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Large-scale magnetic field in spiral galaxies

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Abstract.
Magnetic fields have been detected everywhere in disk galaxies and consist of regular and turbulent components. The large-scale regular magnetic field is mainly of spiral structure in grand-design spirals as well as in flocculent and even irregular galaxies. The regular field in spirals is aligned along the optical spiral arms but generally strongest in the interarm region, sometimes forming *magnetic arms*. The strongest total field is found in the optical arms, it is mainly irregular.
The large-scale regular field can be best explained by some kind of dynamo action. Only a few galaxies seen face-on show a dominant axisymmetric field pattern - as expected by the mean field $\alpha - \omega$ dynamo model. Most field structures seem to be a superposition of different dynamo modes or rather reveal more local effects related to density waves, bars or shocks. Recent observations of edge-on galaxies, however, indicate indeed the existence of an underlying even axisymmetric mode with quadrupolar vertical symmetry, which is the field configuration that is most easily excited by the mean field $\alpha - \omega$ dynamo.

Key words. radio continuum:galaxies – polarization – galaxies:spirals – magnetic field – theory: dynamo action

1. Introduction

Radio observations of the continuum emission in the cm-wavelength regime are the best way to study magnetic fields in galaxies. The total intensity of the synchrotron emission gives the strength of the total magnetic field. The linearly polarized intensity reveals the strength and the structure of the resolved regular field in the sky plane (i.e. perpendicular to the line of sight). However, the observed polarization vectors suffer Faraday rotation and depolarization on their way from the radiation's origin to us. Correction for Faraday rotation is possible with observations at two – or better more – wavelengths by determining the rotation measure RM (being proportional to $\int n_e B_{\|} dl$). $B_{\|}$ is the coherent magnetic field parallel to the line of sight, and its sign gives the direction of this magnetic field component. Both field components, parallel and perpendicular to the line of sight, enables us in principle to perform a 3-dimensional 'tomography' of the large-scale magnetic field.

Note, however, that the polarized intensity is only sensitive to the field orientation, but not to the field directions (i.e. it does not distinguish between parallel and antiparallel field directions) in the plane of the sky, whereas the RM is large for parallel fields along the line of sight, but zero for antiparallel fields (of equal strength).

Magnetic fields consist of regular and turbulent components. The total magnetic field strength in a galaxy can be estimated from the nonthermal radio emission under the assumption of equipartition between the energies of the magnetic field and the relativistic particles (the so called *energy equipartition*) as described in Beck & Krause (2005).

2. Observational results of magnetic fields

2.1. Galaxies seen face-on

The mean equipartition value for the total magnetic field strength for a sample of 74 spiral galaxies observed by Niklas (1995) is on average $9 \pm 3\mu$G. It can, however, reach locally higher values *within* the spiral arms of up to $20\,\mu$G. Strongly interacting galaxies or galaxies with a high star formation rate tend to have generally stronger total magnetic fields. The strength of the regular magnetic fields in spiral galaxies (observed with a spatial resolution of a few 100 pc) are typically 1–5 μG, and may reach locally values up to $10\,\mu$G.

The turbulent magnetic field is typically strongest along the optical spiral arms, whereas the regular fields are strongest in between the optical spiral arms, or at the inner edge of the density-wave spiral arm. Sometimes, the interarm region is filled smoothly with regular fields, in other cases the large-scale field form so-called *magnetic spiral arms*.

The magnetic lines of the large-scale field form generally a spiral pattern with pitch-angles from 10° to 40° which are similar to the pitch angles of the optical spiral arms. However, spiral magnetic fields have even been observed in flocculent and irregular galaxies.

2.2. Spiral galaxies seen edge-on

Several galaxies seen edge-on have been observed in radio continuum and linear polarization. These observations confirm that the strongest magnetic field is within the galactic disk and show directly that its field structure is mainly *parallel to the disk*. Recent observations with enough sensitivity revealed however, that the magnetic field at higher z-distances from the disk also shows large-scale vertical components, increasing with radius (e.g. Soida 2005, Krause et al. 2006). Hence, the large-scale field looks x-shaped away from the plane (see Fig. 1). The corresponding map of the rotation measure RM determined between our 3.6cm-map and the 6.2cm-map of Sukumar & Allen (1991) is also shown in Fig. 1. The RM values are negative in the northern part of the galaxy, and positive in the southern part that indicates a large-scale azimuthal field within the galactic disk.

