Reconstructing magnetic fields of spiral galaxies from radiopolarimetric observations

Shneider, C.

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English Summary

Cosmic Magnetism in brief

As a young person you may have displayed interest in fridge magnets and been intrigued by a compass. Perhaps you may also have tinkered with bar magnets and iron filings in which case 7.1 would be familiar.

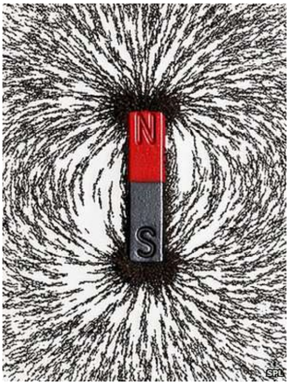

Figure 7.1: Bar magnet with iron filings tracing the dipole field lines.
Source: http://www.bbc.com/news/science-environment-25946734.

In fact, Fig. 7.1 illustrates a dipole magnetic field. Such a field configuration serves as a simple description of the Earth's magnetic field. If this were a compass dial, the 'N' and 'S' labels in Fig. 7.1 would indicate the direction of Earth's north and south magnetic poles. However, the 'N' and 'S' labels on the compass actually correspond to the south and north poles of the compass needle itself, respectively, as it is opposite poles that attract. A dipole field is also the dominant mode in planets (in the solar system) which have a magnetic field. The presence of a planetary magnetic field both shields us from high-energy radiation from space, thereby protecting our fragile atmosphere and, at the same time, conducts the greatest light show on Earth - the Aurora Borealis/Australis, depending on whether one is in the northern or southern hemisphere. The sun's magnetic field, besides heating the outer atmosphere of the sun, contributes to our space weather through solar wind, the release of coronal mass ejections (CME), and solar flares which can affect space missions, disrupt radio and satellite communication, and overload power grids. Although bacteria, arthropods, mollusks, and a very large number of vertebrates had long obtained their bearings via Earth's magnetic field, it was not until the 11th century that a magnetic compass was first used for navigation by humans. Sixteen hundred was a landmark year for terrestrial magnetism with William Gilbert's treatise "On the Magnet and Magnetic Bodies, and on the Great Magnet the Earth" providing an experimental basis for the notion of 'Earth as a magnet'. At the close of the 17th century, Edmond Halley[1] boldly charted the magnetic spatial variation in a region of the Atlantic spanning 52° north and 52° south. The expansion of our 'magnetic universe' was dramatically accelerated in the 20th century by the discoveries, among notable others, of solar magnetism in 1908, galactic magnetism in 1949, and extra-galactic magnetism in 1972. Magnetic fields are ubiquitous throughout the universe: on planets (where there is a molten core), stars (of which collapsed stars have the highest known field strengths in the universe - about a billion times the strength of a medical MRI), accretion disks, jets, interstellar clouds, supernova remnants, the tenuous gas between stars, galaxies, the highly rarefied filamentary gas between galaxies, galaxy clusters, and at the largest scale of connecting galaxy clusters. Their study over these vast spatial and temporal scales comes under the umbrella term of *Cosmic Magnetism*. For further popular reading on Cosmic Magnetism please consult, for example, ***Extreme Cosmos*** by Bryan Gaensler and the Square Kilometre Array Cosmic Magnetism website: https://www.skatelescope.org/magnetism.

Magnetic fields in galaxies

In this PhD thesis we focus on galactic magnetic fields as they thread the interstellar gas. Magnetic fields are very important since they affect the dynamics of the gas as well as the gas distribution. The magnetic field strengths dealt with here (micro-Gauss, μG) are several thousand times stronger than those in our brain but still several million times weaker than a typical fridge magnet. The field's structure is also far from the idealized dipole field configuration shown in Fig. 7.1. Broadly speaking, magnetic fields are classified according to whether they occur on large scales or small scales. A large-scale field is a field that typically follows the spiral shape of the gaseous arms of a galaxy as in Fig. 7.2 and extends to at least several thousand light years. In the left-most panel of Fig. 7.2, the small dashes denote the measured orientation of the large-scale magnetic field which visually traces the orientation of the spiral arms of the galaxy. A small-scale magnetic field, on the other hand, is at spatial scales of turbulent processes that occur within the spiral arms, and extends over distances of at most several hundred light years. This distance is still quite vast when one considers that the Earth is located at only a bit over eight light

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[1] Of Halley's Comet.

