

PHYSICS OF OUR DAYS

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Magnetic helicity and prospects for its observation in the interstellar medium

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Contents

Abstract. **Magnetic helicity is one of the integrals of nonviscous flows in magnetohydrodynamics that determines the number of linkages of magnetic field lines in a medium. It is among a number of helicities that characterize the degree of mirror asymmetry of velocity and magnetic fields. The helicities play a crucial role in driving the generation of large-scale magnetic fields in stars and spiral galaxies. Until recently, measurements of various helicities were based on astronomical observations of the Sun's active regions, but not in the Sun's deep layers where the solar dynamo is operative. Galaxies are transparent to some extent and are therefore very attractive in this sense for observing the helicity of its magnetic field. Theoretical advances and the first successful attempts at such observations are reviewed.**

Keywords: galactic magnetic fields, magnetic helicity, astrophysical observations, synchrotron emission, Faraday rotation, dynamo theory

1. Introduction

The world of everyday and laboratory physics around us are mirror symmetric with a high degree of accuracy, although one example of slight mirror symmetry violation is well known. According to Baer's Law, erosion takes place predominantly on the right banks of rivers flowing (in an arbitrary direction) in the Northern Hemisphere, whereas the left banks are more affected in the Southern Hemisphere. This is one of most well-known laws of geography, and the mirror symmetry violation is attributed to Earth's rotation and the Coriolis force, although a closer look into the literature (see, e.g., [1]) indicates that both the state of observational data and details of the phenomenon still leave much to be desired.

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Violations of mirror symmetry unrelated to Earth's rotation were discovered in the middle of the 20th century in physical processes with elementary particles, opening an epoch in studies of weak interactions (see, e.g., [2]). However, the world of weak interactions fills a very important but rather special subdomain of physics, and in many of its traditional branches, violations of mirror symmetry can be safely ignored.

It turns out that there is one more area of physics where violations of mirror symmetry play a big role, even larger than in the previous examples. It is the branch of physics studying the generation and evolution of large-scale magnetic fields in various celestial bodies. The most well-known phenomenon studied in this branch of science is the celebrated 11-year solar activity cycle. Approximately every 11 years, the Sun's dipole magnetic field changes sign, and the number of solar spots and other characteristics rendering on the Sun's surface the toroidal magnetic field, confined to the Sun's interior, oscillate with the same period.

In 1955, E Parker in [3] conjectured that the nature of the solar cycle is linked to mirror-asymmetric convective motions in the Sun's interior: there are somewhat more right convective vortices in one hemisphere, and there are more left vortices in the other one. As a result, the electric current $\mathbf{J}$ averaged over an ensemble of convective vortices acquires a component that is parallel (not perpendicular, as is commonly the case) to the magnetic field $\mathbf{B}$. Mirror asymmetry, measured by some pseudoscalar α, is needed to allow writing $\mathbf{J} = \alpha\mathbf{B} + \ldots$, i.e., the equality connecting the vector $\mathbf{J}$ with the pseudovector $\mathbf{B}$. As a result, the action of electromagnetic induction leads to self-excitation of a quasi-stationary magnetic field.

Parker dealt with namely such qualitative arguments, but 10 years later Steenbeck, Krause, and R'adler [4], physicists from the GDR, independently came to the same ideas and developed electrodynamics for mirror asymmetric media.

Since then, several generations of researchers have extended these ideas to explain the generation of magnetic fields in various rotating celestial bodies: planets, stars, and spiral galaxies [5]. As a whole, this branch of science is conventionally called the dynamo theory. The word 'theory', although it does not fully correspond to the present state of the problem — already since the beginning of the present century, the dynamo can be reproduced in laboratory conditions (see, for example, review [6]) — is firmly associated with research aimed at the phenomenon of the dynamo, for a difficult problem in studying it is the measurement of the degree of mirror asymmetry in convection or turbulence.

