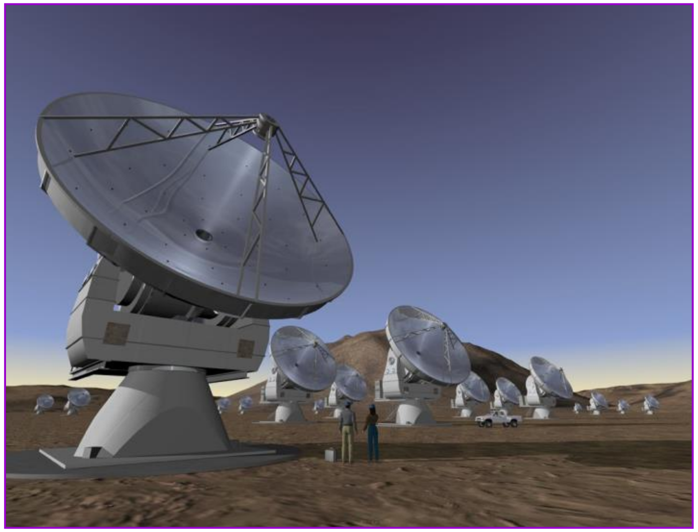
Galactic and extragalactic magnetic fields (**B** or **H**)

(see also Beck and Wielebinski “Magnetic Fields in Galaxies” in “Planets, Stars and Stellar Systems” Vol. 5 Chapter 13, Springer 2013)

Information on Magnetic Field

- **Synchrotron Emission**: total intensity of **B**
- **Polarization:** orientation of **B**, projected on the sky plane, and degree of ordered field
- **Faraday Rotation:** value of the median direction and intensity of **B** along the line of sight
- **Zeeman effect:** intensity of **B** in the clouds of cold gas



- **Polarization**: at radio wavelengths the synchrotron emission is highly polarized; at IR and mm-submm wavelengths the elongated dust grains themselves emit polarized emission; at optical wavelengths the different extinction along the minor and major axis of dust grains produces polarized radiation.
- **Future instruments**: SKA and ALMA

Synchrotron Emission

- From the synchrotron theory, the brightness is:

$$B(\nu) \propto N_0 H^{(\delta+1)/2} l \qquad N = N_0 E^{-\delta}$$

l is the depth of the source

Given N_0 ~ 0.01 eV/cm^3 (in the vicinity of the Sun) → H ~ 10 microG

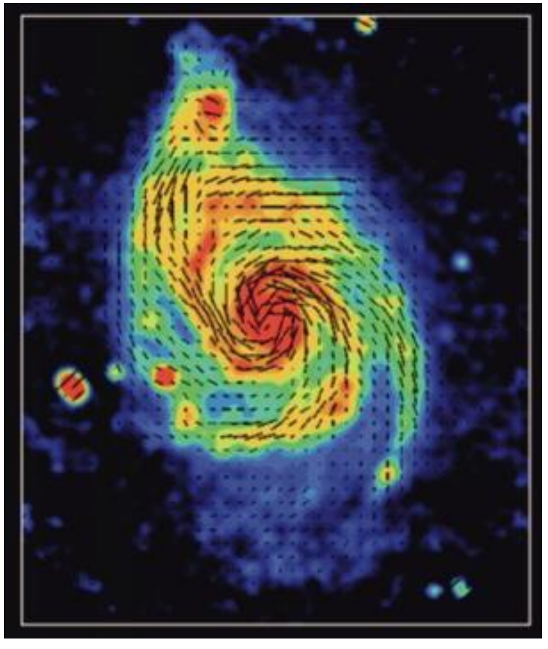
> than the value obtained with pulsars

On the contrary if H ~ 5-6 microG → N_0 5-6 times the value near the Sun

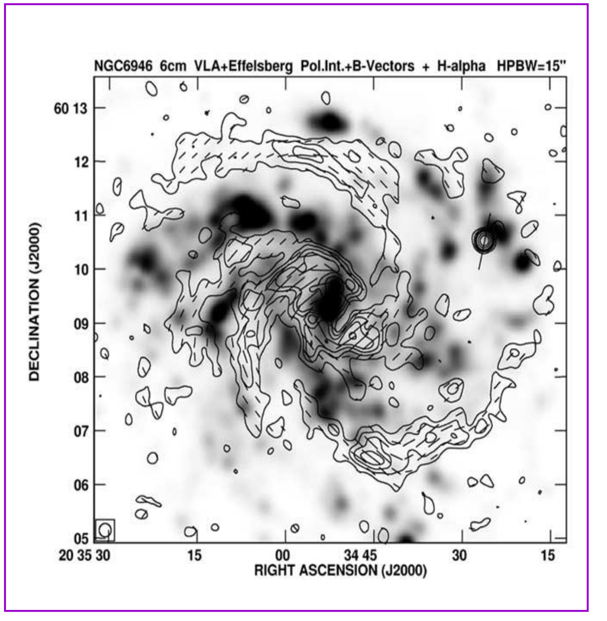
Probably H has strong fluctuations

Polarization

Linear polarization of the continuum emission is a more direct indicator of **B**, because there is no confusing thermal component. However, linear polarization is subject to Faraday effects.



