Proceedings of The Magnetized Plasma in Galaxy Evolution
Sep. 27th – Oct. 1st 2004, Jagiellonian University, Kraków, Poland
Eds. K.T. Chyży, K. Otmianowska-Mazur, M. Soida and R.-J. Dettmar

The Magnetic Helicity Current in an Alpha-Omega Dynamo

Ethan T. Vishniac

Johns Hopkins University, 3400 N. Charles St., Baltimore, USA

Abstract

Conservation of magnetic helicity plays a critical role in suppressing mean-field dynamo action. Successful large scale dynamo action can occur if, and only if, the local turbulence is biased to drive a magnetic helicity current. In the case of a disk dynamo, the required magnetic helicity current is vertical and imposes a connection between the corona and the dynamo. The sign of the magnetic helicity current determines whether we get a dynamo or an anti-dynamo. The latter is more likely in systems in which angular momentum is driven outward by local turbulence. A successful galactic dynamo in an L_* spiral disk will magnetize the surrounding intergalactic medium within several hundred kpc to $\sim 10^{-9}$ Gauss.

1 Introduction

The existence of large scale magnetic fields in the universe is one of the more difficult problems in astrophysics. If we restrict ourselves to known physics, then the early universe provides seed fields which are many orders of magnitude weaker than what we see in the interstellar medium today. The generation of magnetic fields in highly conducting fluids has been conventionally approached via mean-field dynamo theory, which can give exponential growth of the magnetic field in a shearing turbulent fluid. However, substantial theoretical objections have been raised against this formalism, and numerical experiments seem to confirm its inability to generate fields which approach equipartition with the turbulent energy density in the ISM. Moreover, even without these problems it has never been clear that dynamo theory provides enough growth to explain existence of strong galactic fields after only a few billion years. Here I will discuss a modified version of mean-field dynamo theory which can overcome these problems. I begin with a brief review of previous work. For a detailed review of mean-field dynamo see, for example, Moffatt (1978).

It is useful to divide the dynamo problem in two. First, there is the generation of magnetic fields within an initially unmagnetized turbulent conducting fluid. Given a very weak seed field we can expect that field line stretching in the turbulent eddies will rapidly transfer energy into the magnetic field. Since the magnetic field is generated passively, by the action of the turbulent eddies, the correlation length of the magnetic field can be no larger than the scale of the largest eddies. In fact, unless the magnetic field can reconnect and undergo some kind of systematic reorganization, the correlation length will be much smaller. This is the *small scale dynamo problem.* Very early work (Batchelor 1950) suggested that the field would evolve to large energy densities, but very short correlation lengths perpendicular to the local field direction. However, computer simulations of this process (e.g. Ponty et al. 2004) show that the field evolves toward large eddy correlation lengths. Even very weak seed fields evolve close to equipartition with the turbulence in a few large eddy scale turn over times.

The second kind of dynamo problem is the *large scale dynamo*. In many cases we find magnetic fields with significant power on scales comparable to the scale of the object itself, e.g. the Sun, or planetary fields. Galaxies seem to show this kind of organization, in at least some cases. Observationally we can't say much about accretion disk fields, but simulations seem to show that they have at least a large axisymmetric component. The large scale dynamo problem is the subject of mean-field dynamo theory, and is the focus of this paper.

When we consider cosmological magnetic fields, we can see examples of both kinds of dynamo. For example, galaxy clusters show a strong intracluster magnetic field, with a scale of organization on the order of tens of kpc, comparable to the inferred size of turbulent eddies in the intracluster medium. In this case the major question we face is understanding the injection of seed fields into the intracluster medium, presumably by the disk galaxies accreted by the cluster. On the other hand, while spiral disks contain turbulent eddies with scales $\sim$ tens of parsecs, their magnetic fields are organized on much larger scales, which can only be understood by solving the large scale dynamo problem.