Indeed, the simplest measure of mirror asymmetry is the quantity $h = \mathbf{V} \cdot \mathrm{rot}\, \mathbf{V}$, which is a pseudoscalar. It is called the density of hydrodynamic helicity, and its volume integral is the hydrodynamic helicity. Among other things, it is a motion integral in fluid dynamics [7, 8], proportional to the linking number of vortex tubes. This topological interpretation goes back to Gauss, but its modern state is due to V I Arnold (historically, he presented this fundamental result at a small conference in Dilijan and published it in proceedings that were difficult to access; see one of the latest reprints in [9]).

In order to measure hydrodynamical helicity directly, one needs to know three velocity components and be able to differentiate them. However, in astronomy, as well as in many other branches of physics, velocity is measured through the Doppler effect, which gives only one (longitudinal) of its components. This is the reason why measurements of hydrodynamical helicity, even under laboratory conditions, are anything but simple.

At first glance, the situation seems hopeless, and any in-depth theoretical development lacking direct support from observations or measurements is a dangerous endeavor.

The first constructive idea on how to overcome this difficulty came at the end of the 20th century and was formulated by Seehafer [10]. The idea exploits the fact that the degree of mirror asymmetry in a medium may be governed not only by the Coriolis force and measured by hydrodynamical helicity, but also by the magnetic force and measured by the current helicity density $h_j = \mathbf{BJ}$. The question of which of the contributions to mirror asymmetry prevails on the Sun is the subject of hot debates. At present, the opinion of the largest share of specialists tends toward the statement that the magnetic contribution prevails (this is the so-called Babcock–Leighton scheme), but for us now it is not essential. It is only important that the current helicity can be measured much more easily than can the hydrodynamical helicity: the Zeeman effect, used to measure magnetic fields, in particular on the Sun's surface, in principle allows one to measure all three magnetic field components (and not only the component perpendicular to the line of sight, as done in the simplest cases). In Ref. [10], Seehafer paid attention to the fact that the current helicity density is the sum of three components, which are equal on average in a homogeneous and isotropic medium; in order to compute one of them, it suffices to have a magnetogram obtained for a region of the solar surface, so that there is no need to compute derivatives in the direction of the Sun's interior. At present, several research groups are systematically observing the current helicity in the Sun's active regions using this approximation. This is done most systematically at the Huairou solar station close to Beijing, where the space-latitudinal distribution of current helicity was monitored for two solar cycles [11].

Alongside the current helicity (current line linking the coefficient), the mirror asymmetry of magnetic fields can be naturally characterized by one more quantity — the magnetic helicity, i.e., the field line-linking coefficient. Different from the current helicity, the magnetic helicity is a motion integral [12]. The magnetic helicity is expressed through the integral of $h_{\mathrm{m}} = \mathbf{AB}$, where $\mathbf{A}$ is the magnetic field vector potential. Since $\mathbf{A}$ is defined up to a gauge, the density of magnetic helicity, generally speaking, can be changed by the choice of the gauge (but its integral is gauge invariant). However, in practice, in problems concerning magnetic field generation, the gauge is to a sufficient extent fixed by the assumption that the large-scale magnetic field is close to an axisymmetric one, and that the small-scale magnetic field is statistically homogeneous and isotropic [13]. As a result, one can even obtain the spectra of magnetic helicity [14].

It is gradually becoming possible to advance methods of computing hydrodynamical helicity from helioseismology data [15] and even the net contribution from both sources of mirror asymmetry to magnetic field generation [16].

2. Observations of magnetic fields in the interstellar medium

The achievements of solar physics in the observation of mirror asymmetry of magnetic fields and motions are impressive, and yet they give only an indirect idea as to what exactly happens in the region where the solar dynamo is operating. All agree that the solar dynamo operates under the Sun's surface. The opinions start to diverge with respect to what precisely can be said about the Sun's interior, in particular, about the lower boundary of the convective zone. On the other hand, all the helicity tracers discussed above characterize processes on or just above the Sun's surface. The Sun's deeper layers are nontransparent, and we cannot directly observe subsurface the magnetic field distribution. Spiral galaxies are void of this disappointing drawback.

Galaxies in the first approximation are transparent in the optical band and, more importantly, in the radio band, because namely in this band can their magnetic fields mainly be observed. In particular, the Milky Way, where we live, is such a galaxy. In fact, extragalactic astronomy is possible just because other galaxies can be observed through the Milky Way. Galaxies possess a large-scale magnetic field, which is thought (see, for example, [17]) to be excited also by the dynamo mechanism. For this reason, a natural extension of helicity observations on the Sun is the search for ways to observe helicity in galaxies, and, above all, in the Milky Way.