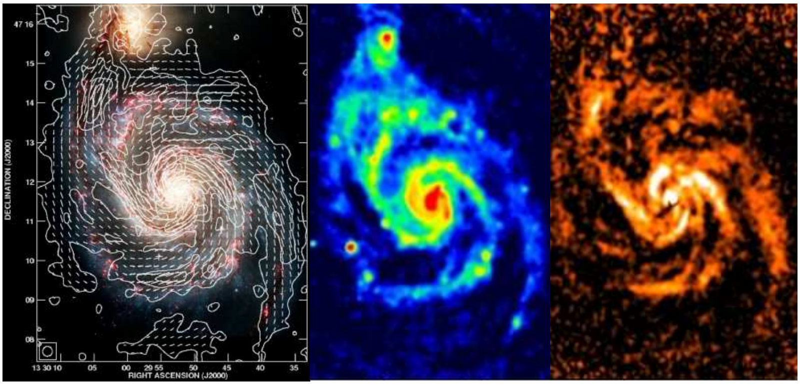

Figure 7.2: A spiral galaxy shown with a color scheme for (left) optical light, (center) total radio radiation with red denoting high intensity values, and (right) polarized radio radiation with white denoting high polarized intensity values. Images reproduced from the Atlas of Galaxies (MPIfR Bonn) available at http://www.mpifr-bonn.mpg.de.

minutes from the Sun[2]. Stellar explosions (supernovae) in the spiral arms yield the largest source of energy input and, consequently, stir up turbulent processes in the interstellar gas most vigorously. In analogy with a cosmic tsunami wave measuring 200 billion Earth diameters across, energy from a supernova is cascaded to ever smaller scales via whirling turbulent motions in the wave until about 10 Earth diameters is reached at which scale the energy is finally dissipated as froth. The small-scale magnetic field thus acquires the imprint of this energy distribution across spatial scales or energy spectrum.

Magnetic fields are invisible lines of force so how is it possible to detect their presence? The answer is provided by the interaction between the magnetic field and highly energetic particles called cosmic rays[3]. Upon encountering magnetic fields, cosmic rays begin to spiral around the field lines (e.g., as in Fig. 7.1), emitting a type of radiation known as synchrotron radiation in the process. The central panel of Fig. 7.2 reveals a galaxy in synchrotron radiation. This radiation occurs at the radio frequency range of the electromagnetic spectrum with frequencies typically higher than those carried by FM radio and TV signals but still many thousands of time smaller than the frequency of visible light[4]. Hence, *radio astronomy* is very important for the study of cosmic magnetic fields.

A key aspect of this radiation is that it is highly linearly polarized, meaning that the electromagnetic wave oscillates with a certain orientation as it moves along a straight path (i.e., not in a circle). As illustrated in Fig. 7.3, light streaming from the flashlight is unpolarized as it is composed of a sum of electromagnetic waves propagating in random

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[2] A coincidence among units allows for a simple distance analogy: if the Earth-Sun distance is scaled to one inch, then the light year on this scale corresponds to one mile.

[3] These are not actual ‘rays’ which are names given to photons of different energies (e.g., X-rays) which have no intrinsic mass but are rather particles with an intrinsic mass. Some of these particles can achieve ultra high energy levels making their impact comparable to that of a baseball pitched at 60 mph (97 kph).

[4] Just as all electromagnetic waves, radio waves travel at the speed of light.

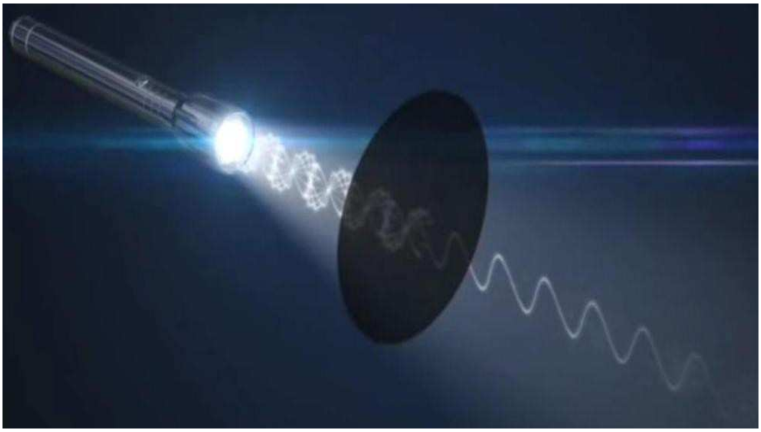

Figure 7.3: Schematic of polarization. Still from an animation on polarized light available from the European Southern Observatory at https://www.eso.org/public/videos/polarisedlight1. Credit: ESO/L. Calçada.

directions. However, when a filter (represented by the dark filled oval) that transmits only vertically polarized light is placed in the beam's path, the emerging light behind the filter oscillates straight up and straight down in the example shown here[5]. Hence, the electromagnetic oscillations are restricted to move only along this vertical plane in space and no other. This light is thus completely polarized. Since the orientation is both up and down there is no single 'direction' but rather a bi-direction. This is the reason for the dashes in the left-most panel of Fig. 7.2 instead of vectors. Were oscillations with a different orientation to hypothetically leak through the filter, the polarization would become 'diluted' and so partially polarized. This naturally leads to the notion of the degree of polarization which indicates how much polarization there is or, equivalently, to what extent or degree the signal is polarized. Returning to our discussion on cosmic rays and magnetic fields, a large-scale field would result in synchrotron emission from all neighboring cosmic rays which is closely synchronized in orientation, while for a small-scale field such neighboring synchrotron emission would already be randomly oriented. From this consideration we might already anticipate a higher degree of polarization from large-scale magnetic fields than from small-scale magnetic fields. Examining the right-most panel of Fig. 7.2 reveals a high degree of polarization tracing the spiral arms coinciding with the presence of the large-scale magnetic field.