M 51

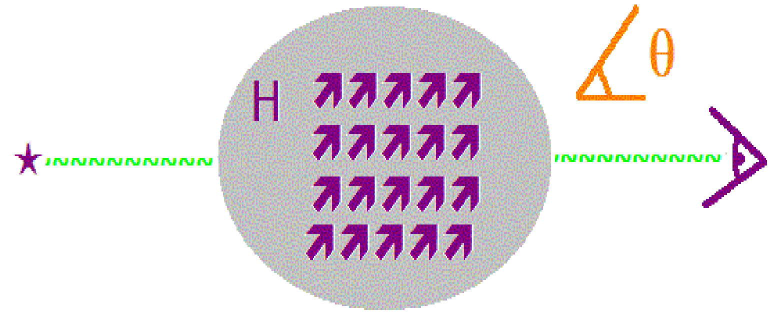


Polarized radio intensity (contours) and B-vectors of polarized intensity of **NGC 6946** at 15 arcsec. The grey-scale image shows the Halpha emission at the same resolution (Beck, 2004)

The ordered field fills the inter-arm regions, where the ISM is less dense. In correspondence of molecular clouds, mostly located in spiral arms, the ordered field is generally weaker.

Faraday Rotation

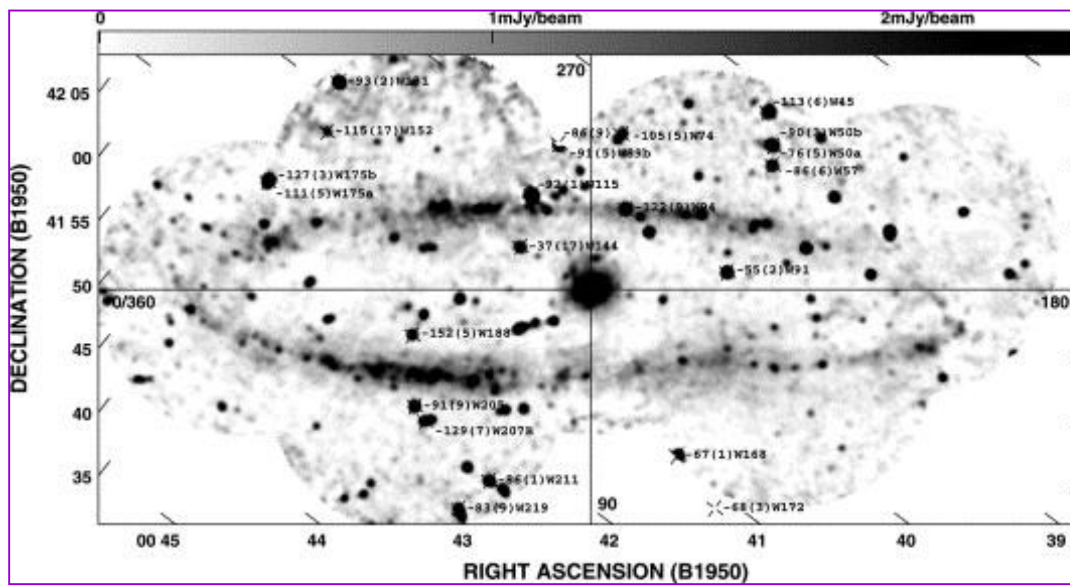
- **Birefringence**, or **double refraction** which causes the rotation of the palne of polarization.
- RM can be obtained from observations at different wavelengths.



$$\Delta\psi \propto \lambda^2 \int n_e H_\parallel \, dl = \lambda^2 (RM)$$

The polarized radio sources, marked as crosses, are superimposed onto the 20 cm radio emission from M 31 (Beck et al. 1998). The numbers near the sources are the RMs with their 1 standard deviation in brackets.

RM observations of background radio sources suggest that the regular magnetic field in the bright “ring” of M 31 extends from a radius of about 5 kpc interior to the “ring” to as far as 25 kpc from the center, probably with similar structure.