The Zeeman effect plays a subordinate role in observations of magnetic fields in galaxies — Doppler broadening of spectral lines is too large to allow easy observation of Zeeman splitting on its background. Therefore, the main volume of our knowledge on the structure of galactic magnetic fields is gained in the analysis of observational data on the measure of Faraday rotation (RM) of synchrotron emission in a magnetized interstellar medium, which is detected by a change in the observed polarization plane as a function of wavelength λ:

$$\mathrm{RM} = \frac{\mathrm{d}\chi}{\mathrm{d}(\lambda^2)}\,. \tag{1}$$

The polarization angle χ is set by the phase of complex-valued polarization

$$P(\lambda^2) \equiv Q + \mathrm{i}U = p_0 \int_{-\infty}^{\infty} \epsilon(z, \lambda) \exp\left[2\mathrm{i}\big(\psi(z) + \phi(z)\lambda^2\big)\right] \mathrm{d}z\,, \tag{2}$$

where Q and U are the Stokes parameters, and $\epsilon(z)$ is the density of synchrotron emission. In the framework of standard views on the spectral distribution of cosmic rays n_c, one can assume that $\epsilon(z) \sim n_c B_\perp^2(z)$ (admittedly, we do not consider here all details of depolarization of synchrotron emission in the interstellar medium; for more details, see, for example, [18]). Synchrotron emission initially possesses some degree of polarization p_0, with the polarization angle being determined by the direction perpendicular to $\mathbf{B}_\perp$ (magnetic field in the plane perpendicular to the line of sight). The initial polarization angle is $\psi = \arctan(B_y/B_x) + \pi/2$. The net rotation is governed by the Faraday depth

$$\phi(z) = -K \int_z^{\infty} n_e(s) B_\parallel(s)\, \mathrm{d}s\,, \tag{3}$$

where n_e is the density of thermal electrons, $K = 0.81\ \mathrm{m}^{-2}\ \mathrm{cm}^3\ \mu\mathrm{Gs}^{-1}\ \mathrm{pc}^{-1}$, and $B_\parallel$ is the magnetic field along the line of sight. The total intensity of synchrotron emission is given by the expression

$$I = \int_{-\infty}^{\infty} \epsilon(z)\, \mathrm{d}z\,, \tag{4}$$

allowing computations of the polarization degree $p = |P|/I$. Expressions (1)–(4) for polarized emission at some point (x, y) in the sky along the line of sight are written along the direction z to the observer located at $+\infty$ (see Ref. [19] on the consistency of definitions (1)–(3)).

However, the Faraday rotation measure gives information only on the mean value of the magnetic field longitudinal component. The situation seems to be almost hopeless; however, a step forward can be made by analyzing a function of Faraday dispersion [20], which is obtained by inverting the integral transformation (2) in the form

$$F_{\mathrm{syn}}(\phi) = \frac{1}{2\pi} \int_{-\infty}^{\infty} P(\lambda^2)\, \exp(-2\mathrm{i}\phi\lambda^2)\, \mathrm{d}(2\lambda^2)\,. \tag{5}$$

This method is called RM synthesis [21] and was later substantially extended, in particular, in Refs [22–25] with account for the specifics of modern radio telescopes [26] and laid the foundation of numerous attempts to recover the three-dimensional structure of a magnetic field. A fundamental difficulty lies in the inversion of the dependence $\phi(z)$. In essence, just as in medical tomography, the question is on the reconstruction of a three-dimensional magnetic field from sounding data. The approach bears the name tomography, and since our ability to look at galaxies from different sides is very limited, we are talking about 2.5D tomography.

2.1 Methods to detect magnetic field helicity

The first ideas on how to detect the helicity of galactic magnetic fields relied on fluctuations in cosmic microwave background radiation [27] or the properties of cosmic rays if their source is known [28]. However, as mentioned by the authors of these ideas, they call for highly accurate observational data, which are practically unavailable at present.