Moreover, studies of magnetic fields in other galaxies, including galaxies that may be morphologically similar to our own Galaxy, provide a 'bird's eye view' of global magnetic field structures that may indeed be zoomed-out versions of the global magnetic field structure of the Milky Way. In contrast, studies of the Milky Way provide spatial detail that is unrivaled by any other galaxy.

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[5] What is shown is actually the electric oscillations of the electromagnetic wave; the magnet oscillations are always perpendicular to the electric oscillations

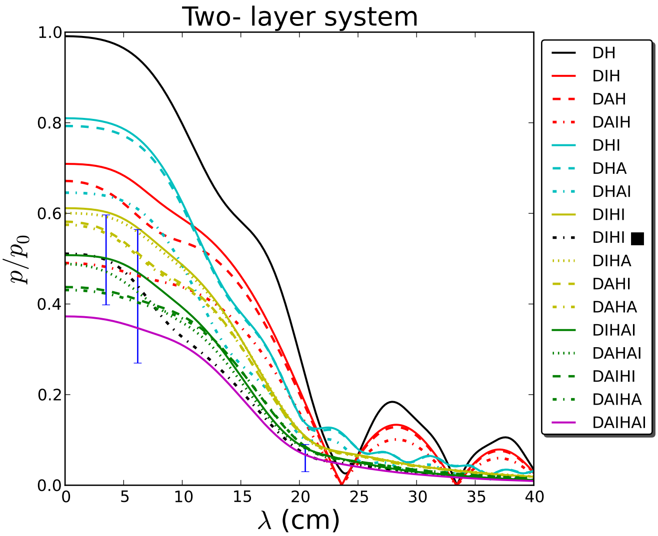

Figure 7.4: Simulation of the resulting degree of polarization of synchrotron radiation as a function of observing wavelength for all possible magnetic field configurations based on our approach.

Contributions of this thesis

In this thesis we reconstruct properties of magnetic fields in spiral galaxies by means of the polarization of synchrotron radiation. The goal of this research project has been to infer the structure of the magnetic field across various spatial scales in our own Galaxy (Chapter 2) and the strength and structure of the magnetic field in other galaxies (Chapters 3 - 5).

In Chapter 2, we use novel methods to simulate both total synchrotron intensity and polarized synchrotron intensity for our own Galaxy by varying certain properties of the numerically generated turbulent magnetic field and interstellar gas. We then compare the resulting distribution of structure across spatial scales between these synchrotron intensities on the one hand, and turbulent magnetic fields on the other. We find that total intensity traces the turbulent magnetic field in terms of such a distribution of structure but that uncertainties in the measurement make actual predictions unlikely. A further prediction of our model is that for certain frequencies at which observations are simulated, the polarized intensity acquires two different distributions of structure, instead of a single distribution. The scale at which the break occurs has a frequency dependence. This, in turn, can serve as a possible marker for establishing turbulence parameters.

In Chapters 3 & 4, we focus on extracting information on large- and small-scale magnetic fields from degree of polarization maps determined for a specific galaxy at several observing frequencies (or, similarly, observing wavelengths). We, therefore, establish a mathematical framework for describing the simultaneous influence of several physically relevant mechanisms on the measured degree of polarization of the synchrotron signal as it propagates through this galaxy. A preliminary small region study was first performed as a proof of concept of our methods. All possible unique model combinations using our methods were applied as shown in Fig. 7.4. This figure is a plot of the degree of polarization on the y-axis versus the observing wavelength (in centimeters) on the x-axis. The legend displays the different models. The blue solid vertical bars denote the actual measured values along with the associated uncertainty in those measurements. Curves passing through all of the data are more plausible than the other models. We also model the galaxy as a multilayer sandwich composed of varying interstellar gas layers. Subsequently, we applied our methods to model the entire galaxy and were able to make robust predictions for large- and small-scale magnetic field strengths.

In Chapter 5, we model so called ‘X-shape’ magnetic fields in a galaxy for which excellent multiwavelength data are available. It has recently been realized that at the outskirts of galaxies there can be large-scale vertical magnetic fields that point away from the galaxy. As this configuration is thought to be common in spiral galaxies, the inclusion of such complex geometries is necessary. Our ab-initio model yields large-scale magnetic field strengths consistent with literature values but requires additional complexity to fit the data well.