Why are dynamos surprising? In a resistive fluid the induction equation reads

$$\partial_t \mathbf{B} = \nabla \times \mathbf{v} \times \mathbf{B} - \nabla \times (\eta \nabla \times \mathbf{B}), \tag{1}$$

where η is the resistivity. We can estimate the importance of the last term by considering the magnetic Reynolds number

$$\mathcal{R}_B \equiv \frac{vL}{\eta}, \tag{2}$$

where v is the rms turbulent velocity, and L is a typical eddy scale. For astrophysical systems this is number is very large. For the galaxy as a whole it is $\sim 10^{20}$. The ratio of the resistive term to the first term on the RHS of the induction equation is roughly $\mathcal{R}_B^{-1}$. It would appear to be negligible. However, if we neglect it altogether then the magnetic field is frozen into the fluid. The flux threading a fluid element is a constant of motion and the topology of the magnetic field is unchanging. This rules out a large scale dynamo. It also makes the appearance of the large eddy scale in the small scale dynamo problem difficult to understand. It is true that a simple scalar resistivity does not adequately describe a collisionless plasma, but the same scaling arguments apply to more sophisticated versions of the induction equation.

We can solve part of this difficulty if reconnection of magnetic field lines is much more efficient than suggested by the value $\mathcal{R}_B$. While Sweet-Parker reconnection speeds scale as $\mathcal{R}_B^{-1/2}$, the topologically more complicated process of stochastic reconnection (Lazarian and Vishniac 1999) can give reconnection speeds which are comparable to the local turbulent velocity, in collisionless and collisional plasmas. This works by assigning a large role to resistivity, but only in a volume of measure $\sim$ zero. Fast reconnection breaks topological invariance, which eliminates the only major problem with the small scale dynamo. It does not completely solve the large scale dynamo problem. We are still faced with the point that magnetic helicity conservation imposes severe constraints on the evolution of the large scale magnetic field. We explore these, and suggest a resolution, in the next section. Some of the work mentioned here is described, at much greater length, in a review paper by Vishniac, Lazarian and Cho (2003).

2 The Magnetic Helicity Current

Neglecting resistivity, the induction equation has two conserved quantities. The more obvious one is the magnetic flux. In addition, if we define the magnetic helicity, $H \equiv \mathbf{A} \cdot \mathbf{B}$, where $\mathbf{A}$

is the vector potential, then it is straightforward to show that

$$\partial_t H = -\nabla \cdot [H\mathbf{v} + \mathbf{B}(\mathbf{\Phi} - \mathbf{A} \cdot \mathbf{v})] - \eta \mathbf{B} \cdot \mathbf{J}, \tag{3}$$

where Φ is a gauge variable. Note that the helicity current is not simply the trivial transport of preexisting magnetic helicity, but includes a term which describes the effects of twisting a field line, so that regions magnetic helicity of opposing signs move away from each other along field lines. The gauge variable Φ is defined by the condition

$$\partial_t \mathbf{A} = \mathbf{v} \times \mathbf{B} - \nabla \mathbf{\Phi}. \tag{4}$$

For reasons that will soon become clear, it is extremely useful to restrict ourselves to the Coulomb gauge, so that

$$\nabla^2 \Phi = \nabla \cdot (\mathbf{v} \times \mathbf{B}). \tag{5}$$

With this definition equation (3) is Galilean-invariant. >From the form of the magnetic helicity current, we can see that it is separately conserved along each magnetic field line. However, in the presence of fast reconnection its mobility is not significantly limited.