Han +1998

Pulsar Dispersion Measure

- Pulsars have high polarization and no intrinsic RM
- RM/DM gives the median value of B along l.o.s. weighted with the electronic density

$$\Delta T = DM\left[\frac{e^2}{\pi m_e}\right]\frac{\Delta\nu}{\langle\nu\rangle^3}$$

$$DM = \int_0^L n_e\, dl$$

$$\langle H_{\parallel} \rangle \propto \frac{RM}{DM} \propto \frac{\int n_e H_{\parallel}\, dl}{\int n_e dl}$$

Depolarization

The intrinsic brightness decreases with a law sinx/x and the plane rotates of ½ with respect to the value obtained if the polarized radiation comes from behind the cloud.

$$B_p = \frac{1}{4\pi} J_p l_0 e^{2i\left(\lambda^2 R.M./2+\psi_0\right)}\left[\frac{\sin\left(\lambda^2 R.M.\right)}{\lambda^2 R.M.}\right]$$

Zeeman Effect

The **Zeeman effect** is the splitting of a spectral line into several components in the presence of a static magnetic field: for example the HI (λ=21) splits in:

- Two components (H // to los)
- Three components (H perpendicular to los)

$$\Delta\nu = \frac{1}{2\pi}\cdot\frac{eH}{m_e c} \cong 2{,}8H(\mu G)$$

Considering H~1microG→ $\Delta\nu \approx 2.8MHz$

the thermal motion of the gas causes the broadening of the line, then it is not possible to measure the Z effect.

Possible only if right and left polarized radiation are observed separately →different frequency of the HI line

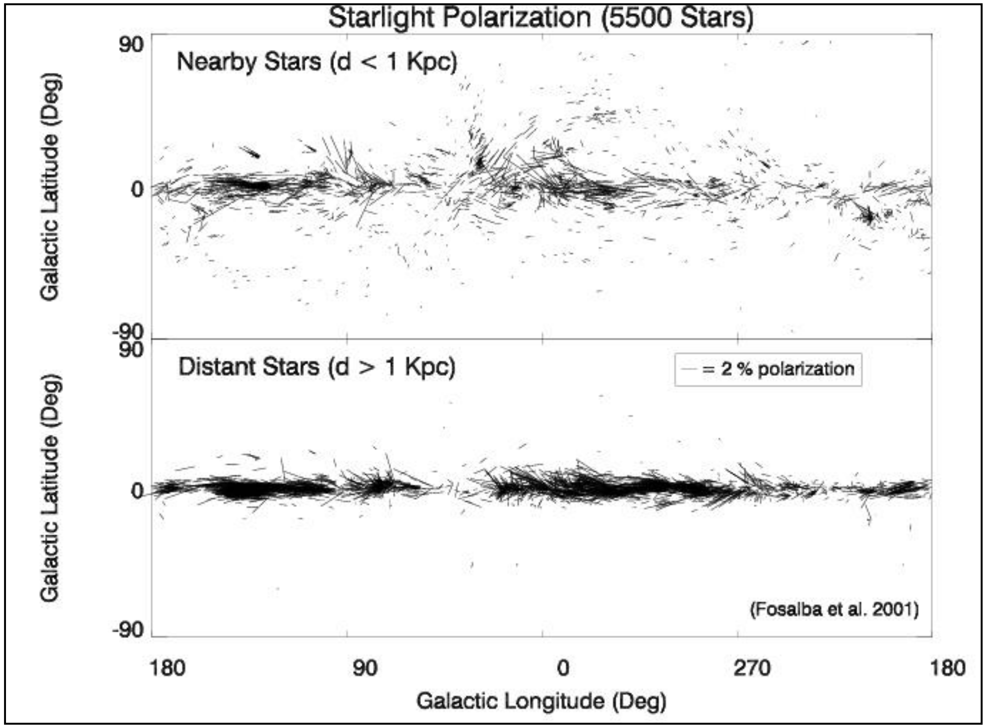
•In molecular clouds (e.g. Bourke+ 2001) H~20 microG

•In masers (Fish+ 2003) H~a few mG

Regions with high hydrogen density

Polarization of stellar light

- First information: **B** on large scale
- The stellar light is scattered by the interstellar dust
- The dust particles have preferentially their minor axis // **B**
- Information on **B** up to 8kpc (only some stars)
- In the disk B is // to the galactic plane



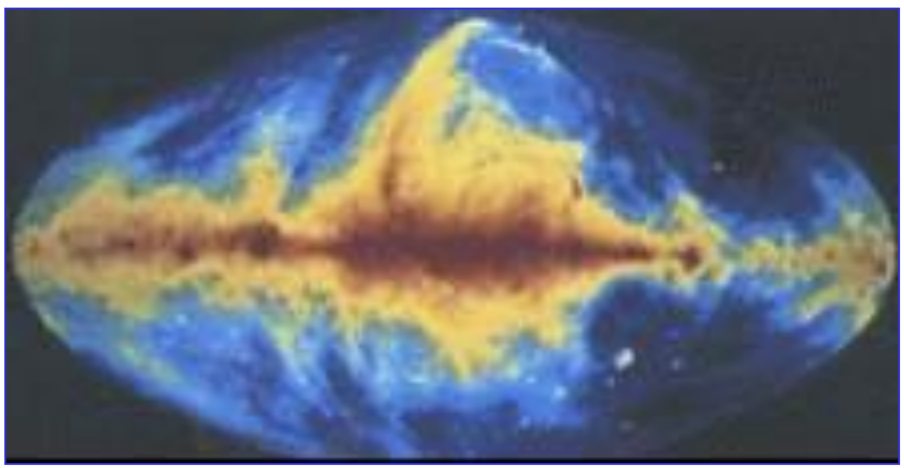
On the basis of optical polarization alone it is not possible to model the magnetic field of the Milky way

