RM Synthesis: Problems and Perspectives

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Main bulk of our knowledge concerning magnetic fields of spiral galaxies comes from observations of radio emission of the galaxies and in particular from Faraday rotation measures. We consider here traditional methods of this procedure in context of the new method known as RM Synthesis. RM Synthesis looks as an important tool for investigation of magnetic fields of spiral galaxies. Long wavelength observations allows a limited application of the method while expected facilities of SKA should allow such application in the full extent. Of course, it is desirable to combine RM Synthesis with options based on solution of inverse problem for multiwavelength observations.

1 Introduction

Magnetic field of the Milky Way is known for more than 60 years, and magnetic field of external spiral galaxies has been investigated since the 1980s. The main bulk of contemporary knowledge in this field comes from observations of polarized synchrotron emission in radio range. Polarization gives a hint that spiral galaxies contain magnetic fields of the scale comparable with galactic radius, while Faraday rotation of polarization plane confirms presence of this field and gives an estimate for it strength. The large-scale magnetic field component is almost parallel to the central galactic plane, and its direction is close to the azimuthal direction. The magnetic field strength is about several μG, i.e. magnetic field energy is close to equipartition with turbulent flows in the interstellar medium (see for a review, e.g., [1]).

Observations supporting the above understanding of galactic magnetism were obtained mainly at Effelsberg and VLA at 4 wavelengths (about 3, 6, 18, and 22 cm. A new generation of radio telescopes, which includes LOFAR and forthcoming SKA, opens a new perspective to obtain instructive information concerning galactic magnetic fields. The main novelty here is that it becomes possible to observe polarized radio emission at many (hundreds and possibly thousands) wavelengths instead of few ones only. Importance of this novelty is obvious for experts (see below), the question is, however, how to use this new ability. The aim of this paper is to discuss available suggestions in this respect.

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2 Rotation measures and polarization angles

Starting points to use polarization data to get information concerning large-scale galactic magnetic fields are as follows. Synchrotron emission is polarized and its polarization angle is determined by magnetic field direction. If magnetic field is a small-scale random field, the emission becomes to be depolarized because of cancellation of many incomes with various polarization angles which contribute in one beam. In fact, the observed degree of polarization p (about 10–20%) is much lower than the initial one p_0 (about 70%) that gives a hint that a small-scale magnetic field b is superimposed on the large-scale one B, which leads to substantial depolarization. A simple estimate [2]

$$p = p_0/(1 + b^2/B^2) \tag{1}$$

tells that b is about two times larger than B. This estimate is supported by other available information (see for details [1]), however the point is that from one hand depolarization by small-scale magnetic field is far to be the only source of depolarization (see [2, 3]), and from the other hand anisotropic small-scale magnetic field can give polarization without large-scale one (so-called Laing effect – see, e.g., [3]).

Faraday rotation of polarization plane gives more direct information concerning large-scale magnetic field than just polarization. If polarized emission propagates through a slab with the line of sight magnetic field component $\mathbf{B}_{||}$, electron density n_e and thickness L, then its polarization angle ψ scales with λ as

$$\psi = \psi_0 + 0.81\ [\mathrm{rad\,m^{-2}cm^3\mu G^{-1}pc^{-1}}]\ B_{||} n_e L \lambda^2, \tag{2}$$

where the coefficient at λ^2 is known as rotation measure (RM).

An important point is that from the observational point of view ψ varies in the range $-\pi/2 \leq \psi \leq \pi/2$, while Eq. (2) does not take into account this constraint. This is known as $\pm k\pi$ problem. A natural resolution of the problem is to use such range of wavelengths, where $\mathrm{RM}\lambda^2 \leq \pi$ (Faraday thin source [4]) and include λ short enough to makes $\mathrm{RM}\lambda^2$ comparable with observational uncertainties. The range 3–22 cm fits more or less the requirements.

Basing on RM obtained observationally and known electron density, one obtains the line of sight magnetic field component only. Reconstruction of magnetic configuration in galactic disc as a whole requires fitting of a magnetic configuration model based on theoretical expectation from galactic dynamo to RM [5] or position angles [6] distribution in projection of galactic disc on the sky plane. This fitting is a highly non trivial task because the theoretical expectations are far to be very firm. Correspondingly, quite a lot of time and efforts are required to obtain a self-consistent model of galactic magnetic field from polarized observations.

3 Multiwavelength observations

The traditional procedure of magnetic configuration reconstruction from observational data has several substantial constraints. First of all, it does not take into account in an explicit form degree of polarization p and polarized intensity. A possible way to include such data in consideration is to fit a model to observed Stokes parameters $Q(\lambda^2)$ and $U(\lambda^2)$ [7].

A much more substantial point is that Eq. (2) implies that emission and Faraday rotation occur in separate regions at the line of sight so the case of so-called Faraday screen is considered. It happens, e.g., for Faraday rotation of radiation of extragalactic radio sources propagating through a nearby galaxy, say M 31, what can be used for reconstruction of magnetic field in such a galaxy [8]. A much more usual situation is, however, the case of radiation emitted and rotated in the same region in the galaxy in investigation. If such source is Faraday thick, polarization angle may deviate from the simple scaling Eq. (2) [3]. An important additional point is that LOFAR is constructed to observe at wavelengths of about 1 m and longer, so almost all spiral galaxies are expected to be Faraday thick in this spectral range.

