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Magnetic fields in star-forming galaxies at low and high redshifts

Rainer Beck

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Abstract. Magnetic fields in nearby galaxies are amplified and structured by compressing and shearing gas flows and by dynamo action. Large-scale coherent fields can be expected in young galaxies after several 10^8yr, while turbulent flows and small-scale dynamos can generate turbulent magnetic fields on the timescale of the first supernova explosions. Frequent interactions and ram pressure in the early Universe produced strong anisotropic fields. Distant, unresolved galaxies are expected to be polarized in radio continuum and will be ideal sources for the SKA all-sky survey of Faraday rotation measures. Models of magnetic field evolution in galaxies are required to investigate the relation of total radio continuum emission to the star-formation rate.

1. Introduction

The Square Kilometre Array (SKA) will allow to detect radio continuum emission from star-forming galaxies out to redshifts of at least 3. At frequencies $\leq$ 10 GHz the radio continuum from spiral galaxies is dominated by synchrotron emission. The SKA will provide information about magnetic field generation and cosmic-ray acceleration as a function of galaxy age.

Polarized synchrotron emission from young star-forming galaxies may serve as background sources for measurements of Faraday rotation measures (RM) in the intervening media. The SKA Key Science Project "The origin and evolution of cosmic magnetism" will perform an all-sky RM survey to model the three-dimensional structure and strength of the magnetic fields in the intergalactic medium (IGM) and the interstellar medium (ISM) of intervening galaxies and of the Milky Way (Gaensler et al. 2004). Simulation of the polarized sky is one of the tasks of the EU-funded SKA Design Study (SKADS) and will derive constraints on the SKA design concerning sensitivity and purity of polarization observations.

In this paper our present knowledge on magnetic fields in nearby star-forming galaxies is summarized and expectations for distant, young galaxies are discussed.

2. Radio continuum and star formation

The correlation between radio and far-infrared (FIR) luminosities of star-forming galaxies is one of the tightest correlations known in astrophysics. It extends over more than five orders of magnitude (Bell 2003) and is valid to redshifts of 1–3 (Garrett 2002, Appleton et al. 2004, Kovács et al. 2006). The slope of this correlation for pure radio synchrotron emission, at frequencies below about 1 GHz, is 1.2–1.3 (Fitt et al. 1988, Price & Duric 1992, Hughes et al. 2006) and slightly flatter (1.1) for a mixture of synchrotron and thermal emission at frequencies $\geq$ 10 GHz (Niklas 1997). The correlation also holds for blue compact and low-surface brightness galaxies (Chyży et al. 2006b) for which thermal emission dominates at frequencies beyond $\simeq$ 5 GHz. A radio excess is observed in NGC 2276 (Hummel & Beck 1995) and for galaxies in the inner part of the Virgo cluster (Niklas et al. 1995) where magnetic fields are compressed by ram pressure. A radio deficit was found in a few galaxies with very recent starbursts (Roussel et al. 2003).

The radio–infrared correlation also holds locally within galaxies, between the radio intensity and mid-infrared intensity at 7μm or 15μm or the far–infrared intensity at 60μm, with slopes of 0.7–0.9 (Walsh et al. 2002, Vogler et al. 2005, Hughes et al. 2006). In NGC 6946 the wavelet cross-correlation coefficient is high at all spatial scales down to 400 pc (Frick et al. 2001). In the LMC, where the observations had sufficiently high spatial resolution, the correlation breaks down below a scale of about 50 pc (Hughes et al. 2006).

The physical background of the relation is hardly understood. Energetic photons from massive stars cause infrared and thermal radio emission. Cosmic rays, responsible for synchrotron emission, are most probably accelerated in supernova remnants. To achieve an almost linear correlation between the total nonthermal radio luminosity and the supernova rate, the magnetic field strength either has to be almost constant between galaxies (e.g. Condon 1992), which is an unphysical assumption, or the magnetic fields plays no role due to strong synchrotron losses of the cosmic-ray electrons (as in the calorimeter model, Völk 1989) which, however, cannot explain the local correlation observed within galaxies. Assuming optically thick dust, energy equipartition between magnetic field cosmic rays and that the magnetic fields are coupled to the dense gas clouds, Niklas & Beck (1997) derived a nonlinear scaling of radio continuum emission with star-formation rate, and global and local correlations with a slope of about 1.3. Related models for optically thin dust were proposed by Helou & Bicay (1993) and Hoernes et al. (1998), where the slope of the correlation depends on several parameters and can also be smaller than 1.