Information on Magnetic Field

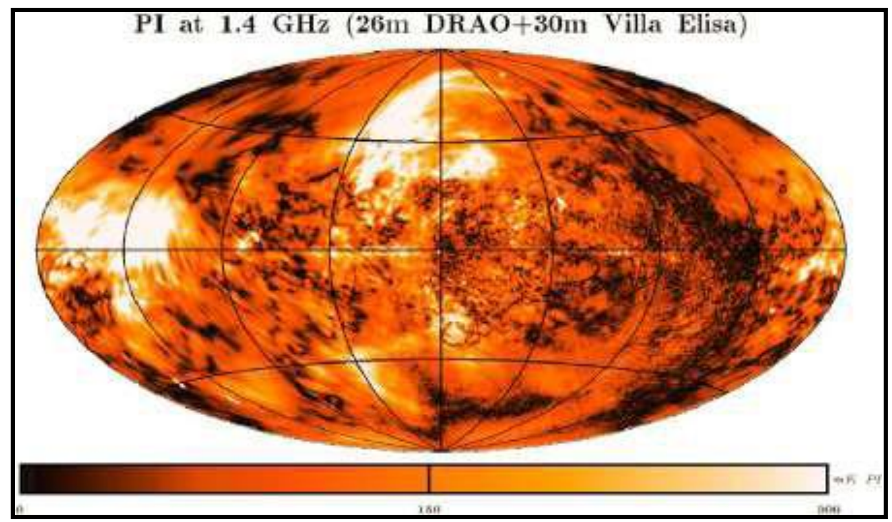
The contribution of thermal radio emission is generally small, except in bright star-forming regions. Only at frequencies > 10 GHz the thermal emission may dominate locally. At frequencies below ~ 300 MHz absorption of synchrotron emission by thermal gas can become strong. Hence the observation of total radio continuum intensity in the frequency range of ~ 300 MHz – 10 GHz is a perfect method to investigate the magnetic fields.

Polarization

The North Galactic Spur emerges at l=30deg. And can be followed, in polarization, to the southern sky. Towards the inner Galaxy strong turbulence in the polarization intensity are seen, due to Faraday effects on small scales..



Radio Sky at 408 MGz



Whole sky in linear polarization at 1.4 GHz
with angular resolution = 36 arcmin.

Faraday Rotation Measures (RM)

Faraday RM towards extragalactic radio sources originate in the source itself and in the magnetoionic media in the foreground (intergalactic space, intervening galaxies, Milky Way, interplanetary space and ionosphere of the Earth).

The contributions from intergalactic space, intervening galaxies and interplanetary space are generally small.

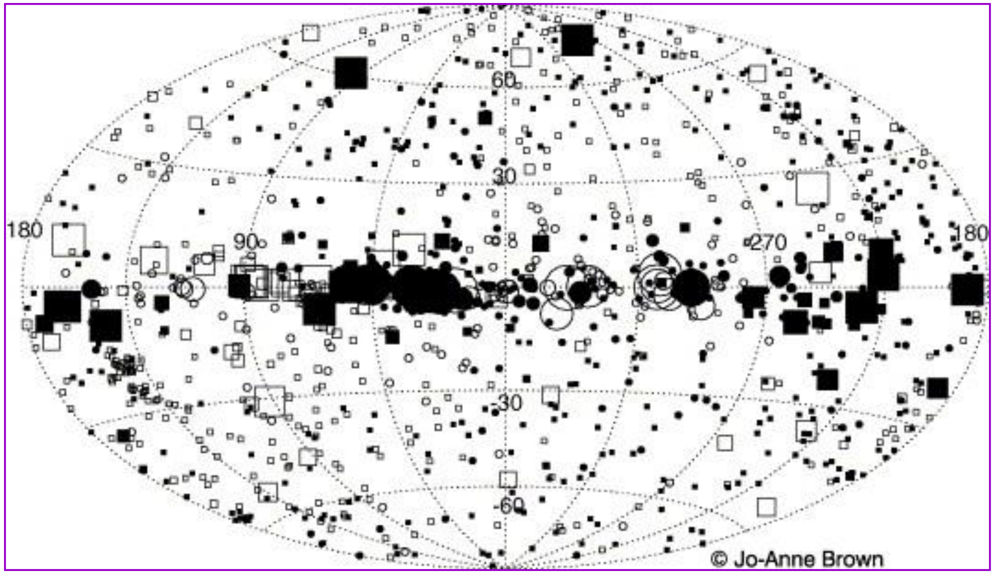
The contribution from the ionosphere of the Earth is subtracted with help of calibration sources with known polarization angle, leaving RM from the Milky Way and intrinsic RM.