In physical terms, the magnetic helicity is a measure of the topology, the "twistiness", of the magnetic field. It is not unique in this respect. The current helicity $\mathbf{B} \cdot \mathbf{J}$ is a similar measure, with a different weighting in Fourier space, but is not conserved in the limit $\eta \to 0$. It is important to note that the magnetic helicity has the dimensions of an energy density times a length scale. Embedding the same magnetic helicity in increasingly smaller structures requires an increasingly large expenditure of energy. Consequently, unless the turbulent spectrum is inverted, the amount of magnetic helicity contained on the resistive scale is negligible. In particular, in a turbulent cascade, where the energy scales as $k^{-2/3}$, magnetic helicity is robustly conserved. This even makes it a useful guide to experiments, where resistivity is not negligible (see Taylor 1986 for a review). By contrast, the kinetic helicity, $\mathbf{v} \cdot \omega$, is exactly conserved for inviscid hydrodynamic turbulence, but since it scales as an energy density divided by a length scale, it is efficiently dissipated in the limit of small viscosity. In MHD turbulence the cross helicity, $\mathbf{v} \cdot \mathbf{B}$ is also a conserved variable, but scales as an energy density and is not robustly conserved. Magnetic helicity is uniquely useful as a guide to the evolution of large scale magnetic fields.

I note that while we can choose any gauge and still get a conserved quantity, the choice of gauge is not arbitrary. The physical manifestations of magnetic field topology follow from current helicity and are gauge-invariant. Only in the Coulomb gauge is there a close relationship between H and the current helicity.

How does this affect the mean-field dynamo? If we divide the magnetic field into large and small scale components, $\mathbf{B_{tot}} = \mathbf{B} + \mathbf{b}$, and average the induction equation we see that

$$\partial_t \mathbf{B} = \nabla \times \langle \mathbf{v} \times \mathbf{b} \rangle, \tag{6}$$

where the brackets denote averaging over small scale features. The component of the electromotive force, $\equiv \langle \mathbf{v} \times \mathbf{b} \rangle$, perpendicular to $\mathbf{B}$ can be modeled as an field line velocity. It does not violate the flux-freezing condition for the large scale field. In contrast, the parallel component of the electromotive force can generate new large scale flux. While a detailed understanding of the evolution of the large scale magnetic field depends on all the components of the electromotive force, the *existence* of a large scale dynamo depends on $\mathbf{B} \cdot \langle \mathbf{v} \times \mathbf{b} \rangle$.

If we divide the spatially averaged magnetic helicity into the part arising from the large scale and small scale fields we have

$$\langle \mathbf{A_{tot}} \cdot \mathbf{B_{tot}} \rangle = \mathbf{A} \cdot \mathbf{B} + \langle \mathbf{a} \cdot \mathbf{b} \rangle \equiv \mathbf{H} + \mathbf{h}. \tag{7}$$

Note that h is *not* the fluctuating part of the magnetic helicity. It is the part of the large scale average which arises from small scale magnetic structures. The evolution equations for h and H are

$$\partial_t H = 2\mathbf{B} \cdot \langle \mathbf{v} \times \mathbf{b} \rangle - \nabla \cdot [\mathbf{B\Phi} + \mathbf{A} \cdot \langle \mathbf{v} \times \mathbf{b} \rangle], \tag{8}$$

and

$$\partial_t h = -2\mathbf{B} \cdot \langle \mathbf{v} \times \mathbf{b} \rangle - \nabla \cdot \mathbf{j_h}, \tag{9}$$

where

$$\mathbf{j_h} \equiv \langle (\mathbf{a} \cdot \mathbf{B})\mathbf{v} + \langle \mathbf{b}\phi \rangle - \mathbf{B} \langle \mathbf{a} \cdot \mathbf{v} \rangle + \langle \mathbf{a} \times (\mathbf{v} \times \mathbf{b}) \rangle \tag{10}$$

and

$$\nabla^2 \Phi \equiv \nabla \cdot \langle \mathbf{v} \times \mathbf{b} \rangle, \tag{11}$$

$$\nabla^2 \phi \equiv \nabla \cdot (\mathbf{v} \times \mathbf{b} - \langle \mathbf{v} \times \mathbf{b} \rangle). \tag{12}$$

We can see from this that the transfer of magnetic helicity between scales is mediated by exactly the same component of the electromotive force that drives the dynamo.