One of the main questions of cosmology with the SKA is whether the radio–infrared correlation still holds for

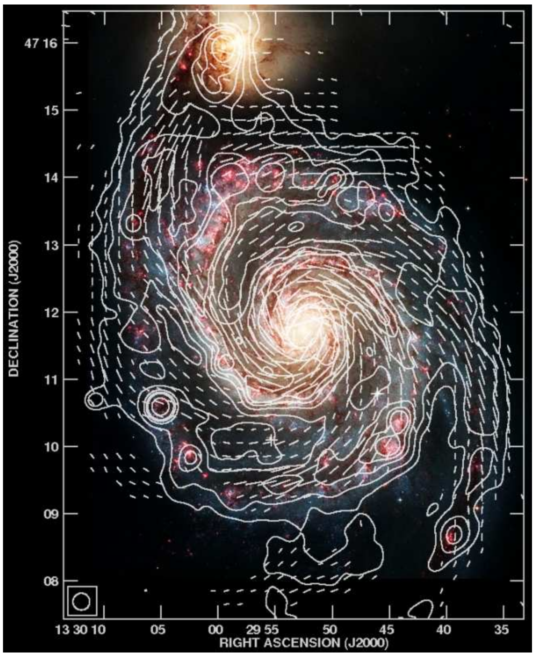

Fig. 1. Total emission (contours) and **B**–vectors of polarized emission of the spiral galaxy M 51, combined from data at 4.8 GHz observed with the VLA and Effelsberg telescopes. Vector lengths are proportional to the polarization intensity (from Fletcher et al., in prep.)

young galaxies in the early Universe, i.e. whether the radio flux of a distant galaxy can be used as a measure of its star-formation rate. This question critically depends on the evolution of galactic magnetic fields (see Sect. 6).

3. Magnetic fields in nearby galaxies

The average strength of the total field in the plane of the sky can be derived from the total radio synchrotron intensity, the strength of the resolved coherent regular field and anisotropic random field from the polarized intensity, if energy-density equipartition between cosmic rays and magnetic fields is assumed (Beck & Krause 2005). The mean equipartition strength of the total field for a sample of 74 spiral galaxies is $\simeq$ 9 μG (Niklas 1995). Radio-faint galaxies like M 31 and M 33 have $\simeq$ 6 μG, while $\simeq$ 15 μG is typical for grand-design galaxies like M 51, M 83 and NGC 6946. In the prominent spiral arms of M 51 the total field strength is $\simeq$ 30 μG (Fletcher et al. 2004) along the prominent dust lanes (Fig. 1). The strongest fields in spiral galaxies were found in starburst galaxies like M 82 with $\simeq$ 50 μG strength (Klein et al. 1988) and the "Antennae" (Chyży & Beck 2004), and in nuclear starburst regions with 50-100 μG (Beck et al. 2004). The energy density of the magnetic field E_{magn} (assuming energy density equipartition) in spiral galaxies is generally one order of magnitude larger than that of the ionized gas E_{th}, but similar to that of the turbulent gas motions.

The strengths of the resolved regular and anisotropic random fields in spiral galaxies (observed with a spatial resolution of a few 100 pc) are typically 1–5 μG. In most galaxies, the regular fields are strongest *between* the optical arms, sometimes forming *magnetic spiral arms* with ridge lines between the optical arms, like in NGC 6946 with $\simeq$ 10 μG strength (Beck & Hoernes 1996). Within the spiral arms the regular fields are generally weak. Compression by the strong density waves of M 51 at the inner edge of the inner spiral arms generates anisotropic fields of $\simeq$ 15 μG strength (Fletcher et al. 2004, Fig. 1).

The **B**–vectors of polarized emission form spiral patterns, in spiral galaxies, in flocculent and in several bright irregular galaxies (see examples shown in Beck 2005). The magnetic fields in spiral galaxies run almost parallel to the spiral arms. In M 51 (Fig. 1) the field orientation varies by 10°–20° around the pitch angles of the spiral arms as traced by CO emission (Patrikeev et al. 2006).

In galaxies with massive bars the total radio intensity is strongest in the region of the dust lanes by compression in the bar's shock. However, the contrast in polarized intensity is much smaller, probably the result of a decoupling of the regular field from the dense molecular clouds (Beck et al. 2005). The regular field around bars is probably strong enough to resist to be sheared by the diffuse gas, indicating that magnetic forces can control the flow of the diffuse interstellar gas at kiloparsec scales.

