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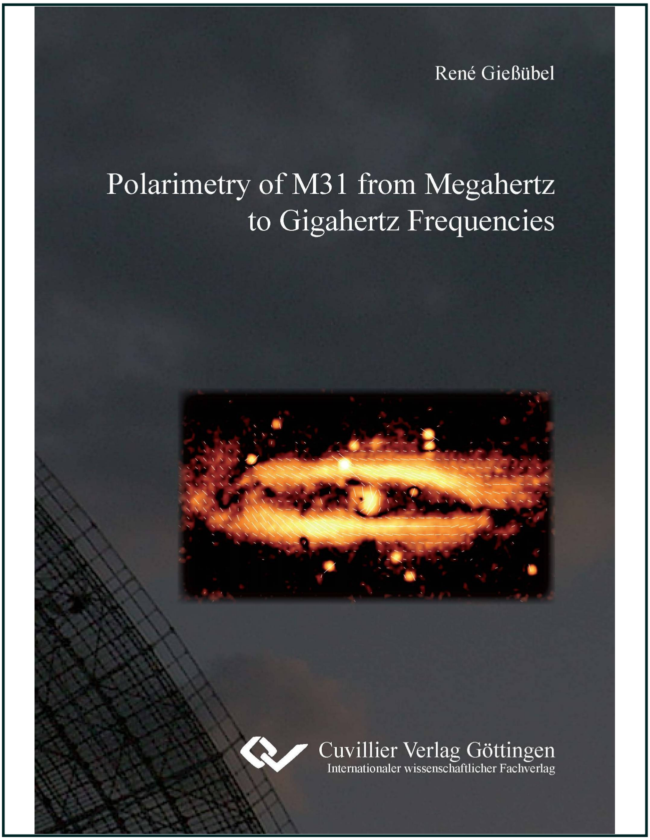
Polarimetry of M31 from Megahertz to Gigahertz Frequencies



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Chapter 1

Introduction

We are about to enter a new golden age of radio astronomy, with a number of new instruments being build (like LOFAR, Section 2.1.4) or planned (like the Square Kilometre Array (SKA)), and current telescopes receiving major upgrades which will immensely extend their capabilities. The new and updated instruments provide large bandwidth in full polarization. This results in huge amounts of data, which can only be processed thanks to today's modern computers. These developments go hand in hand with new methods of data analysis, like RM Synthesis (see Section 2.2), which can already be applied to current observational data (Chapter 6 and 7).

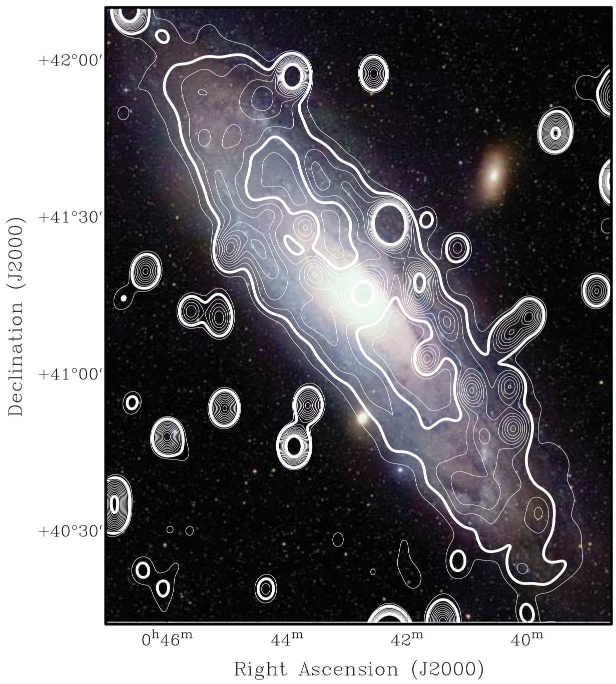

Figure 1.1: Contours of M31 at 92 cm (see Chapter 7) superimposed on an optical image of the Thüringer Landessternwarte, Tautenburg by Jens Brunzendorf and Dirk Fröbrich.

