GALACTIC MAGNETIC FIELDS

Introduction

Magnetic fields are a major agent in the interstellar medium (ISM) of spiral, barred, irregular and dwarf galaxies. They contribute significantly to the total pressure which balances the ISM against gravity. They may affect the gas flows in spiral arms, around bars and in galaxy halos. Magnetic fields are essential for the onset of star formation as they enable the removal of angular momentum from the protostellar cloud during its collapse. MHD turbulence distributes energy from supernova explosions within the ISM. Magnetic reconnection is a possible heating source for the ISM and halo gas. Magnetic fields also control the density and distribution of cosmic rays in the ISM.

Radio galaxies form a separate class and are not considered in this article. They are powered by violent processes around black holes in their centers and show *jets* and *radio lobes* in the radio range, hosting strong magnetic fields and energetic cosmic-ray particles.

Galactic magnetic fields can be observed in the optical range via starlight which is polarized by interstellar *dust grains* in the foreground. These grains are elongated and can be aligned by magnetic fields, where the major axis becomes perpendicular to the field lines. Measurements of many stars revealed a general picture of the magnetic field in the Milky Way near the Sun. Aligned dust grains also emit polarized *infrared emission*, which is very useful to show magnetic fields in dust clouds in the Milky Way. *Zeeman splitting* of radio spectral lines allows measurement of relatively strong fields in nearby, dense gas clouds in the Milky Way. For those three techniques observations in external galaxies are still difficult to obtain. The fourth technique, measuring *synchrotron emission*, is the most powerful one and can be applied over the whole Milky Way, to nearby galaxies and also to distant galaxies.

Cosmic-ray electrons in galaxies, accelerated in supernova remnants or in jets and spiraling around interstellar magnetic field lines with almost the speed of light. They emit *synchrotron emission* over a large range of radio wavelengths. The intensity of synchrotron emission increases with observation wavelength to a power of about 0.8. The most energetic electrons can even emit synchrotron infrared or optical light.

The intensity of synchrotron emission is a measure of the density of cosmic-ray electrons and of the strength of the total magnetic field component in the sky plane. The degree of linear polarization of synchrotron emission can be as high as 75% in a completely ordered field, which is a field with a constant orientation within the volume traced by the telescope's beam. Any variation of the field orientation within the beam reduces the degree of polarization. Regular fields are believed to be generated e.g. by a *dynamo* (see below). Polarized emission can also emerge from *anisotropic turbulent* fields (with random orientations in two dimensions), which are generated from isotropic turbulent fields (with random orientations in three dimensions) by compressing or shearing gas flows and frequently reverse their field direction by 180 degrees on scales smaller than the telescope beam. Unpolarized synchrotron emission indicates isotropic turbulent fields that have been generated by turbulent gas flows. Hence, three components of the total field are distinguished by observations: regular, anisotropic turbulent and isotropic turbulent fields.

Typical degrees of polarization are 10-20% on average, indicating that isotropic turbulent fields dominate in galaxies. Locally, 50% is observed (e.g. in the interarm regions of NGC 6946, see Fig.2 below); the regular and/or anisotropic turbulent field dominates in such regions.

The intrinsic orientation of the observed polarization plane of an electromagnetic wave is perpendicular to the field orientation. When the wave travels through a magnetized plasma, the orientation of the polarization plane is changed by *Faraday rotation*. The rotation angle increases with the plasma density, the strength of the component of the regular field along the line of sight, and the square of the observation wavelength. Fields directed towards us cause an anticlockwise sense of rotation, fields directed away from us a clockwise rotation. Anisotropic and isotropic turbulent fields do not Faraday-rotate. For typical plasma densities and regular field strengths in the interstellar medium of galaxies, Faraday rotation becomes significant at wavelengths larger than a few centimeters. At decimeter wavelengths, Faraday rotation is generally strong and can lead to *Faraday depolarization*. In the meterwave range (below frequencies of about 300 MHz), polarized emission from galaxies is generally too weak to be detected.

Measurement of the Faraday rotation from multi-wavelength observations allows us to determine the strength and direction of the regular field component along the line of sight. Combination with the polarization vectors yields a fully three-dimensional picture of the magnetic field.

The most sensitive instruments for radio polarization measurements are the 100-m single-dish telescopes in Effelsberg (Germany) and Parkes (Australia) and the synthesis (interferometer) telescopes in Westerbork (Netherlands), the Jansky Very Large Array (USA) and the Australia Telescope Compact Array. Low-frequency instruments like LOFAR did not yet detect polarization from galaxies because of strong Faraday depolarization at long wavelengths. A major increase in sensitivity and angular resolution is expected from the Square Kilometre Array(see below).

The Origin of Galactic Magnetic Fields

The origin of the first magnetic fields in the Universe is still a mystery (Widrow 2002). Protogalaxies probably were already magnetic due to field ejection from the first stars or from jets generated by the first black holes. However, a *primordial* field in a young galaxy is hard to maintain because a galaxy rotates *differentially* (the angular velocity decreases with radius), so that the magnetic field lines get strongly wound up (in contrast to observations, see below) and field lines with opposite polarity may cancel via *magnetic reconnection*. This calls for a mechanism to sustain and organize the magnetic field.

The most promising mechanism is the *dynamo* which transfers mechanical energy into magnetic energy (e.g. Beck et al. 1996, Rüdiger & Hollerbach 2004, Brandenburg & Subramanian 2005). With a suitable configuration of the fluid or gas flow, a strong magnetic field with a stationary or oscillating configuration can be generated from a weak *seed* field. Seed fields could have been generated in the early Universe, e.g. at phase transitions, or in shocks in protogalactic halos (*Biermann battery*), or in fluctuations in the protogalactic plasma.

In astronomical objects like stars, planets or galaxies, an efficient dynamo needs turbulent motions and non-uniform (*differential*) rotation and is called *alpha-Omega* dynamo. It generates large-scale regular fields, even if the seed field was turbulent (*order out of chaos*). The regular field structure obtained in dynamo models is described by *modes* of different azimuthal symmetry in the disk and vertical symmetry perpendicular to the disk plane. Such modes can be identified from the pattern of polarization angles and Faraday rotation in multi-wavelength radio observations. Several modes can be excited in the same object. In spherical bodies like stars or planets or galactic halos, the strongest mode is a double torus near the equator with a reversal across the equatorial plane, surrounded by a *dipolar* field (*odd* vertical symmetry). In flat objects like galactic disks, the strongest mode is a single torus in the plane with a field of*axisymmetric* spiral shape, without reversals, surrounded by a weaker *quadrupolar* field (*even* vertical symmetry). This mode is frequently observed. The next mode, of *bisymmetric* spiral shape with two field reversals in the disk, possibly excited by gravitational interaction, seems to be rare. The next higher *quadrisymmetric* mode can be excited by spiral and was found in many spiral galaxies.

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