Edge-on galaxies possess thick radio disks of about 2 kpc scale height (Krause 2003). The mean scale height of the total magnetic field is $\simeq$ 8 kpc (in case of equipartition between the energy densities of magnetic field and cosmic rays). The field's scale height may even be larger if cosmic rays originate from star-forming regions in the plane and are not re-accelerated in the halo, so that the electrons lose their energy beyond some height. The orientations of the field near the midplane are mainly parallel to the disk, but with increasing vertical components with increasing distance from the midplane (Tüllmann et al. 2000, Krause et al.2006). If star formation in the disk is very strong, the vertical field can be dominant, as in the central part of NGC 4631 (Krause 2003). Several magnetic spurs are connected to star-forming regions in the disk of NGC 4631 (Golla & Hummel 1994).

Present-day polarization observations are limited by sensitivity at high resolution. The best available spatial resolution is 10 pc in the LMC (Gaensler et al. 2005). The SKA will have much improved sensitivities and allow to study magnetic fields in galaxies at angular resolutions more than 10× better than today (Beck & Gaensler 2004).

4. Faraday rotation and dynamo models

Faraday rotation is a signature of *coherent* regular fields, and the sense of Faraday rotation reveals the direction of the field. Only dynamos are able to generate magnetic fields with large-scale coherence. Compression or shearing of turbulent fields by gas flows generates anisotropic random fields. These are *incoherent* and reverse direction frequently within the telescope beam, so that Faraday rotation is small while the degree of polarization can still be high (polarization angles are insensitive to field reversals in the sky plane).

"Mean-field" dynamos require turbulent helical gas flows and large-scale differential rotation. They generate large-scale coherent field structures which are described as modes of different azimuthal, radial and vertical symmetries (Beck et al. 1996). Several modes can be excited. In flat disks with axisymmetric gas distribution and smooth rotation, the strongest mode is the axisymmetric spiral one ($m = 0$), followed by $m = 1$ (a bisymmetric spiral field), etc. These modes can be identified by Fourier analysis of their specific azimuthal patterns of Faraday rotation measures (RM) (Krause 1990). The SKA will allow detailed tests of galactic dynamo models (Beck 2006).

M 31 and possibly the LMC host dominating axisymmetric fields (Berkhuijsen et al. 2003, Gaensler et al. 2005). The magnetic arms observed in NGC 6946 can be described as a superposition of an axisymmetric $m = 0$ and a quadrisymmetric $m = 2$ mode (Rohde et al. 1999). However, for most of about 20 nearby galaxies for which RM data are available, no dominating magnetic modes could be reliably determined (Beck 2000). In M 51 the anisotropic random field is stronger than the coherent regular field, due to shearing and compressing in the strong density wave flow (Fletcher et al., in prep).

5. Magnetic fields in galaxies at large redshifts

Our present knowledge on magnetic fields in distant star-forming galaxies is very limited. Radio synchrotron emission and hence magnetic fields are observed in galaxies out to redshifts of 3 (Ivison et al. 2005). As the radio–FIR correlation holds to the same distances, the magnetic fields in young galaxies are similarly strong with respect to their star-formation rate compared to nearby galaxies. Whether this holds still at larger redshifts has to be investigated (see Sect. 6).

The magnetic field structure cannot be observed directly in distant galaxies due to the lack of resolution with present-day telescopes. If a galaxy happens to be on the line of sight towards an extended polarized background source, Faraday rotation (RM) within its ISM can be measured. Kronberg et al. (1992) derived a few RM values of a galaxy at $z = 0.395$ towards the background quasar PKS1229-021 and proposed a bisymmetric structure in the galaxy with a regular field strength of a few μG. A Faraday depolarization silhouette by the nearby spiral galaxy NGC 1310 was found by Fomalont et al. (1989) against the giant radio galaxy Fornax A. These results indicate the future possibilities with the SKA.

The magnetic field structure in galaxies depends on the following processes: dynamo action (Sect. 6), shearing or compressing gas flows (Sect. 6), star formation, ram pressure by the surrounding IGM, and interactions. Galaxies in the early Universe were smaller, the IGM density was higher, and they were subject to more frequent interactions and starbursts. Studying the polarized radio emission from nearby galaxies with signs of interactions or starbursts may give some idea about galaxies in the early Universe.