The contribution of the Galactic foreground becomes very important at low and intermediate Galactic latitudes.

RM and the Milky Way

- **B** in the Milky Way is obtained from a compiled sample of 1203 RMs. Closed symbols represent positive RMs, while open symbols correspond to negative RMs.. The 887 squares represent RMs toward extragalactic sources, while the 316 circles indicate RMs of radio pulsars.
- The source density is not enough for detailed models → SKA

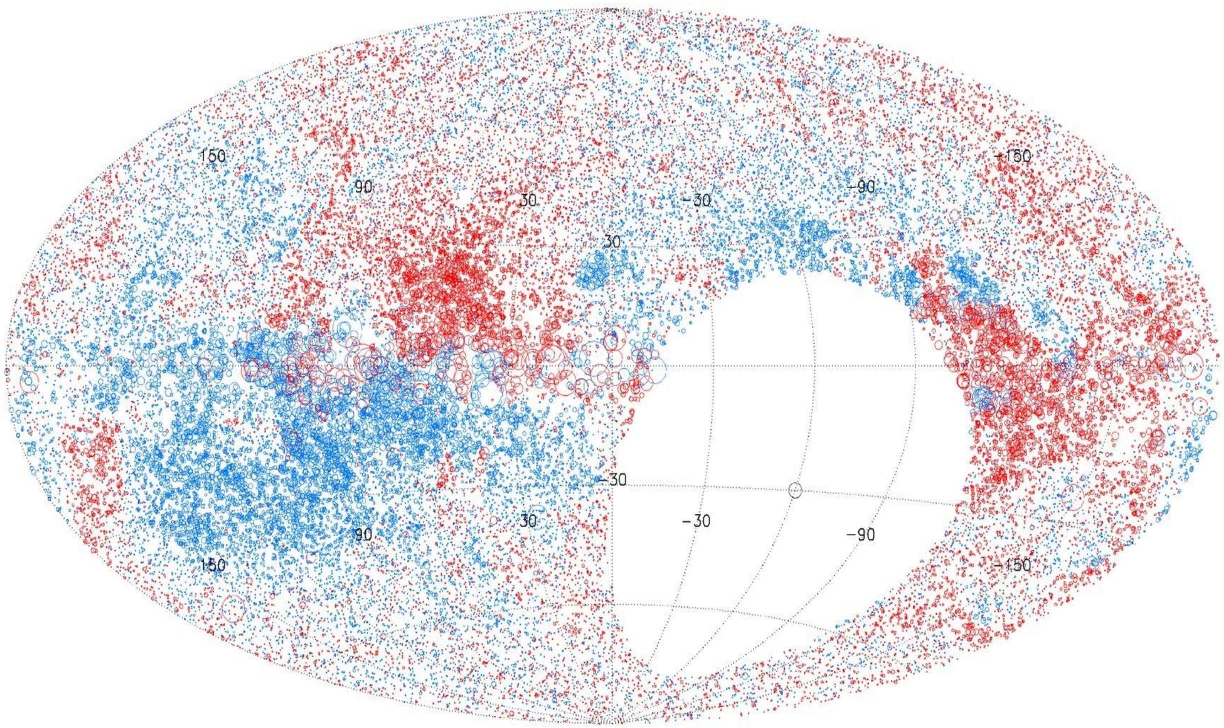
  Example: ~ 100 polarized sources in the field of the LMCloud → ~ 10^5 with SKA



In the range 100 < RM < 600 rad m^{-2}, the linear size of a symbol is proportional to RM for the corresponding source; for magnitudes of RM outside this range, the sizes of symbols are fixed at those corresponding to either RM = 100 rad m^{-2} or RM = 600 rad m^{-2} .

RM and the Milky Way

In the solar neighborhood the field perpendicular to the plane =+0.30 microG for z<0 and -0.14microG for z>0.
The reversal of sign across the Galactic plane is consistent with local features or with an antisymmetric toroidal field (+0.83 microG for z<0 and -0.39 microG for z>0) in the Milky Way's halo.



Plot of 37,543 RM values over the sky north of δ = –40°. Red circles are positive rotation measure and blue circles are negative. The size of the circle scales linearly with magnitude of rotation measure.
(Taylor et al. ApJ 2009, 702, 1230)
RM derived from NVSS **(1364,9 MHz and 1435.1 MHz)** over 82% of the sky with a typical error of +/- 1-2 rad/m^2

