Cosmic Magnetic Fields: From Planets, to Stars and Galaxies
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Magnetism in the nearby galaxy M 33

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Abstract. Using high-resolution data of the linearly polarized intensity and polarization angle at 3.6, 6.2, and 20 cm together with a 3-D model of the regular magnetic field, we study variations of the structure, strength, and energy density of the magnetic field in the Scd galaxy M 33. The regular magnetic field consists of a horizontal component (represented by an axisymmetric mode from 1 to 3 kpc radius and a superposition of axisymmetric and bisymmetric modes from 3 to 5 kpc radius) and a vertical component. However, the inferred 'vertical field' may be partly due to a galactic warp. We estimate the average total and regular magnetic field strengths as $\simeq 6.4$ and $2.5\,\mu$G, respectively. Generation of interstellar magnetic fields by turbulent gas motion in M 33 is indicated as the turbulent and magnetic energy densities are about equal.

Keywords. Galaxies: individual: M33 – radio continuum: galaxies – galaxies: magnetic field – galaxies: ISM

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1. Introduction

M 33, the nearest Scd galaxy at a distance of 840 kpc, with its large angular size and medium inclination, allows determination of the magnetic field components both parallel and perpendicular to the line of sight equally well. The RM studies of M 33 by Beck (1979) and Buczilowski *et al.* (1991) suggested a bisymmetric regular magnetic field structure in the disk of M 33. However, due to the low-resolution (1.8 kpc) and low-sensitivity of their observations, these results were affected by high uncertainty particularly in the southern half of M 33. Our recent observations of this galaxy provide high-resolution (0.7 kpc) maps of total power and linearly polarized intensity at 3.6 cm, 6.2 cm, and 20 cm presented by Tabatabaei *et al.* (2007a). These data are ideal to study the rotation measure (RM), the structure and strength of the magnetic field, and depolarization effects in detail. By combining an analysis of multi-wavelength polarization angles with modeling of the wavelength-dependent depolarization, Fletcher *et al.* (2004) and Berkhuijsen *et al.* (1997) derived the 3-D regular magnetic field structures in M 31 and M 51, respectively. The high sensitivity of our new observations allows a similar study for M 33.

2. Nonthermal degree of polarization

Using the polarized intensity maps of Tabatabaei *et al.* (2007a) and the nonthermal maps obtained by Tabatabaei *et al.* (2007b), we derived maps of the nonthermal degree of polarization at different wavelengths. Integrating the polarized and nonthermal intensity maps in the galactic plane out to a galactocentric radius of $R \leqslant 7.5$ kpc, we obtained the flux densities of the nonthermal and linearly polarized emission and the average nonthermal degrees of polarization of $10.3\% \pm 2.0\%$, $11.3\% \pm 1.9\%$, and $6.6\% \pm 0.6\%$ at 3.6 cm, 6.2 cm, and 20 cm, respectively, indicating considerable wavelength-dependent depolarization by Faraday effects at 20 cm.

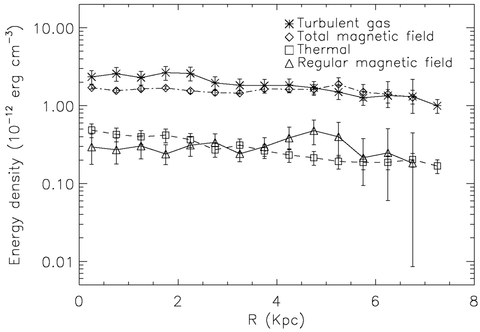

Figure 1. Energy densities and their variations with galactocentric radius in M 33.

3. The regular magnetic field structure

In order to identify the 3-D structure of the *regular* magnetic field $B_{\rm reg}$ we fit a parameterized model of $B_{\rm reg}$ to the observed polarization angles at different wavelengths. We find that the Fourier modes $m = 0 + z0 + z1$ ($z0$ and $z1$ are the first and second Fourier modes of the vertical field) in the 1–3 kpc ring and $m = 0 + 1 + z1$ in the 3–5 kpc ring can best reproduce the observed pattern of polarized intensity at 6.2 cm (see Tabatabaei *et al.* (2008) for details). The horizontal magnetic field component follows an arm-like pattern with pitch angles smaller than those of the optical arm segments, indicating that large-scale gas-dynamical effects such as compression and shear are not solely responsible for the spiral magnetic lines. The dominant axisymmetric mode ($m = 0$) in the disk in both rings indicates that galactic dynamo action is present in M 33. We also find that the fitted 'vertical field', in the outer ring, could be mainly due to the severe warp of M 33 and hence apparent. However, a real vertical field of a broadly comparable strength to the disk field can exist in the inner ring.

4. Magnetic field strengths and energy densities

The strengths of the total magnetic field $B_{\rm tot}$ and its regular component $B_{\rm reg}$ can be found from the total synchrotron intensity and its degree of linear polarization. Assuming equipartition between the energy densities of the magnetic field and cosmic rays leads to $B_{\rm tot} = 6.4 \pm 0.5\,\mu$G and $B_{\rm reg} = 2.5 \pm 1.0\,\mu$G for the disk of M 33 ($R < 7.5$ kpc).

The energy densities of the equipartition magnetic fields in the disk ($B_{\rm tot}^2/8\pi$ and $B_{\rm reg}^2/8\pi$ for the total and regular magnetic fields, respectively) are shown in Fig. 1. The energy densities of the magnetic field and turbulence are about the same, confirming the theory of generation of interstellar magnetic fields from turbulent gas motion. Furthermore, it seems that the ISM in M 33 can be characterized by a low-β plasma and is dominated by supersonic turbulence, as the energy densities of the magnetic field and turbulence are both much higher than the thermal energy density.

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