^{-3} \mathrm{Myr}. \tag{36}$$

The cooling rate (per unit volume) and the cooling time are respectively

$$\Lambda \equiv n^2 \cdot \mathcal{L}, \tag{37}$$

and

$$\begin{aligned} t_{cool} &\equiv \frac{nk_BT}{\Lambda} \\ &= 50 \left[\frac{T}{10^6\ \mathrm{K}}\right] \left[\frac{\mathcal{L}}{10^{-23} \frac{\mathrm{erg\ cm}^3}{\mathrm{s}}}\right]^{-1} \left[\frac{n}{0.01\ \mathrm{cm}^{-3}}\right]\ \mathrm{Myr} \end{aligned} \tag{38}$$

The three relevant time scales t_{rec}, t_{heat} and t_{cool} resulting from formulae (28), (36) and (38) respectively are shown in Fig. 4 for different values of the magnetic field strengths B and the flux tube diameters (or domain sizes) D.

We note in Fig. 4 that the strength of magnetic field determines the relation between the reconnection and heating timescales. For $B \sim 10\mu$G both the timescales are comparable, and the heating timescale is typically shorter than the reconnection timescales for $n_e \leq 0.01$ cm^{-3} (higher levels of the galactic disc/halo system). This implies that at higher levels of the galactic disc the heating process leads to high temperatures in the single reconnection region during the reconnection time. The cooling timescales related to two characteristic values of cooling functions 10^{-21} and $2 \cdot 10^{-23}$ erg cm^{3}s^{-1} are represented by two full lines in all panels. The upper line is for slower cooling typical for higher temperatures (above 10^6 K) and