RM and the Milky Way

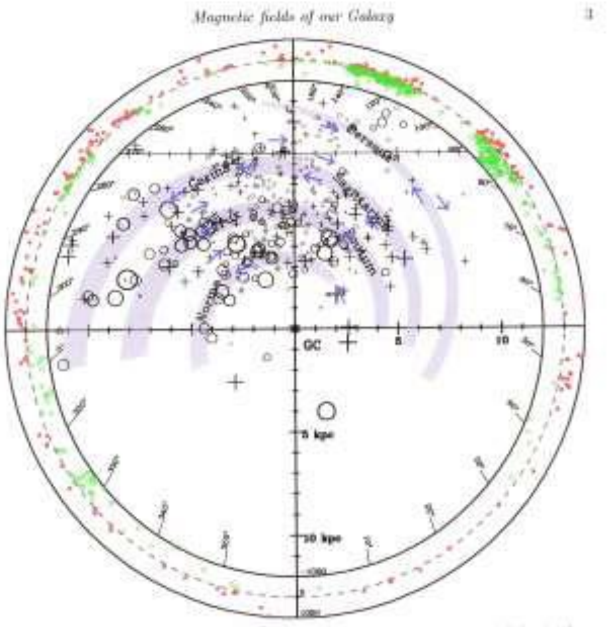
New projects:

- Polarization data in 8 channels in two bands around 1.4 and 1.6 GHz (Effelsberg radio telescope). The preliminary data for 2469 sources were used to model the Galactic magnetic field (Sun et al. 2008).
- A survey of compact sources in the southern hemisphere will be carried out with the Australia Telescope Compact Array for ~ 3000 sightlines. This will fill the gap below dec -40deg. Not covered by the catalogue of Taylor et al. (2009) and for the first time we will have a complete view of the entire Milky Way.

Pulsars

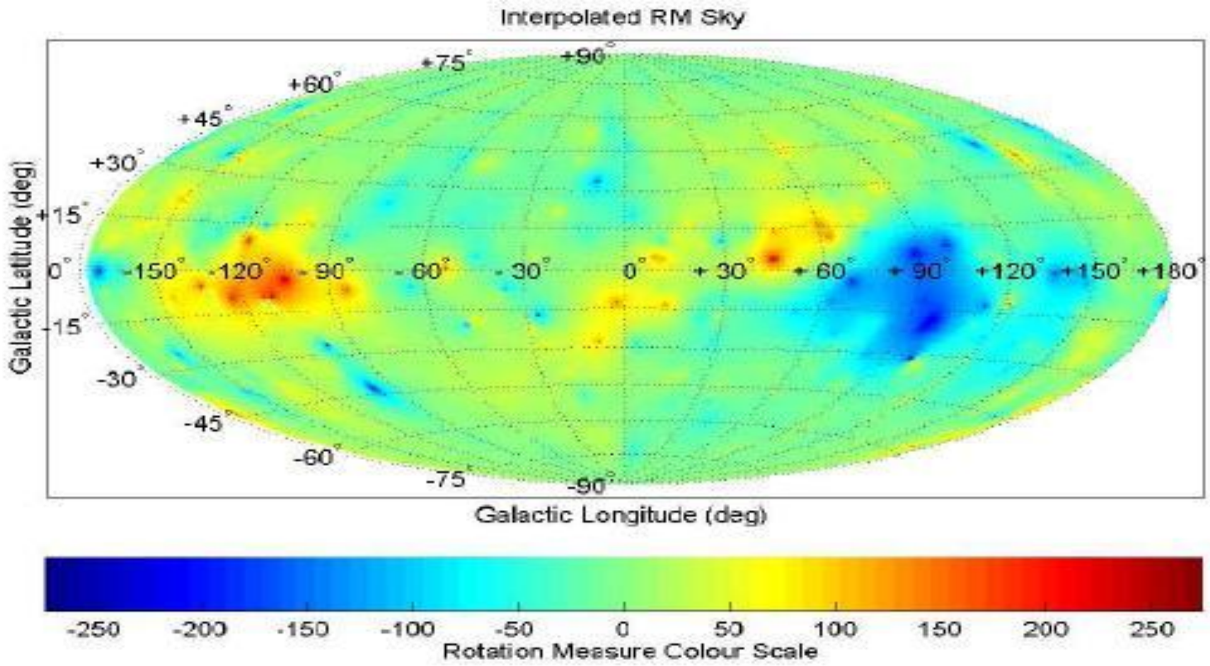
Pulsars are the ideal sources to probe the magnetic fields through the Faraday effect, because they have no measurable angular structure and they are highly polarized. With the combination of RM and DM measures a value of the B parallel was obtained.

The major compilation of pulsar RMs (Han 2007) shows a huge variations of signs and magnitudes, probably indicating a large-scale regular magnetic field with multiple reversals or the effect of localized regions , e.g. HII regions.



Faraday rotation measures (RM) of pulsars in the Milky Way (within inside circle) and of extragalactic radio sources (between inside and outside circles). Plus signs indicate positive RM
towards pulsars, small circles negative RM. Red symbols indicate positive RM towards extragalactic sources, green symbols negative RM. The blue arrows suggest large-scale magnetic fields along a model of spiral arms in the Milky Way. Our sun is located at the upper crossing of coordinate lines (Han 2008).