This last point turns out to play a critical role in damping the kinematic dynamo. If the dynamo is driven by a turbulent velocity field with a mean kinetic helicity, $\mathbf{v} \cdot \omega$, then the electromotive force has a piece proportional to the mean field, $\alpha_{ij} B_j$ where α_{ij} is proportional to the kinetic helicity times the correlation time. Since the kinetic helicity is not a conserved quantity, this will be of order $v\lambda/L$, where λ is an eddy size and L is some large symmetry breaking scale. Unless there is a systematic magnetic helicity current, the dynamo will work by generating a large scale field with a magnetic helicity H of order $B^2 L$ and a corresponding $h = -H$ everywhere. Since h cannot exceed $b^2\lambda \sim v^2\lambda$ this implies that the large scale field will saturate well short of equipartition. Even this turns out to be an overestimate. In general α_{ij} includes a term proportional to the current helicity, which has the effect of transferring magnetic helicity back to large scales. This will overwhelm the kinetic helicity when

$$\frac{h}{\lambda^2} > \mathbf{v} \cdot \omega \sim \frac{\mathbf{v^2}}{\mathbf{L}}, \tag{13}$$

or

$$B^2 L \sim h > v^2 L \left(\frac{\lambda}{L} \right)^2. \tag{14}$$

In other words, saturation will set in when the large scale magnetic field is below the equipartition value by the ratio of the eddy scale to the system scale. In a shearing system the large scale magnetic field gains some of its energy from the large scale shear, and the saturation amplitude will be closer to the equipartition value, although still below it.

The loophole in this argument is provided by the magnetic helicity current $\mathbf{j_h}$, which breaks the constraint on the local value of h. In fact, if the distribution of h is stationary, we have

$$\mathbf{B} \cdot \langle \mathbf{v} \times \mathbf{b} \rangle = \frac{\mathbf{-1}}{\mathbf{2}} \nabla \cdot \mathbf{j_h}. \tag{15}$$

>From symmetry we can see that $\mathbf{j_h}$ is invariant under $\mathbf{B} \rightarrow -\mathbf{B}$ and $\mathbf{r} \rightarrow -\mathbf{r}$. Although it must vanish in totally isotropic turbulence, it can be nonzero in mirror-symmetric turbulence.

The implication is that it is easier to produce a nonzero magnetic helicity current than it is to produce a nonzero kinetic helicity. In particular, $\mathbf{j_h} \neq \mathbf{0}$ in any differentially rotating system.

We can evalute j_h up to quadratic order. Including the possibility of a large scale velocity field, such as would be supplied by differential rotation, we get

$$\mathbf{j_h} = \mathbf{hV} + \langle \int \frac{\mathbf{d^3r'}}{\mathbf{4\pi r'}} \left[\mathbf{r'^2}\partial_\mathbf{s}\mathbf{b}(\mathbf{r})\sigma_\mathbf{sl}\mathbf{j_l}(\mathbf{r}+\mathbf{r'}) - \mathbf{b}(\mathbf{r})\mathbf{B}\cdot\omega(\mathbf{r}+\mathbf{r'}) + \mathbf{v}(\mathbf{r})\mathbf{B}\cdot\mathbf{j}(\mathbf{r}+\mathbf{r'})\right]\rangle \tag{16}$$

where σ_{sl} is the symmetrized part of the shear tensor. For a differentially rotating cylindrical system the only nonzero components are $\sigma_{r\phi} = \sigma_{\phi r} = r\Omega'/2$.

3 The $\alpha - \Omega$ Dynamo

Since the most obvious application of this model is to differentially rotating systems, it is appropriate to pause here to review the $\alpha - \Omega$ dynamo. In a strongly differentially rotating system the large scale magnetic field is predominantly azimuthal. The large scale radial field has to be generated by the mean-field dynamo process, but it can produce the azimuthal field through shearing. In the conventional treatment, this is written as pair of coupled equations

$$\partial_t B_r = -\partial_z(\alpha_{\phi\phi}B_\phi) + \partial_z D_T \partial_z B_r, \tag{17}$$

$$\partial_t B_\phi = r\Omega' B_r + \partial_z D_T \partial_z B_\phi, \tag{18}$$

where D_T is the turbulent diffusion coefficient. The growth rate for the dynamo is

$$\Gamma \sim \left(\frac{\alpha_{\phi\phi}\Omega}{L}\right)^{1/2} \sim \frac{v}{L}(\Omega\tau_c)^{1/2}, \tag{19}$$

where L is the vertical scale of the system and τ_c is the turbulence correlation time.