3. Regular fields and dynamo action

The large-scale magnetic field is generally thought to be amplified and structure-formed by the action of a mean-field $\alpha\omega$-dynamo (e.g. F. Krause & Rädler 1980, Ruzmaikin et al. 1988). The large-scale dynamo mode that can be excited most easily, is the axisymmetric (ASS) mode with a spiral-shaped azimuthal field in the galactic disk and either an even (quadrupole-type) or odd (dipole-type) field with respect to the galactic plane (shown e.g. in Fig.9 in Krause et al. (1989)). Higher modes are the bisymmetric (BSS) mode, the quadrupolar mode, etc. Only a few galaxies seen face-on show a dominant ASS-mode as expected by the dynamo theory. Most field structures seem to be a superposition of different dynamo modes or rather reveal more local effects related to density waves, bars, shocks, or interactions (e.g. Beck et al. 1996, Krause 2003).

4. Conclusions

The magnetic field structures of many edge-on galaxies are found to be very similar: the magnetic field orientation is parallel to the galactic plane along the midplane and x-shaped at larger z-distances from the plane. This configuration has been found for several spirals of different Hubble-type and star formation rate. In two of them, NGC 5775 (Soida et al.,

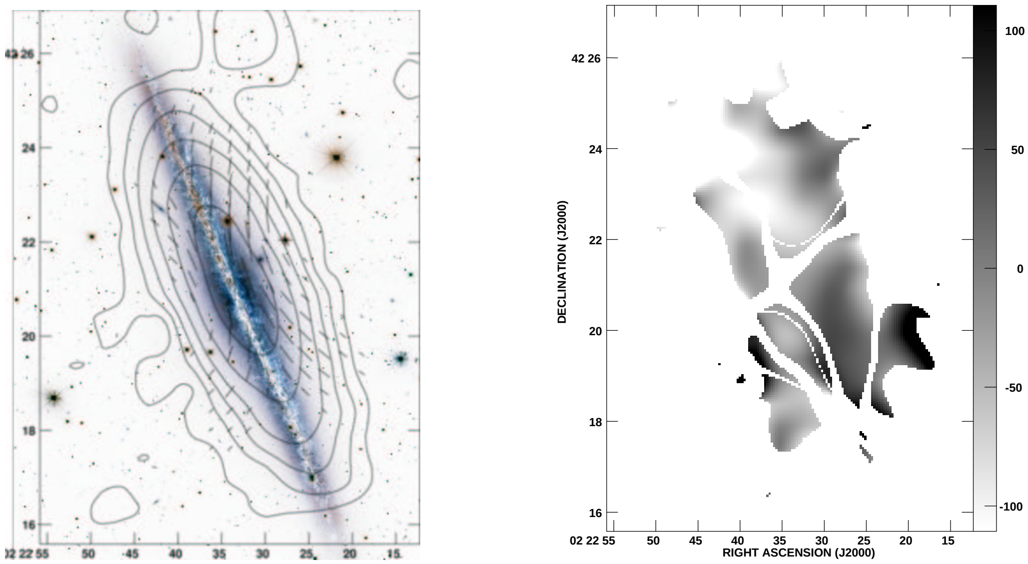

Fig. 1. Radio continuum emission of the edge-on spiral galaxy NGC 891 at 8.35 GHz. The contours in (a) give the total intensities, the vectors the intrinsic magnetic field orientation. (b) shows the intrinsic rotation measure RM of NGC 891 in grey scales.

in prep.) and NGC 891 a systematic change of sign in the RM-values along the midplane has been found. Hence, a magnetic field that is coherent on scales of several kpc seem to be present in these galaxies which could indicate a quadrupolar halo field together with an axisymmetric disk field. This could be the field structure of an ASS field as expected to be produced as first mode of a mean field $\alpha\omega$-dynamo. In fact, model calculations of a nonlinear mean-field dynamo for a disk surrounded by a spherical halo, including a galactic wind (Brandenburg et al. 1993), simulated a similar x-shaped distribution of the intrinsic magnetic field vectors as the observed ones.

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