RM Map

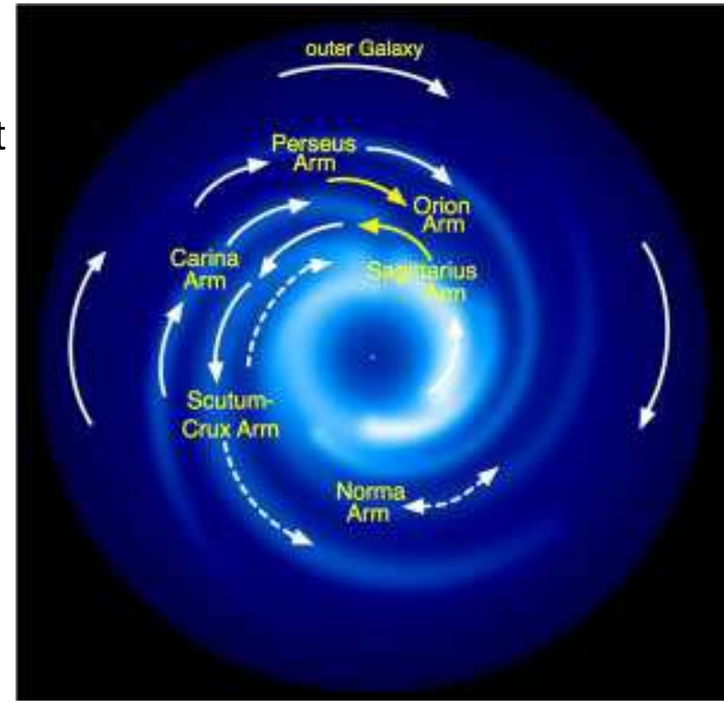


Johnston-Hollit et al. 2003

- Map obtained with ~1000 RM extragalactic sources (EGRS)
- Up to b~30° contribution of the Galaxy

Magnetic field in the Galaxy

Pulsars are ideal objects to deduce the Galactic magnetic field because their RMs provide field directions at many distances from the Sun. Since most pulsars are concentrated along the Galactic plane, they sample the field in the disk. Using pulsars and EGRS the main results are: the local magnetic field in the Perseus arm is clockwise. A large-scale magnetic field reversal is present between the Scutum-Crux-Sagittarius arm and the Carina-Orion arm. This reversal was often used as an argument for a bisymmetric spiral (BSS) field structure, although such a reversal can be local or be part of a more complicated field structure. Detailed analysis (e.g. Vallée 1996;Noutsos et al. 2008) has shown that this concept of a single large-scale field mode is not compatible with the data. The analysis of the previous interpretations by Men et al. (2008) also showed that presently there is no proof of either a BSS or a ASS (axisymmetric) configuration and that the field structure is probably more complicated.



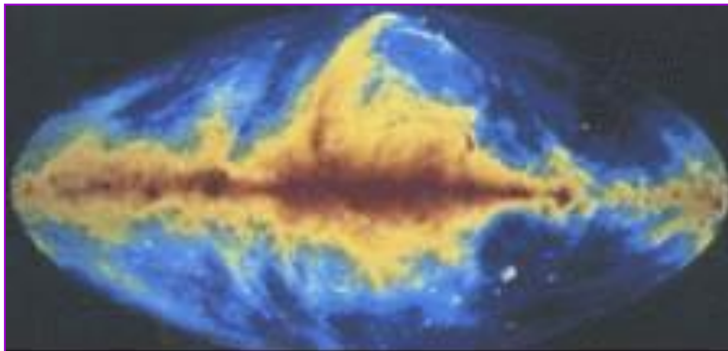
Model of the large-scale magnetic field in the Milky Way's disk, derived from Faraday rotation measures of pulsars and extragalactic sources. Yellow arrows indicate confirmed results, while white and dashed arrows still need confirmation (from Jo-Anne Brown, Calgary).

Magnetic field in the Galaxy

The RMs are dominated by local ISM features and the large scale field is weak and cannot be delineated from the available data. Only RM data free from the effects of HII regions should be used, as demonstrated by Nota & Katgert (2010).

While observations in the Milky Way can trace magnetic structures to much smaller scales than in external galaxies, the large-scale field is much more difficult to measure in the Milky Way. This information gap will be closed with future radio telescopes which will find many new pulsars in the Milky Way (and in nearby galaxies) and which allow us to observe the detailed magnetic field structure also in external galaxies.