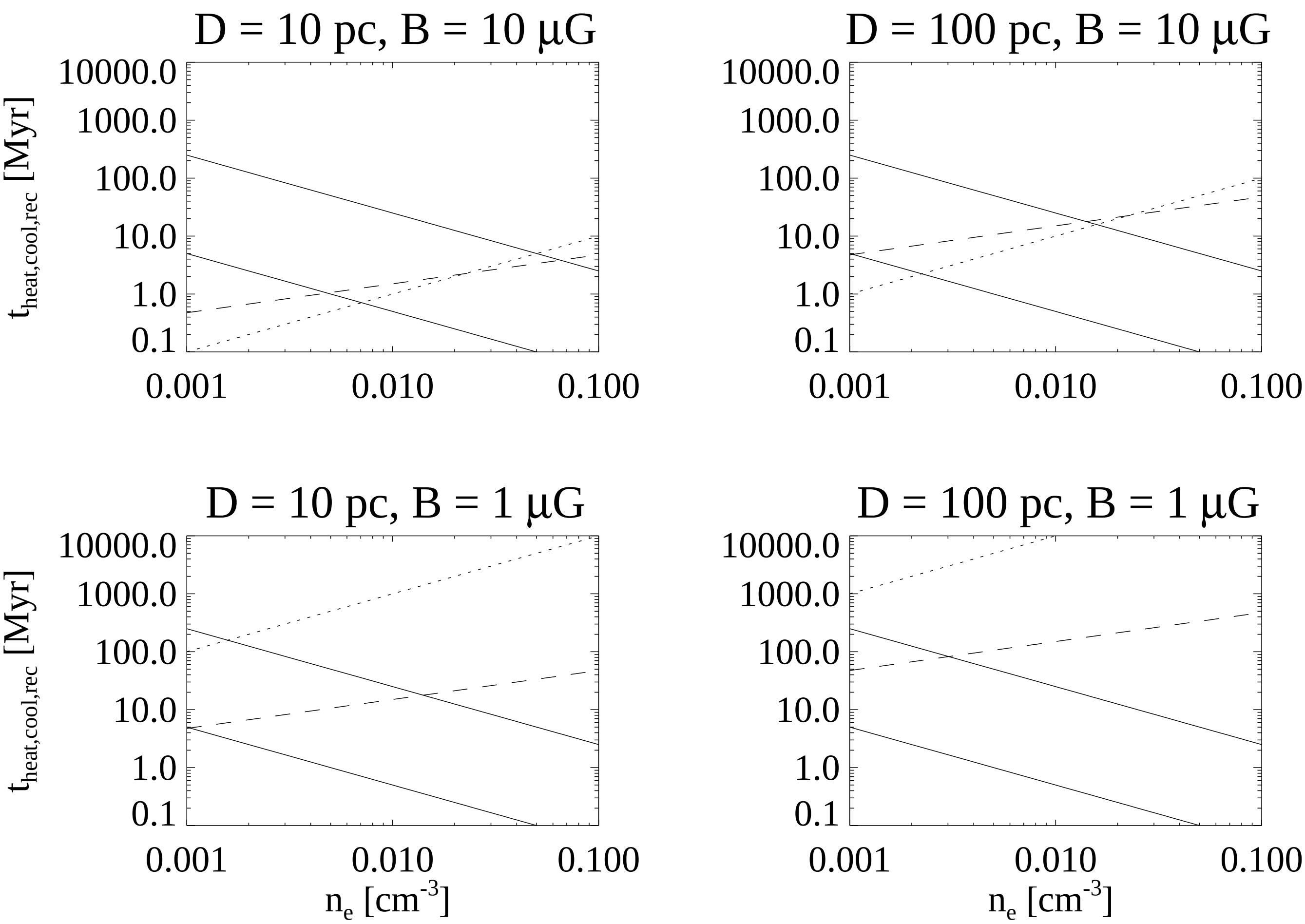

Fig. 4. The three relevant time scales t_{rec}, t_{heat} and t_{cool} resulting are shown for various values of the magnetic field strengths B and the flux tube diameter (or domane size) D. For all panels $T = 10^6$ K, two characteristic values of the cooling function are represented by the upper full line ($\mathcal{L} = 2 \cdot 10^{-23}$ erg cm^{-3}s^{-1}) and the lower full line ($\mathcal{L} = 10^{-21}$ erg cm^{-3}s^{-1}). The heating time is drown with the dotted line and the reconnection time with the dashed line.

the lower line is for faster cooling typical for lower temperatures (below 10^6 K). It is remarkable that strong magnetic fields, densities below 10^{-2} cm^{-3} and moderate flux tube diameters (or domain sizes) allow the interstellar gas to be heated from cool initial states because the heating time is shorter than the shorter of the cooling times. In the case of larger structures the same is possible if $n \le 10^{-3}$ cm^{-3} or the heating process starts from initial temperatures $T \sim 10^6$ K. Such initial temperatures can be attained in many different ways, e.g. in former reconnection events, due to locally very concentrated magnetic structures, streaming of cosmic rays along magnetic field or a supernova contributions.

If magnetic field is weaker, e.g. $B \sim 1\mu$G, the heating timescale is much longer than the reconnection timescale due to different powers of magnetic field in formulae (28) and (36): $t_{rec} \sim B^{-1}$ and $t_{heat} \sim B^{-3}$ respectively. Moreover, the heating timescale starts to exceed the slower cooling timescale at $n_e \sim 10^{-3}$ cm^{-3}, so reconnection is able to heat gas to X-ray emitting temperatures for densities smaller than the mentioned above (in upper levels of galactic halos) in multiple reconnection events, or there is no X-ray emission resulting from reconnection in some cases. The last case however, does not mean a lack of reconnection itself, but only a lack of the associated X-ray emission. One should mention in this context that the other heating processes can still work in such condition and overwhelm the heating by reconnection.

For weaker magnetic fields $\sim 1\mu$G the reconnection timescale, although shorter than the heating timescale is growing inversely to the magnetic field strength. This suggests that in the limit of very weak magnetic fields the reconnection time becomes significantly longer than the galactic dynamical timescale, what would imply that our dynamo model fails to work. One should remember however, that in the range of high plasma betas, magnetic field tends to be more and more intermittent i.e. concentrated in isolated flux tubes. The magnetic field evolution in such a flux tube is then completely determined by the flux tube dynamics. The field concentration should ensure that magnetic field strength within magnetic flux tubes is independent on the total magnetic energy of galactic discs. This in turn would imply an efficient dissipation by reconnection even in the weak (volume average) magnetic field limit.

In the expression (32) we estimated the total heat output from reconnection in the volume of galactic disc, which typically should be of the order of $10^{38} - 10^{39}$ erg/s for galaxies similar to ours or NGC 6946. The heat released is converted to the X-ray luminosity via the cooling processes as described by Dalgarno and McCray (1972). The X-ray luminosity can be computed by multiplying the cooling function by the X-ray emiting volume

$$P_X = \mathcal{L} n^2 V_{disc} \eta, \tag{39}$$

where V_{disc} is the total volume of galactic disc and η is the volume filling factor of the X-ray emiting gas. One can estimate

$$P_X = 1.5 \cdot 10^{40} \left[\frac{n}{0.01\ \mathrm{cm}^{-3}}\right]^2 \left[\frac{H}{0.5\ \mathrm{kpc}}\right] \left[\frac{R}{20\ \mathrm{kpc}}\right]^2 \eta \frac{\mathrm{erg}}{\mathrm{s}}, \tag{40}$$

where H is the disc (full) thickness and R is the disc radius. The volume filling factor of X-ray emitting gas is a poorly determined parameter. On the other hand the X-ray luminosity resulting from reconnection should not exceed the amount of heat released by reconnection. This gives an upper limit of η for the reconnection heated X-ray emiting gas

$$\eta_{rec} \leq 0.1 \tag{41}$$

Finally we would suggest that if t_{heat} is shorter than t_{cool}, a majority of released heat is converted to the X-ray luminosity, which according to our estimations should be $10^{38} - 10^{39}$ erg/s for galaxies like ours or NGC 6946.