Hope arose when it came to rigorous and massive numerical modeling of magnetohydrodynamical (MHD) turbulent fields and statistical analysis of depolarization effects. Volegova and Stepanov [29] constructed model distributions of homogeneous isotropic magnetic fields with a controlled magnetic helicity level and synthesized on their basis maps of polarized emission. Their results suggest that the influence of magnetic helicity may be seen in the asymmetry of the joint probability density for RM and p. Figure 1 shows scatterplots, i.e., planes containing points with coordinates that correspond to the Faraday rotation measure and polarization degree for a given line of sight passing through a magnetized medium. These scatterplots are constructed for two limiting cases of high positive and high negative magnetic helicity, and for the case of zero helicity. A quantitative estimate of this effect has been made computing the coefficient of crosscorrelation between two-dimensional distributions of Faraday rotation and synchrotron emission polarization degree. The sign of the correlation coefficient

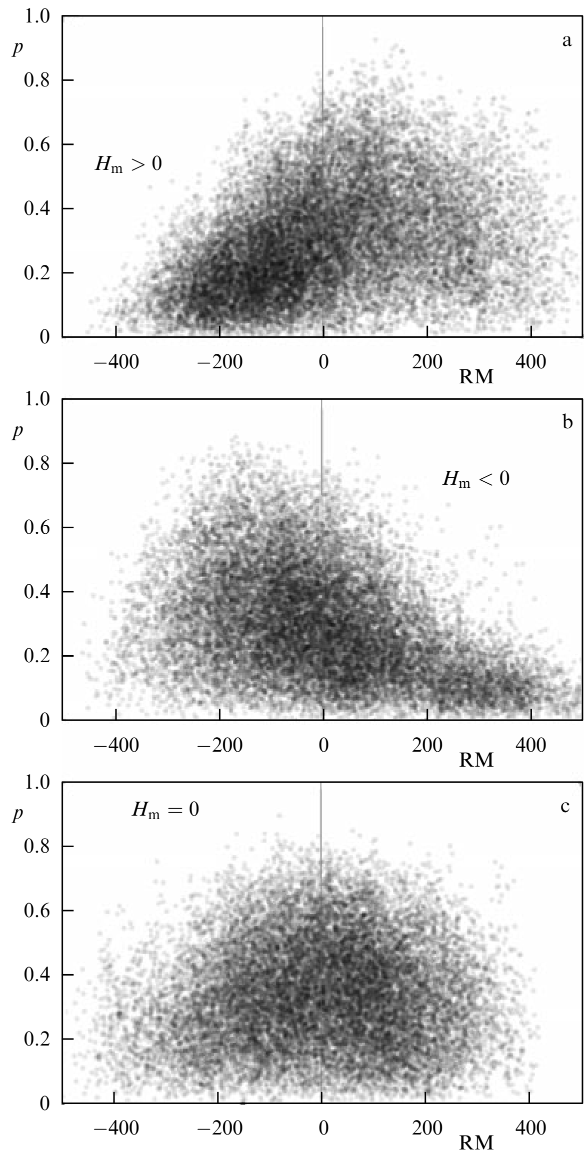

Figure 1. Scatterplots of model distributions of the Faraday measure and polarization degree for different values of magnetic helicity: $H_m > 0$ (a), $H_m < 0$ (b), and $H_m = 0$ (c) (from data in Ref. [29]).

turned out to coincide with the sign of the magnetic helicity, and its absolute value reflected the relative level of magnetic helicity. However, the helicity is never large in practice — it is difficult to ensure that all magnetic field loops are, let us say, right. The largest value of correlation, on the order of 0.4 ± 0.1, was obtained in maximally helical fields at a certain wavelength, such that for given medium parameters Faraday rotation turns the polarization plane through an angle close to 2π. If magnetic helicity is weak, the deviation of correlation from zero is statistically insignificant, and the scatterplot becomes symmetric.

The method does not require reconstructing the three-dimensional structure of the magnetic field, which is its obvious advantage from the perspective of applying it to the data from soundings of galaxies by discrete radio sources. Indeed, the method is based on statistical processing, and can be applied to real data with a known signal-to-noise ratio and other details. Taking into account the ability of modern radio telescopes to measure synchrotron emission in a broad wavelength band, one may hope to detect the effect, even though this task seemed far from simple initially.