Magnetic field in the Galaxy



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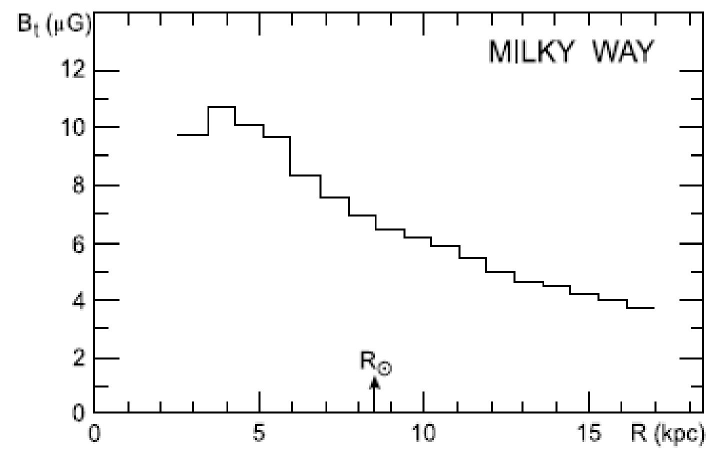


Figure 1. Strength of the total magnetic field in the Galaxy, averaged from the deconvolved surface brightness of the synchrotron emission at 408 MHz (Beuermann *et al.*, 1985), assuming energy equipartition between magnetic field and cosmic-ray energy densities (Berkhuijsen, personal communication). The accuracy is about 30%. The Sun is assumed to be located at $R = 8.5$ kpc.

Beck 2001

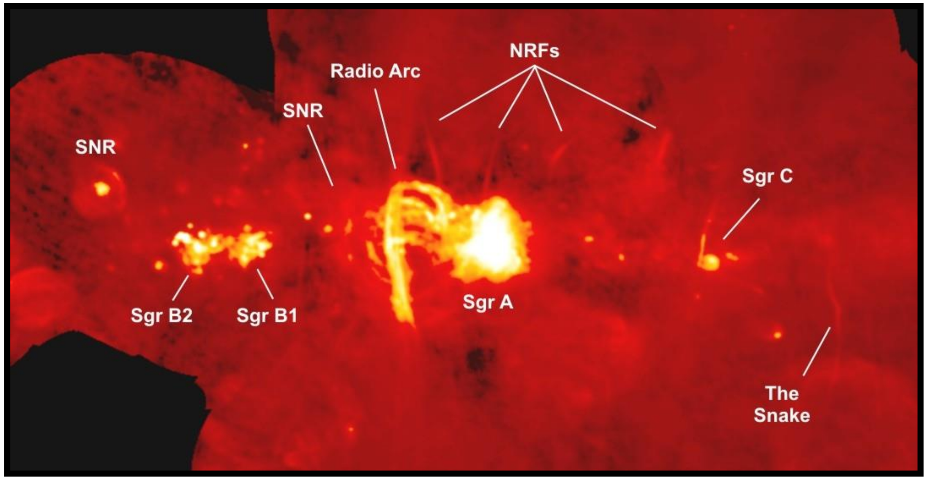
Locally B:

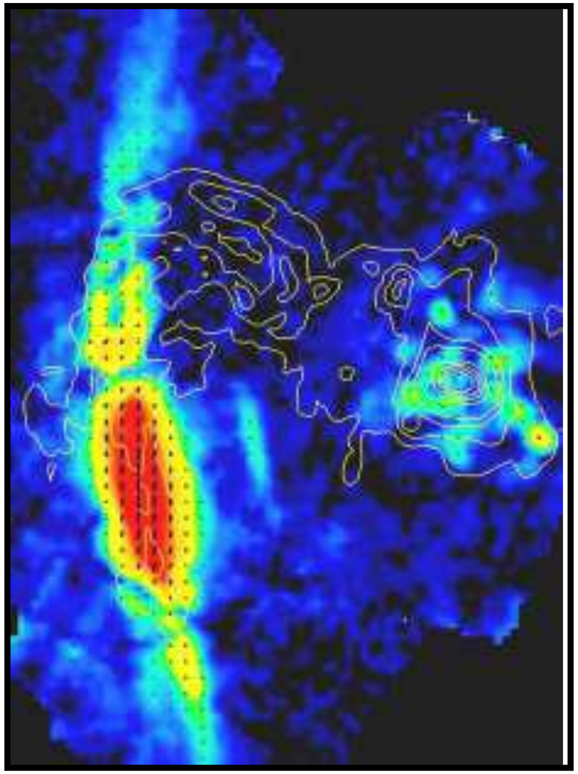
$$6 \pm 2 \mu G$$

At 3 kpc from the galactic center:

$$10 \pm 3 \mu G$$

Galactic Centre





Total intensity (contours), polarized intensity (colors), and B-vectors at 32 GHz, observed with the Effelsberg telescope. The map size is about 23' x 31' along Galactic longitude and latitude. The Galactic Center is located at the peak of total emission (from Wolfgang Reich, MPIfR).

Higher values in the GC:

In the diffuse part of the arc a field of a few hundred microG was detected, RMs in excess of +/-1600 rad m^{-2} in the vertical structures have yielded very high values (mG range).

The vertical field detected close to the center is a local phenomenon.

- Cosmic rays were discussed in “Processi di radiazione e MHD”