If available observations cover a more or less homogeneous spectral range from several cm and up to 1 m and longer, there is an attractive option to fit a particular model of depolarization to available observations to obtain (provided a realistic distributions of electron density and relativistic electrons are somehow known) spatial distribution of magnetic field along the line of sight. Such possibility mentioned already in [9] remains, however, an attractive perspective only. In particular, one needs 25 times longer observational time to get data of comparable quality at 100 wavelengths than at 4 wavelengths. Multiwavelength observations of spiral galaxies are available at the instant for a quite narrow spectral range located at long wavelengths [10]. Expectation that future development of the observational basis will open a possibility to formulate and solve an adequate inverse problem for magnetic field distribution along the line of sight is supported by a positive experience in technique of inverse Doppler imaging in investigations of stellar activity [11] and helioseismology (e.g., [12]), but mathematical problems to be resolved remain very substantial.

4 Concept of RM Synthesis

A fruitful compromise, which allows to use multi-wavelength observations and avoid an extended usage of high-brow mathematical technique of inverse problem theory, was suggested as RM Synthesis in [13].

It was Burn [2] who noted that complex polarized intensity $P = Q + iU$ obtained from a radio source is related to the Faraday dispersion $F(\phi)$ (which is determined by emissivity and intrinsic position angle, see below) as

$$P(\lambda^2) = \int_{-\infty}^{\infty} F(\phi) e^{2i\phi\lambda^2} d\phi. \qquad (3)$$

Here the Faraday depth ϕ is defined by

$$\phi(z) = -0.81 \int B_{||} n_e dz'. \qquad (4)$$

Following Eq. (3), P is the inverse Fourier transform of F. Correspondingly, the Faraday dispersion function F is the Fourier transform $\hat{P}$ of complex polarized intensity

$$F(\phi) = \frac{1}{\pi} \hat{P}(k), \qquad (5)$$

where $k = 2\phi$.

The idea of RM Synthesis is to use multi-wavelength data in order to find Faraday dispersion F as a function of Faraday depth ϕ. Of course, Faraday depth is far to be the desired magnetic field (or at least its line of sight component $B_{||}$) as a function of position at the line of sight however the quantities are reasonably related one to the other to make finding of F an attractive destination (e.g., [14]). Comparison of various realizations of RM Synthesis in application to unresolved radio sources is presented in [15].

5 Wavelet based RM Synthesis

Realization of the attractive idea described above faces at least two obvious problems. From one hand, a straightforward understanding of Eq. (5) requires integration over the parameter λ^2 from $-\infty$ to $+\infty$ while according to its physical meaning $\lambda^2 > 0$. This problem can be resolved using the fact that the galactic magnetic field is symmetric in the respect to the galactic central plane. This symmetry gives a link between complex P for $\lambda^2 > 0$ and that one formally calculated for $\lambda^2 < 0$ [16]. Fortunately, exactly the same symmetry follows from the assumption that the source contains just one spectral detail in Faraday dispersion function [17]. The last assumption usually is exploited for RM Synthesis of unresolved radio sources.

From the other hand, performing a Fourier transform (even using symmetry argument), one needs to know the function for all values of λ^2 while in fact observations provide P for a limited spectral range $\lambda_{\min} < \lambda < \lambda_{\max}$. This problem can be in principle resolved by wavelet technique which allows to calculate contributions to the Fourier transform from each spectral range separately [16, 17]. Of course, a limited spectral range allows to isolate some spectral details in Faraday dispersion function only. Analysis performed in [18] shows that one can expect to isolate such details for which $\phi\lambda^2_{\min} \leq \pi$, i.e. galaxy is Faraday thin at least at the shortest wavelength. It means that using

LOFAR data RM Synthesis can give information concerning turbulent components of galactic magnetic field only. Direct investigation of large-scale galactic magnetic field requires forthcoming facilities of SKA. This result looks for the first sight slightly disappointing, however each telescope allows to observe only some feature of celestial body of an interest and nobody expects that an optical telescope allows to see something, say, inside the Sun. Nevertheless, analysis of [18] stresses the important role of short wavelength observations.

There are indications [19] that RM Synthesis can be used for observational identification of helicity, i.e. crucial driver of galactic dynamo.

6 Conclusions

Summarizing results from the above cited papers, we conclude that RM Synthesis looks as an important tool for investigation of magnetic fields of spiral galaxies. Long wavelength observations allow a limited application of the method, while the expected facilities of SKA should allow such application in the full extent. Of course, it is desirable to combine RM Synthesis with options based on solution of inverse problem for multi-wavelength observations. Of course, fitting of any models to observational data needs to adopt the model to the contemporary understanding of magnetic field symmetries in a celestial body of interest. For spiral galaxies that is magnetic field symmetry in respect to the central plane of the galaxy, however for, say, magnetic field of a jet such symmetry has to be isolated in a particular research.

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