3. Comments on the X-ray emission of selected galaxies

Schlegel (1994) analyzes the X-ray ROSAT observations of NGC 6946. The X-ray image of that galaxy is composed of a number of point sources and a diffuse emission. Schlegel concludes that the diffuse emission is not the sum of unresolved weak point sources like supernova remnants and X-ray binaries. We suggest that the unresolved X-ray emission can be related to magnetic heating process described above.

In M51 (Ehle, Pietsch and Beck, 1995) an X-ray emission comes from outside the optical limits and especially from the intergalactic region between M51 and its companion. This emission is hard to explain by the presence of binary system. As in the case of NGC 6946 a significant part of X-ray emission is not resolved into individual point sources. The authors argue that the diffuse emission can not be explained by a large number of unresolved point sources. The scale lengths of the thermal radio continuum emission and of the diffuse X-ray emission are similar. Although it is suggested that a hot gas from starburst regions (transported via galactic fountains or winds) can be responsible for the diffuse emission, we point out that the Parker-shearing instability together with the magnetic reconnection can lead to the same effect. It is worth noting (see Fig. 1. of Ehle, Pietsch and Beck (1995)) that the X-ray emission of M51 is locally enhanced in the wide interarm region internal to the northern spiral arm. This effect may be explained by the magnetic reconnection, which according to our expectations, should extend toward interarm regions and take part in the regularization of the magnetic structure as we suggest in Papers I and II. In addition, energy densities of magnetic field and hot gas are comparable in galactic halo of M51, which may follow from direct conversion from magnetic to thermal energy due to the magnetic reconnection. There is a similar effect in NGC 1566 (Ehle et al. 1996), where asymmetrically extended X-ray emission flares out from the nucleus in the direction toward the two interarm regions of enhanced polarized radio emission.

4. Discussion and conclusions

The main result of the present paper is the new dynamo model following from our previous results of Papers I and II. Our model is a kind of fast galactic dynamo proposed earlier by Parker (1992). The main difference between the Parker's model and ours results from the remark that due to the cosmic rays, differential force and the density waves, the magnetic tension has only a little influence on the flux tube dynamics. The cyclonic deformation of flux tubes due to the Parker-shearing instability is strong in both the vertical and radial directions. Moreover, the radial deformations exceed the cosmic ray thickening of the upper parts of flux tubes. This implies that the magnetic reconnection operates preferentially at places where two different flux tubes are pressed together in the radial direction by the Coriolis force. With the aid of magnetic reconnection this process (see Figs. 1 and 2) generates two new families of flux tubes from the buckled initial family. Both the families contain new components of the opposite sign, large scale radial magnetic field. The upper family, twisted with respect to the original magnetic field in direction corresponding to the Coriolis force, forms at lower parts of galactic halo, is inflated by cosmic rays and is lost from the disc. The lower family is twisted in the direction opposite to the Coriolis force and forms in the disc. In this way the sign of the α-effect in the disc is negative and the dynamo number D is positive. This circumstance favors the solutions of the dynamo equation which are propagating and are able to couple with density waves providing an additional growth rate to the dynamo waves. The negative

α-effect and the differential rotation considered separately lead to the same sign of the magnetic pitch angle in the disc as the sign of the pitch angle of spiral arms. In the halo, on the other hand the rotation of magnetic field lines corresponding to the α-effect is opposite to the effect of differential rotation. Since the Parker-shearing instability may be in some regions of the galactic discs much more vigorous than in other places, we expect large variations and reversals of the magnetic pitch angle in the adjacent regions of galactic halos. It is a specific feature of our model that the α-effect in disc and halo are closely related and have opposite signs. We would like to point out that the negative α-effect in galactic discs, resulting from the model presented in this paper is not inconsistent with the former Papers I and II. In those papers we calculated the helicity applying the standard formulae. In the present paper we have introduced the new scenario of flux tube interactions, which serves as a physical interpretation of the former formal results. According to this scenario the α-effect resulting from both the Parker-shearing instability and the subsequent relaxation process is negative in discs and positive in halos.

In the frame of our model we estimated the rate of generation of the radial component as well as the loss rate of magnetic field from the disc. The transport coefficients derived on the base of simple geometrical considerations led us to the expressions which are equivalent to the formally derived helicity α_d and diffusivity η_d in Paper I.

