Mapping Galactic Magnetic Fields using Faraday Rotation Measurements

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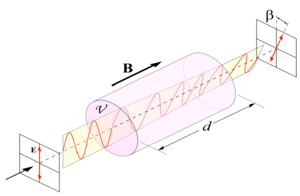
Introduction

Large scale structures of galactic magnetic fields can be determined through observations of linearly polarized radio waves from intergalactic and extragalactic sources.

Knowledge of the structure of galactic magnetic fields is an important aspect in our understanding of galaxy formation.

Faraday Rotation

Rotation of linearly polarized light as it propagates through a dispersive medium in the presence of an external magnetic field.



The angle of rotation is dependent on the parallel component of the magnetic field, the distance travelled, and a frequency-dependent proportionality constant for the medium called the Verdet constant.

Light in the ISM

Free electrons in the interstellar medium (ISM) give it some properties of a very diffuse plasma. Over astronomical distances dispersive effects of the ISM is detectable in radio waves.

A **cold electron plasma** can model the ISM. It assumes that electrons are the only mobile charges in a sea of fixed ions. Two important measurements can be explained using this model.

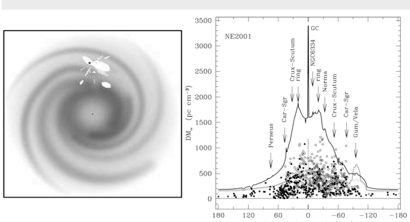
Dispersion Measure

- Plasma frequency depends on electron density n_e.
- Dispersion relation shows that the group velocity depends on the frequency and the plasma frequency. Frequency-dependent time delay.
- Leads directly to the **dispersion measure (DM)**

$$\mathrm{DM} \equiv \int_0^L n_e dL$$

- In practice, the travel time is unknown, and the DM is found using measurements taken at multiple frequencies.

If the distance to a source is known, the DM can be used to determine the average electron density between the source and observer.



Rotation Measure

- Dispersion relation for *circularly polarized* waves depends on the cyclotron frequency of the parallel component of external magnetic field (in addition to frequency and plasma frequency).
- When an external magnetic field is present, the left and right circular polarization modes have different phase velocities.
- Causes a rotation of linearly-polarized light (sum of equal part left/right circular polarized light).

$$\Psi = \mathrm{RM}\ \lambda^2$$

Where the **rotation measure** is defined as

$$\mathrm{RM} \equiv \frac{e^3}{2\pi m_e^2 c^4} \int_0^L n_e B_{\parallel} dL$$

- The initial polarization angle is unknown, so polarization angles of multiple frequencies are used to determine the RM.

RM's depend on the average electron density, and the average parallel component of the magnetic field between a source and observer.

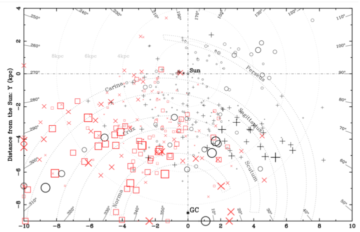


FIG. 1.— The RM distribution of 388 pulsars with $|b| < 8°$, projected onto the Galactic Plane. The linear sizes of the symbols are proportional to the square ro[ot] of the RM values, with limits of 9 and 900 rad m^{-2}. The crosses (+ and ×) represent positive RMs, and the open circles and squares represent negative RMs. Ne

If the distance to a source, and the average electron density is known, RM's can be used to find the average magnetic field.

$$\langle B_{\parallel} \rangle = \frac{2\pi m_e^2 c^4}{e^3} \frac{RM}{DM}$$

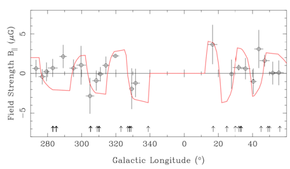


FIG. 13.— Mean line-of-sight field strengths derived from RM vs DM gradients for pulsars lying near the tangent points of an equiangular spiral pattern of −11° pitch angle as a function of Galactic longitude.

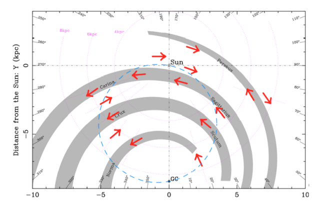


FIG. 12.— Global pattern of magnetic field directions inferred from RM–DM fits to the pulsar data and assuming an overall spiral pattern for the large-

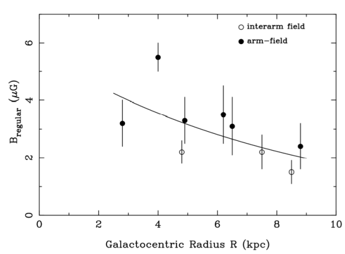


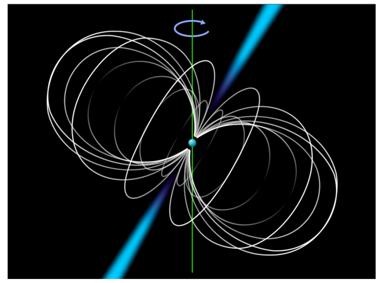
FIG. 11.— Dependence of the strength of the large-scale regular field with the Galactocentric radius. Filled dots are for arm regions and small open circles are for interarm regions. The curved line is a fit of an exponential model

Light Sources

Need strong linearly polarized radio sources (synchrotron emission).

Pulsars

- Variable source, DM can be measured.
- The spread throughout the galaxy gives depth to measurements instead of just mean values over whole line-of-sight.
- Not very bright (only visible in our galaxy and the LMC). There are less than 2000 known pulsars, mostly along the galactic plane.



Active Galactic Nuclei

- Much more abundant than pulsars
- Can be used to study magnetic fields of other galaxies and clusters
- Cannot directly measure $\langle n_e \rangle$.

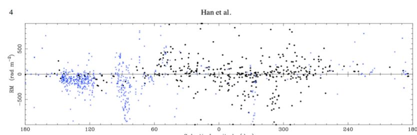


FIG. 3.— Distribution of RMs with Galactic longitude for pulsars (dots) and extra-galactic radio sources (crosses) with Galactic latitudes $|b| < 8°$. The RMs for extra-galactic sources are from Clegg et al. (1992), Gaensler et al. (2001) and Brown et al. (2003a).

Extragalactic Fields

To map the magnetic fields of distant galaxies we can use background AGN's to find RM in distant galaxies. Although the electron density can not be directly observed, the RM's are still useful for observing large scale structures.

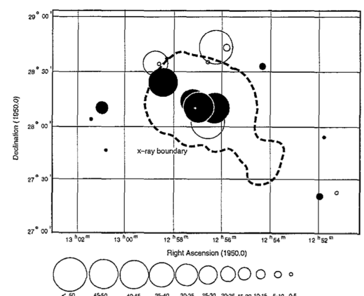
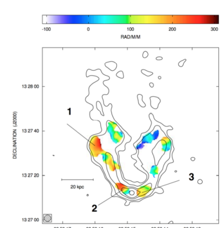


Figure 12. RM distribution of 18 background radio sources relative to the x-ray boundary of the Coma cluster of galaxies, which shows a clear excess RMs added by the intracluster medium (source Kim *et al* 1990). Filled and open circles show positive, and negative RM's respectively. The dashed line shows the ROSAT x-ray boundary at approx. 0.12 counts/

The magnetic fields are more “2 dimensional”, but galaxies can be measured from face-on.



Rotation measures of radio galaxy A401B (2010. Govoni, et al.)

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