It is certainly tempting to take further steps and find more pronounced correlations of quantities related to synchrotron emission polarization. As an alternative approach, Ref. [30] proposed that magnetic helicity be detected based on the alignment of the polarization plane, defined by the angle χ, and the gradient of the squared Faraday rotation measure. However, computations of gradients of observed Faraday rotation, characterized by a large uncertainty, are an exceptionally unreliable procedure. Possibly, this or other internal limitations of the method thus far have not allowed the detection of magnetic helicity [31] based on real data.

The correlation between polarization degree and the Faraday rotation measure relies on the manifestation of the anomalous depolarization effect described, for example, in Ref. [18], together with other basic mechanisms of depolarization. This effect eluded particular attention earlier, for it had not been considered in the magnetic helicity context. Based on an exact solution found in Ref. [19], it has been shown that anomalous polarization–depolarization in a Faraday extended source can indeed be explained by a helical magnetic field distributed along the line of sight. The effect of helicity on polarized emission properties can be described by a simple example. Suppose the magnetic field $\mathbf{B}_{\parallel 0}$ along the line of sight is constant and homogeneous, and the component $\mathbf{B}_{\perp 0}$ perpendicular to the line of sight is also constant in absolute value, but turns along the line of sight, forming a helix with a step κ (Fig. 2). The magnetic helicity of such a field is $H_{\mathrm{m}} = \kappa^{-1} B_{\perp 0}^2$. Consider propagation of a polarized wave along the direction z. Two effects need to be taken into account: Faraday rotation and the turn of the initial emission plane because of the turn of the magnetic field on its own. For a certain combination of interstellar medium parameters (densities of cosmic rays and thermal electrons), RM, λ, and H_{m}, it follows that both rotations coincide in magnitude and direction. In this case, depolarization is minimal. In contrast, if Faraday rotation is opposite to the helix turn, the emission is strongly depolarized. The polarization in such a magnetic field can be computed analytically (Ref. [19] gives expressions for bi-helical magnetic fields). The distributions shown in Fig. 3 indicate that in the case of a passing magnetic helicity the peak of polarized emission enters a zone where formally $\lambda^2 < 0$ and it is, naturally, unobservable, whereas the observed emission is strongly depolarized. The problem of how to formally extend observations for negative λ^2 is a key one in computations of the integral in (5) in tomographic methods; see Ref. [32] on how it can be overcome.

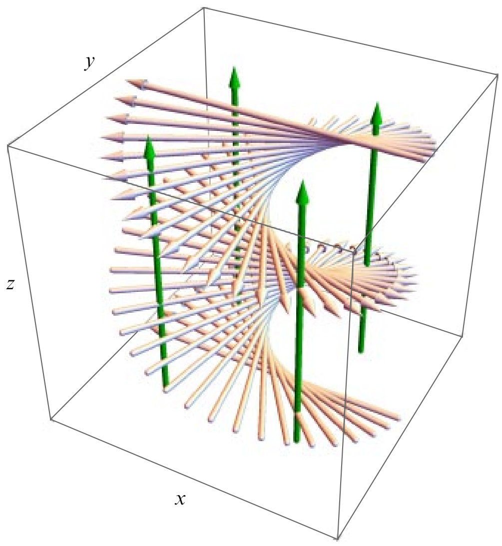

Figure 2. (Color online.) Model configuration of a helical magnetic field. The parallel arrows show the direction to an observer along the line of sight; the rotating arrows show the field rotation in the plane perpendicular to the line of sight.

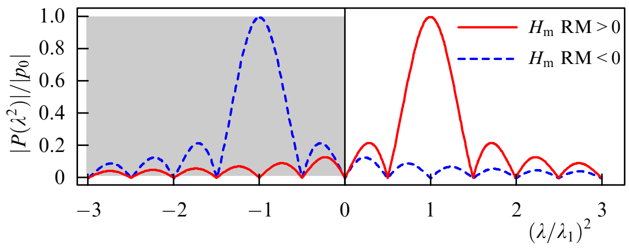

Figure 3. Dependence of polarized emission intensity on the wavelength of observations for various values of H_{m}RM. The region inaccessible to observations is shaded gray.