Since our model involves magnetic reconnection, which is responsible for the relaxation of magnetic field structure, the dynamo process we describe implies the magnetic heating of interstellar gas. The estimated X-ray luminosity of spiral galaxies of the order of $10^{38} - 10^{39}$ erg/s is comparable, to the observed X-ray luminosities of selected nearby galaxies. We would like to point out that in our model only 1 to 10 % of the magnetic turbulent energy is directly dissipated (i.e. converted to the heat) in the described dynamo process by means of the magnetic reconnection. The rest of turbulent energy is replaced, in the described relaxation process, by the large scale component of magnetic field, which in turn is partially expelled to the halo and then to intergalactic space.

Our estimation of X-ray luminosity is not precise, arising as a byproduct of the proposed dynamo model. This X-ray luminosity does not take into account an amount of magnetic reconnection which does not directly take part in the dynamo process, but only smoothes magnetic field irregularities on single, strongly inflated flux tubes in halo. We expect that in some extreme cases of high cosmic ray production rate, the mentioned contribution can be even stronger by more than two orders of magnitude, because of dominating vertical structures (lobes) of magnetic field with opposite polarity extending to the heights of a few kpc. The associated total surface area of current sheets should be extremely large and conditions (mainly low density) very favorable for an efficient reconnection leading to the X-ray emission up to 10^{42} erg/s.

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References

Beck, R., Hoernes, P., 1996, Nature 379, 47
Beck, R., Brandenburg, A., Moss, D. et al., 1996, ARA&A 34, 155
Berkhuijsen, E.M., et al., 1997, A&A318, 700
Biskamp, D., 1994, Phys. Rept. 237, 179
Brandenburg, A., et al., 1995, ApJ446, 741
Chiba, M., Tosa, M., 1990, MNRAS244, 714
Dalgarno, A., McCray, R.A., 1972, ARA&A 10, 375
Ehle, M., Beck, R., 1993, A&A273, 45
Ehle, M., Pietsch, W., Beck, R. 1995, A&A295, 289
Ehle, M., et al. 1996 A&A306, 73
Ferriere, K., 1993, ApJ404, 162
Ferriere, K., 1996, A&A310, 455
Hanasz, M., Lesch, H., Krause, M., 1991, A&A243, 381
Hanasz, M., Lesch, H., 1993, A&A278, 561 (HL'93)
Hanasz, M., Chiba, M., 1994, MNRAS266, 545
Hanasz, M., Lesch, H., 1997, A&A321, 1007 (Paper I)
Hanasz, M., 1997, A&A327, 813 (Paper II)
Kazes, I., Troland, T.H., Crutcher, R.M., 1991, A&A245, L17
Kulsrud, R.M., Anderson, S.W., 1992, ApJ396, 606
Lesch, H., 1991, A&A245, 48
Mestel, L., Subramanian, K., 1991, MNRAS248, 677
Moss, D., 1996, A&A, 308, 381
Papadopoulos, K., 1979 in *Dynamics of the Magnetosphere*, S.I. Akasofu (ed.) Reidel, Dordrecht, p.234
Parker, E.N., 1979, *Cosmical Magnetic Fields*, Oxford
Parker, E.N., 1955, ApJ121, 491
Parker, E.N., 1967a, ApJ149, 517
Parker, E.N., 1967b, ApJ149, 535
Parker, E.N., 1992, ApJ401, 137 (P'92)
Petschek, H.E., 1964, in *AAS/NASA Symp. on the physics of Solar Flares*, W.N. Hess (ed.), NASA, Washington DC, p. 425
Pietsch, W., 1993, in *Panchromatic View of Galaxies* eds. G. Hensler, Ch. Theis, J. Gallagher, p. 138
Ruzmaikin, A.A., Shukurov, A.M., Sokoloff, D.D., 1988, *Magnetic Fields in Galaxies*, Reidel, Dordrecht
Schindler, K., Hesse, M., Birn, J., 1991, ApJ380, 293
Schlegel, E.M., 1994, ApJ434, 523
Schüssler, M., 1993, in: *The Cosmic Dynamo* F. Krause, K.-H. Rädler, G. Ruediger (eds.), IAU-Symp. No. 157, Kluwer, Dordrecht, p. 27
Starchenko, S.V., Shukurov, A.M., 1989, A&A214, 47
Subramanian, K., Mestel, L., 1993, MNRAS265, 649
Vainshtein, S.I., Cattaneo, F., 1992, ApJ393, 165
Zimmer, F., Lesch, H., Birk, G.T., 1997, A&A320, 746

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