How does this work when the dynamo is driven by the magnetic helicity current? The magnetic helicity in the $\hat{z}$ direction is the piece that enters into the simplest version of the $\alpha-\Omega$ dynamo. We can estimate the value of j_{hz} using equation (16). When the shear is weak we can ignore the first term in the integrand. We can estimate the other terms by taking

$$\mathbf{b} \approx \tau_\mathbf{c}\mathbf{B}\cdot\nabla\mathbf{v}, \tag{20}$$

and

$$\mathbf{v} \approx \tau_\mathbf{c}\mathbf{B}\cdot\nabla\mathbf{b}. \tag{21}$$

Using each of these in turn, and remembering that the integration in equation (16) is equivalent to $-\nabla^{-2}$ we can write the vertical anomalous magnetic helicity current as

$$J_{hz} \approx \frac{-2\tau_c}{k_c^2}\langle \mathbf{B}\cdot\mathbf{j}(\mathbf{B}\cdot\nabla)\mathbf{b_z} - \mathbf{B}\cdot\omega(\mathbf{B}\cdot\nabla)\mathbf{v_z}\rangle. \tag{22}$$

Assuming that the large scale magnetic field is mainly azimuthal, using integration by parts and incompressibility to rearrange the terms in this expression we get, after some algebra,

$$J_{hz} \approx \frac{2\tau_c}{k_c^2}B_\theta^2\left(k_\theta^2(\langle v_r v_\theta\rangle - \langle b_r b_\theta\rangle) + k_r k_\theta\langle v_r^2 + v_z^2 - b_r^2 - b_z^2\rangle\right). \tag{23}$$

Two points are immediately apparent. First, the magnetic helicity current depends on breaking the symmetry between the velocity and magnetic fields. Second, we see from the first term that there is a close and unexpected connection between the radial transport of angular momentum and the magnetic helicity current. Processes that transport angular momentum outward in the galactic disk will tend to produce a positive vertical flux of magnetic helicity.

Assuming again that $\partial_t h \sim 0$ we can rewrite the equation for B_r as

$$\partial_t B_r = \partial_z \frac{1}{2B} \partial_z j_{hz}. \tag{24}$$

If the turbulence is independent of B this is a linear equation in B. It will give exponential growth if the j_{hz} has the same sign as $-\Omega'$. A disk dynamo will be driven efficiently by a positive vertical magnetic helicity flux. (The large scale magnetic helicity current turns out to have the same sign as j_{hz} in this model.) Since this is a natural sign to expect in both accretion disks and galactic disks, we see that in both cases we expect a successful dynamo. We note that in the Sun both the sign of Ω' and the magnetic helicity are reversed.

How strong is the expected magnetic helicity current? A precise answer is beyond the scope of this paper. However, a cursory inspection of equation (16) tells us that it must be of order

$$j_{hz} \sim B^2 v^2 \tau_c, \tag{25}$$

or the large scale magnetic energy density times the turbulent diffusion coefficient. The consequent dynamo growth rate is

$$\Gamma \sim \left(\frac{\Omega j_{hz}}{B^2 L^2} \right)^{1/2} \sim \frac{v}{L} (\Omega \tau_c)^{1/2}. \tag{26}$$

We have recovered our earlier estimate. However, by taking into account the magnetic helicity current we have removed the low saturation limit on the magnetic field strength. The magnetic field will saturate only when it becomes strong enough to distort the turbulent eddies, i.e. at equipartition with the turbulent energy density.