Of all wavelength domains, the radio regime is best suited for studying interstellar and intergalactic magnetic fields. Radio continuum emission is predominantly synchrotron emission, which originates from cosmic ray electrons that spiral around the interstellar magnetic field lines. This means that polarized radio emission directly traces the orientation of the magnetic field lines.
Also polarized optical and near infrared light can be used to (indirectly) trace magnetic fields, if the polarization is the result of extinction by elongated dust grains. These dust grains have a magnetic moment and thus align with the interstellar magnetic field with their major axis perpendicular to the field. The optical and near infrared extinction is strongest along this major axis of the dust grains, which results in a net linear polarization. Unlike synchrotron emission, the $\vec{E}$-vectors of the polarized emission points parallel to the magnetic field lines. But scattering by interstellar dust can also polarize the starlight, in which case the polarization is completely unrelated to magnetic fields. Hiltner (1958) was the first to detect starlight polarization in an external galaxy, the Andromeda Nebula (M31). His results showed that, like the Milky Way, M31 has a magnetic field, and that it is aligned along the galaxy's major axis.
Andromeda is the nearest grand spiral galaxy, and right after the Milky Way and the Magellanic Clouds the largest object on the sky. This makes it an ideal object for detailed studies, because even with single dish radio telescopes with relatively low angular resolution one can already achieve high spatial resolutions of less than a kiloparsec in M31, which in other galaxies can only be achieved with interferometers. At the same time its huge angular extent (around 1° by 2°) makes it quite a challenge to observe, as we will see in the following Chapters.
Table 1.1 summarizes some facts about M31 and the assumed values used for calculations in this thesis.

RA (J2000)	$00^{h}\,42^{m}\,44^{s}.3$
DEC (J2000)	$41^\circ\,16'\,9''.0$
Hubble type	Sb
Distance[1]	690 kpc
Position angle of major axis	37°
Inclination[2] (0°=face on)	78°
1′ along major axis	200 pc
1′ along minor axis	726 pc
B_{tot} (ring)[3]	$7.0 \pm 0.5\ \mu$G
B_{reg} (ring)[3]	$4.9 \pm 0.2\ \mu$G
B_{turb} (ring)[3]	$5.0 \pm 0.5\ \mu$G
Satellites	M32 (NGC221)
	M110 (NGC205)

Table 1.1: List of facts about M31 and assumed values for calculations in this thesis.

[1] Historic value for comparison with old results (de Vaucouleurs & de Vaucouleurs 1964). More recent measurements indicate a larger distance, e.g. 752 ± 27 kpc from luminosity of cepheids (Riess et al. 2012) or 744 ± 33 kpc using eclipsing binaries (Vilardell et al. 2010).

[2] Braun (1991)

[3] Equipartition field strength for the 10 kpc ring by Fletcher et al. (2004)

The first detection of polarized radio continuum emission in an external galaxy was achieved by Mathewson et al. (1972) in M51 with the Westerbork Synthesis Radio Telescope (see Section 2.1.3), the construction of which was just finished in 1970. Shortly after, Beck et al. (1978) mapped the magnetic field of M31 with the Effelsberg telescope (Section 2.1.1). It was followed by several polarization surveys at 6 cm, 11 cm and 20 cm (e.g. Beck 1982; Berkhuijsen et al. 1987; Beck et al. 1998; Berkhuijsen et al. 2003 and this thesis).
The turbulent and large-scale magnetic field is concentrated in a ring-like structure at 10 kpc radius. This star-forming "ring" is a superposition of several tightly wound spiral arms with small pitch angles, seen under a high inclination. The origin of the ring is still a matter of discussion. It is either the result of interaction with one of its satellite galaxies, M32 (Gordon et al. 2006; Block et al. 2006) or it can be explained with a major merger event between two large galaxies which possibly formed M31 (Hammer et al. 2010; Fouquet et al. 2012). Faraday rotation measures (RM) showed that the regular field of M31 is coherent, i.e. it preserves its direction around 360° in azimuth and across several kiloparsecs in radius (Beck 1982).
By now we know that all spiral (and even some irregular) galaxies exhibit an ordered magnetic field (Beck 2005) with an average field strength of 5 ± 3 μG, at which the random field can reach 3 times the strength of the ordered field (Fletcher 2010). The presence of these ordered fields on scales of the entire galaxy can be best explained by dynamo theory (Beck et al. 1996). It requires the presence of weak magnetic seed fields and an interplay of turbulence and shear to generate and maintain such a field. The turbulence can be provided by supernova explosions, while shear is a consequence of the differential rotation of the galactic disk.
The detection of M31's large-scale magnetic field was a breakthrough for galactic dynamo theory, and it still is considered the prototype of a galactic dynamo field. However, the structure of the field is unusually simple – an almost purely axisymmetric field was not found in any other spiral galaxy. The aim of this work is to provide new clues to the understanding of M31's magnetic field structure. This is achieved by utilizing new methods for data analysis, better resolutions and higher sensitivities than ever before, and by advancing into new wavelength regimes, both short and long.