Thus, the effect enabling detection of magnetic helicity in galaxies is an expression of anomalous depolarization. Note that this effect was successfully adapted to conditions imposed by observations of synchrotron emission in the solar corona [33] and estimating the spectral distribution of magnetic helicity [34].

3. Observational data processing

A theoretical analysis of the effect of magnetic helicity on the properties of polarized emission and tests carried out on synthetic signals allows one to formulate necessary requirements for observational data. In the ideal case, the desired data set would include the distributions of Faraday measure and intensities of total and polarized emission. Furthermore, the wavelength of observations should be sufficiently large for the effect to be detectable, but not too large to rule out that depolarization reduces the signal to the noise level. The Faraday measures of extragalactic sources are among the most reliable data on the large-scale magnetic field in the Galaxy. It is indeed so if the estimate of the mean magnetic field parallel to the line of sight is considered. However, the

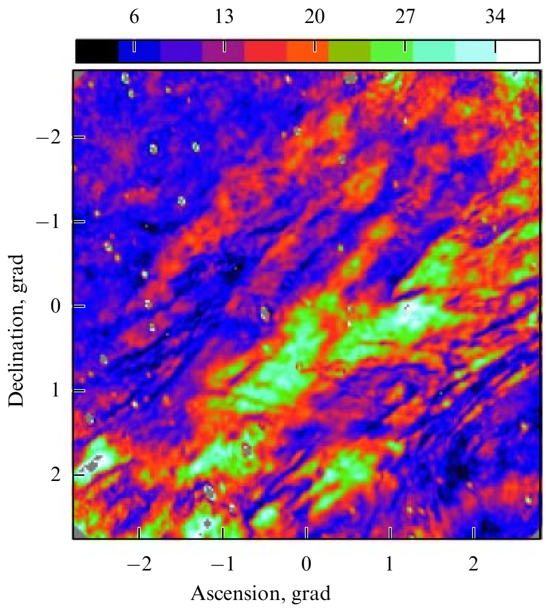

Figure 4. (Color online.) The distribution of the intensity of the maximum in $F_{\rm syn}^{\max}$ taken at the Faraday depth $\phi^{\max}$. The region of observations is about $5.5° \times 5.5°$. The center is directed to the galaxy IC342 ($\alpha = 03^{\rm h}46^{\rm m}48.5^{\rm s}$, $\delta = +68°05'46''$, $l = 138.1726°$, $b = +10.5799°$).

magnitude and direction of the perpendicular magnetic field elude detection, because it is difficult to separate the contributions to polarization from the source and interstellar medium in the Galaxy.

Great hopes come from surveys of diffuse polarized emission in galactic and intergalactic space. Observations through the Planck cosmic mission open wide perspectives for studying the global and turbulent structure of the galactic magnetic field (see review [35]). Many results are still in the development phase, but preliminary analysis of these data in comparison with galactic rotation measures [36] in all probability detects the helicity of the magnetic field in our Galaxy [37]. J West presented this result at a conference in May 2018, and her talk is, apparently, the first clear statement on the feasibility of such research (a full description is being prepared for publication).

Modern terrestrial radiotelescopes occupy a niche on their own in extending the observational base and also offer material for searching for traces of magnetic helicity. Spectra of interstellar MHD-turbulence, based on measurements of the intensity of total synchrotron emission with the help of the LOFAR radiotelescope have already been obtained. Very recently, the polarized emission of the galactic magnetic field was recorded at frequencies of 115–178 MHz ($\lambda = 1.7-2.6$ m), which are very low for the radioastronomy of magnetic fields [38]. The uniqueness of these data is that at such frequencies, as a rule, one may only count on detecting strong point sources. Nevertheless, a signal was detected that is related to diffuse emission in the interstellar medium of our Galaxy. The observations are presented as a data cube — the dependences of $F_{\rm syn}$ on two angular coordinates and ϕ. Such a representation is commonly referred to as an RM-cube [1]. Figure 4 shows the intensity distribution of the maximum of $|F_{\rm syn}^{\max}|$ over the Faraday depth ϕ. The largest extragalactic source in this portion of the sky is the galaxy IC342; angular coordinates are counted from its center. Despite its substantial angular size of about 0.5°, the galaxy proper is not visible in this wavelength range, and everything is determined by the interstellar medium of the Milky Way.