There is one other point that need to be stressed. Considering magnetic helicity conservation has led us directly to an $\alpha - \Omega$ dynamo model in which magnetic helicity flows vertically through a differentially rotating disk. What happens at the disk boundaries? The magnetic helicity will accumulate at the boundary until it can be ejected. Since the magnetic helicity flux is also an energy flux, crudely given by dividing $\mathbf{J_H}$ by the scale of the magnetic structures, there is energy available to eject the magnetic helicity by expanding magnetic structures into the disk corona. The energy required for this is comparable to the energy invested in the dynamo process itself, i.e. in practice this is not a significant obstacle. A successful disk dynamo will produce local chromospheric heating through the release of magnetic tension and a large scale magnetic helicity current which will effect the disk corona.

4 Seeding Magnetic Fields in the Universe

Magnetic helicity conservation an immediate implication for seed magnetic fields in the presence of turbulence. Assuming, as appears to the case, that the small scale dynamo operates efficiently, then disk turbulence will create an equipartition field with a coherence length of an eddy scale, i.e. some tens of parsecs, within a few eddy turn over times. This, in turn, will give rise to a Poisson distribution of magnetic helicity on larger scales. Since the long wavelength components of the magnetic helicity will quickly manifest themselves in large scale components of the magnetic field, we get a magnetic field strength which falls as $L^{-5/4}$ on large scales. Annular domains, with a radial extent of a few hundred parsecs, will have seed fields of order the equipartition strength divided by $N^{-1/2} \sim 30^{-1}$, or $\sim 10^{-7}$ gauss. This is many orders of magnitude stronger than the usual estimates for galactic seed fields. The galactic dynamo does not have to operate for more than a few e-foldings to produce fields close to the current amplitude.

This field will not stay confined to the galaxy. As we have already noted, an $\alpha-\Omega$ dynamo in the galactic disk involves a vertical magnetic helicity current. The magnetic helicity ejected from each face of the disk will be of order

$$J_H \sim B^2 \lambda v (\pi R^2). \tag{27}$$

We can estimate this by plugging in values appropriate to our own galaxy, i.e. $B \sim 10^{-5.5}$ gauss, $R \sim 10$ kpc, $v \sim 10$ km/sec, and $\lambda \sim 30pc$, to get the total magnetic helicity ejected over one rotation period ($\sim 2 \times 10^8$ yr.). Dividing this by the scale of the galactic halo (also R),and the volume of the halo, we find a mean halo magnetic field of $\sim 10^{-7}$ gauss. Of course, this is not the end of the process. The galaxy will continue to eject magnetic helicity, with the same sign, into its environment as long as the disk dynamo operates. This effect does not depend on assuming any particular symmetry or polarity for the disk field. For a disk in a cluster it will operate for only a short time before ram pressure strips the gas from the disk and truncates the dynamo process. Nevertheless, this implies that the intracluster medium is supplied with large seed fields whenever disk galaxies fall into the cluster.

An isolated spiral galaxy will pump out magnetic helicity for about 50 rotation periods. If the field is confined to the galactic halo this will raise its amplitude by a factor of about 7. More probably, the field will disperse into the intergalactic medium, falling as the inverse square of the scale of the magnetized wind. The implication is that the intergalactic medium within a few hundred kpc of a disk galaxy could plausibly be magnetized at an amplitude of $\sim 10^{-9}$ gauss, assuming that the field is organized coherently on this scale.

We can compare this to the magnetic helicity injection due to a supermassive black hole at the center of a typical disk galaxy. Assuming an Eddington accretion rate, the resulting magnetic helicity flux is down from the disk contribution by about 10^5. Moreover, we do not actually expect a typical black hole to continue accreting at the Eddington rate up until the present day. The implication is that AGN play a negligible role in magnetizing the IGM. (Note that this argument does *not* apply to the energy injection rate from the AGN, which can swamp any contribution from a galactic wind.)