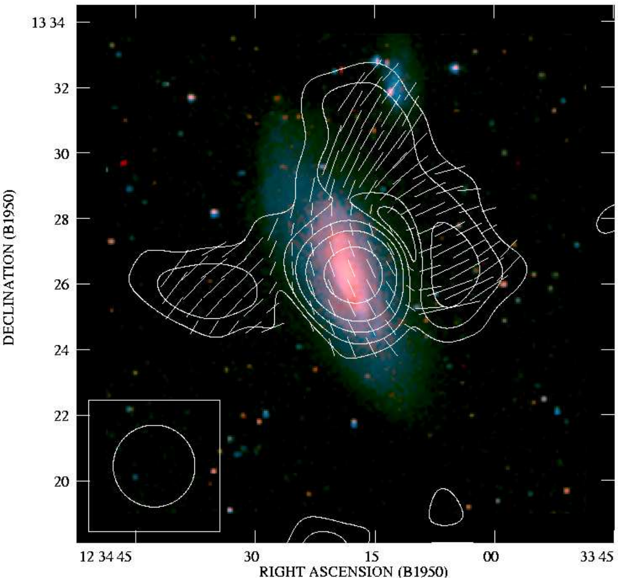

Fig. 2. Polarized emission (contours) and **B**–vectors of the spiral galaxy NGC 4569, observed at 4.8 GHz with the Effelsberg 100-m telescope. Vector lengths are proportional to the polarization degree (from Chyży et al. 2006a)

Ram pressure by a dense IGM compresses the magnetic field and leads to a highly regular or anisotropic fields, observable as strong polarized emission (Hummel & Beck 1995, Vollmer et al. 2004). Interaction-driven outflows can generate polarized emission far away from the galaxy disks (Fig. 2). Massive irregular galaxies host fields of similar strength as spiral galaxies, but with less regular, asymmetric field structure. Strongly interacting galaxies like the "Antennae" reveal compressed magnetic fields with strong polarized emission (Chyży & Beck 2004). At a redshift of z=3, the Antennae would be unresolved with the SKA, but still 2% polarized.

In conclusion, distant star-forming galaxies are expected to reveal significant polarization, even if they are not resolved by the telescope beam. Regular spiral field structures, which would yield weak polarization at large distances, were probably rare in the early Universe. This means that a large number of polarized sources will be available for the planned SKA survey of Faraday rotation measures (Gaensler et al. 2004).

6. Models of magnetic fields in young galaxies

Galactic magnetism has probably evolved in subsequent stages: primordial seed fields or ejection of seed fields into the protogalaxy by AGN jets or early supernova remnants; field amplification by compressing or shearing flows, turbulent flows, magneto-rotational instability and dynamos; and field ordering by the large-scale dynamo.

The strength and structure of galactic magnetic fields can be the result of local compression and shear by non-uniform gas flows, which were especially important in young galaxies. Otmianowska-Mazur et al. (2002) showed that the gas flow in a barred galaxy can amplify fields and generate spiral structures with coherence lengths of a few 100 pc. However, the total magnetic energy and total magnetic flux of the galaxy cannot be increased, so that additional dynamo action is required.

In MHD models of turbulent gas flows in galaxies driven by supernova explosions (de Avillez & Breitschwerdt 2005) the magnetic field is sheared and compressed by the flow. The strongest fields are located in the regions of cold, dense gas. This agrees well with the interpretation of the radio–infrared correlation (Sect. 2).

The dynamo is the only known model which is able to generate *coherent* magnetic fields of spiral shape and to increase the magnetic flux. The standard "mean-field" dynamo builds up large-scale coherent fields within about 10^9 yr (Beck et al. 1994). Faster amplification of higher dynamo modes can occur for the gas flow in a bar potential (Moss et al. 2001), or for gravitational interaction with another galaxy (Moss 1995). Such cases were more frequent in early galaxies. A spectrum of dynamo modes can be expected after several 10^8 yr, to be detected with the SKA as typical Faraday rotation (RM) patterns. Younger galaxies, however, should not host large-scale coherent fields and hence reveal no large-scale Faraday rotation.

The small-scale or fluctuation dynamo (Beck et al. 1994, 1996, Brandenburg & Subramanian 2005) amplifies turbulent, incoherent magnetic fields. It does not rely on differential rotation and can also work in small galaxies. The typical timescale is 10^6–10^7 yr. Strong turbulent magnetic fields can be expected in young galaxies with high supernova rates. Compression and shear by turbulent flows, interactions and ram pressure (Sect. 5) can further amplify the field and generate anisotropic random fields, observable as polarized radio emission.

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