[1] The data are available online in the VizieR catalogue at URL https://cdsarc.u-strasburg.fr/viz-bin/qcat?J/A + A/597/A98.

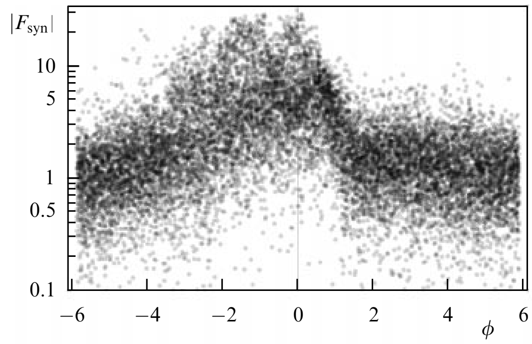

Figure 5. Scatterplot of $\phi^{\max}$ and $|F_{\rm syn}(\phi^{\max})|$ based on the RM-cube data of Ref. [39].

The application of the method proposed in Ref. [29] to the RM-cube data needs additional clarification. Let us consider $\phi^{\max}$, the Faraday depth where the polarization maximum along the line of sight is observed, as the measure of Faraday rotation RM. If regions with strong pointwise sources are excluded, the net intensity I can be considered constant, and $F_{\rm syn}$ can be used instead of polarization degree p. As mentioned in Refs [19, 29], such an approximation is possible, although it reduces the resulting effect.

Thus, for each point in the map shown in Fig. 4, a scatterplot of quantity $\phi^{\max}$ and the related $|F_{\rm syn}(\phi^{\max})|$ can be created (Fig. 5). The distribution shows a clear asymmetry relatively $\phi = 0$. For sources with $1 > \phi > 0$, a sharp depolarization is observed, and sources with $\phi < 0$ are distributed over a broad interval, so that their polarization disappears only for $\phi \lesssim -5$. Bearing in mind the effect of anomalous depolarization and comparing the results of simulated distributions, one can conclude that the magnetic field with a negative helicity prevails in this part of the stellar sky. One should remember that in the wavelength range used in observations only polarized emission from the region nearest to the observer is recorded. Therefore, this result is only pertinent to the Sun's vicinity, measuring several hundred parsecs. To detect the helicity of a magnetic field in the entire Galaxy, one needs observations for the whole celestial sphere and at shorter wavelengths.

4. Conclusions

We therefore see that only now are the first real possibilities of directly observing the magnetic helicity of the galactic magnetic field beginning to emerge. In other words, one more important step is made to ensure that views on magnetic field generation by the astrophysical dynamo rely not only on theoretical estimates, but also on the data of astronomical observations of the medium generating the magnetic field.

At the present stage of the problem solution, one can claim with certainty that the reality of the effect giving a theoretical feasibility to detect the helicity of the galactic magnetic field is confirmed. The development of an observational network also opens new approaches to analysis. Measurements of polarization in a broad frequency range and in large regions of the stellar sky are being carried out. These data are more and more often becoming openly accessible, which certainly attracts the interest of a wider research circle. Of course, one can hardly hope that the inverse problem of reconstructing a magnetic field three-dimensional structure based on integral projections will get a comprehensive solution in the foreseeable future. However, statistical characteristics, including those caused by the violation of magnetic field mirror symmetry, can already be detected. A new result in this area is demonstrated by us on the basis of LOFAR longwave measurements for a sky segment of $5.5^\circ \times 5.5^\circ$. Much remains to be done for a reliable statement on the helicity of the global magnetic field in the Galaxy, both in the direction of improving statistical fidelity of observations and in model construction. One thing raises no doubt — the problem of detecting magnetic helicity based on radio observational data is already entering the field of modern radioastronomy and the astrophysics of cosmic magnetic fields.

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