5 Conclusions

After several decades of work, our understanding of the dynamo problem continues to change. Here I have concentrated on the discovery that magnetic helicity conservation gives us a powerful tool to understand the production of large scale ordered fields. Although earlier models of mean-field dynamos are heavily constrained by magnetic helicity conservation, including the magnetic helicity current in our models gives us growth rates comparable to earlier estimates, while avoiding the low saturation levels for the large scale field. Moreover, the amount of symmetry breaking necessary to produce such currents is actually less than one needs to get a significant kinetic helicity and drive a dynamo in the conventional manner.

Magnetic helicity conservation has several further implications. First, the operation of the small scale dynamo automatically supplies seed fields on galactic scales that are only a few orders of magnitude smaller than equipartition. Large scale galactic fields should appear within a few e-folding times of the galactic dynamo. Second, disk dynamos produce systematic ejection of magnetic helicity into the immediate environment of disk galaxies, even the disk magnetic field contains numerous reversals. This will bring the magnetic field of the galactic corona close to microgauss levels as soon as the galactic field reaches equipartition. This provides a powerful source of seed fields for intracluster gas in galaxy clusters. Isolated disk galaxies will continue to magnetize their environments. By the present day fields of order 10^{-9} gauss should fill space around a typical spiral galaxy out to distances of several hundred kpc.

Acknowledgements

I would like to thank my collaborators, Jungyeon Cho and Alex Lazarian. The work described here was supported by NSF grant AST-0098615.

References

G. Batchelor, 1950, Proc. R. Soc. London A, 201, 405

A. Lazarian, and E. T. Vishniac, 1999, ApJ, 517, 700

H. K. Moffatt, 1978, Magnetic Field Generation in Electrically Conducting Fluids (Cambridge: Cambridge University Press)

Y. Ponty, P. D. Mininni, D. C. Montgomery, J.-F. Pinton, H. Politano, and A. Pouquet, 2004, astro-ph/0410046

J. B. Taylor, 1986, Reviews of Modern Physics, 58, 741

E. T. Vishniac, A. Lazarian, and J. Cho, 2003, in Turbulence and Magnetic Fields in Astrophysics, edited by E. Falgarone and T. Passot, Lecture Notes in Physics, 614, 376

Proceedings of The Magnetized Plasma in Galaxy Evolution
Sep. 27th – Oct. 1st 2004, Jagiellonian University, Kraków, Poland
Eds. K.T. Chyży, K. Otmianowska-Mazur, M. Soida and R.-J. Dettmar

Can we observe the poloidal magnetic field?

Marian Soida

Astronomical Observatory of Jagiellonian University, ul. Orla 171, 30-244 Kraków, Poland

Abstract

We present results of radio continuum observations of a few edge-on spiral galaxies. Observed polarization magnetic vectors follow the X-shaped pattern, sticking out of the galactic plane far into the halo. The picture seem to be common among galaxies seen edge-on. In the most cases the magnetic vectors are plane parallel close to the galactic disk and the whole pattern resembles poloidal component of the dynamo-produced magnetic field. The best studied case of NGC 5775 show that the picture is well free of the Faraday effects.

1 Introduction

Looking at nearly face-on spiral galaxies in continuum emission at radio feequencies we see more or less regular spiral structure of magnetic vectors of polarized emission (see e.g. Beck or Urbanik this volume). Such configuration can be attributed to magnetic field close to the galactic plane, being "illuminated" by relativistic electrons spiraling around field lines and emitting synchrotron radiation.

The magnetic field configuration itself can be explained by galactic dynamo mechanisms. Very simplified dynamo-made magetic field consists of thoroidal component with substantial radial component (inclined to the azimuthal direction) in the vicinity the galactic disk, but also a poloidal (with dipolar or quadrupolar symmetry) magnetic field component extending far into the galactic halo (see e.g. Widrow 2002).

If global galactic magnetic field is made due to some kind of dynamo mechanism, and if there are enough relativistic electrons away from the galactic plane we shall be able to detect synchrotron radiation in galactic halos while observing edge-on spiral galaxies.

2 Observations

2.1 NGC 5775

The most clear picture so far of polarized radio emission of edge-on galaxy NGC 5775 can be seen in Tüllmann et al (2000) and is reproduced here as Fig. 1.

Detectable radio continuum seen at 4.86 GHz extends far into the galactic halo (up to about 10 kpc from the galactic plane) having significant polarization degree reaching 50% in some places.

Polarization magnetic vectors, close to the galactic plane, form plane parallel configuration, and X-shaped structure in all four quadrants in the halo of the galaxy. It is better seen on the polarized intensity map (Fig. 1 right) where magnetic vectors follow ridges of polarized emission intensity.

The X-shaped polarized emission intensity distribution seem to follow the Hα filaments. This fact and the very high star formation rate of this object (Lee et al. 2001) can lead to the

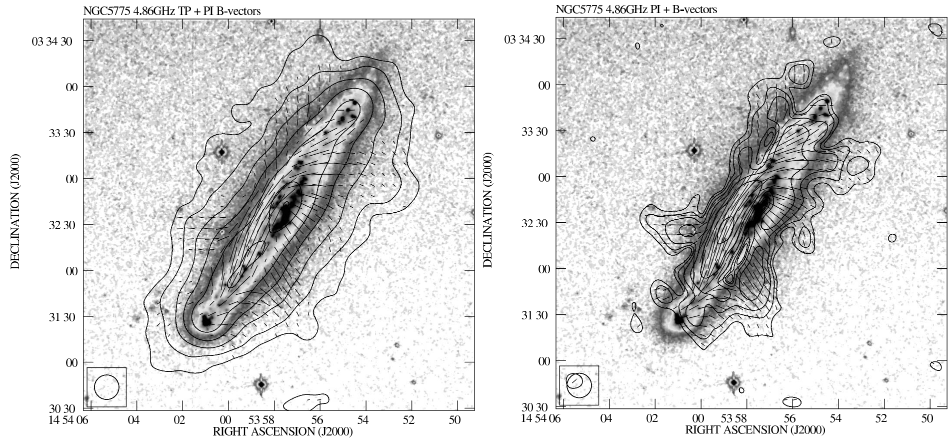

Figure 1: Radio continuum emission at 4.86 GHz of NGC 5775. Total intensity (left) and polarized intensity (right) contours with apparent polarization B-vectors proportional to the polarized intensity, both ovarlaid onto the Hα image (digitally processed to see faint extensions in the galactic halo)

concluson, that the observed magnetic field configuration is caused by galactic wind blowing out of the galaxy and pooling magnetic field lines out of the disk along the Hα filaments, and thus ordering it (seen as enhanced polarization degree).

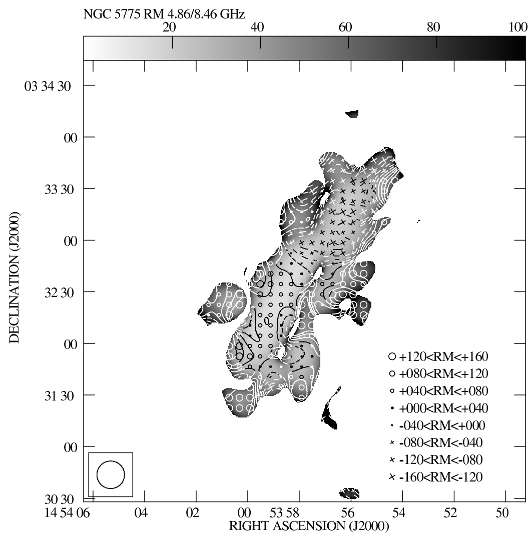

Figure 2: Faraday rotation measure distribution of NGC 5775 calculated between 8.46 and 4.86 GHz shown as symbols (and contours), overlaid onto the uncertainty of this quantity shown as gray-scale

An argument against the hypothesis described above comes from the Faraday rotation distribution. Using the VLA[1] we obtained deep polarized continuum map of NGC 5775 at

[1]Very Large Array of the National Radio Aastronomy Observatory is a facility of National Science Foundation operated under cooperative agreement by Associated Universities, Inc.