Giant magnetic fields spanning across the Andromeda Galaxy

40 years of observations with the Effelsberg telescope

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Astronomers at MPIfR obtained the so far most comprehensive and detailed map of the magnetic fields in the Andromeda Galaxy, our Milky Way's neighbour, using the Effelsberg telescope. The magnetic fields form a broad ring with a diameter of 40,000-100,000 light years. The field orientation almost follows the ring, as was predicted by the dynamo theory of field origin. Such giant magnetic fields play an important role in the formation and development of galaxies.

The Andromeda Galaxy Messier 31 (M31 in short), at a distance of "only" 2.5 million light years, is the nearest spiral galaxy. It surpasses our Milky Way galaxy in size and total mass. M31 is visible to the naked eye in clear nights. Ancient Arabic star maps show M31 as a nebulous spot. Modern telescopes operating at many wavelengths allow us to study its stars, gas, and dust in unique detail. Warm dust and hot gas trace regions of recent star formation, while cold gas indicates where star formation will happen in future. Radio continuum waves open the view onto another, often neglected constituent of galaxies: the magnetic fields.

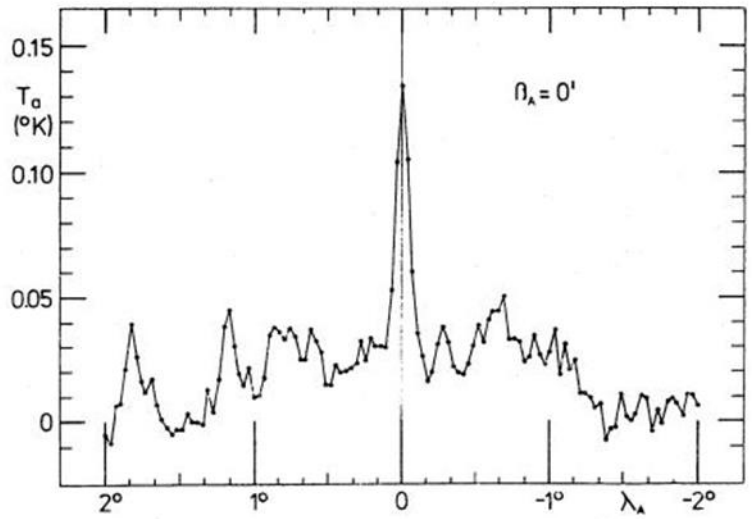

Figure 1: Scan along the major axis of M31 at 11.1 cm wavelength with the Effelsberg telescope at a wavelength of 11 cm, showing the central region and several spiral arms (from Berkhuijsen & Wielebinski, Astrophysical Letters 13, 169 (1973)).

Galaxies are continuously forming new stars. The most massive stars may explode as supernovae. These generate shock waves that rush through the gas between the stars (the interstellar medium) and accelerate particles to almost the speed of light, called "cosmic rays". If an electron (or a much rarer positron) crosses a magnetic field, it spirals around the field line and emits linearly polarized radio waves, called “synchrotron radiation”. The intensity of this emission allows us to calculate the field strength. The polarization angle indicates the field orientation in the plane of the sky. Additional measurement of the variation of the polarization angle with wavelength (“Faraday rotation”) gives the field direction along the line of sight, so that the field structure in three dimensions can be investigated.

Thanks to its enormous angular extent of about two degrees on the northern sky, M31 is an ideal target for observations with the Effelsberg telescope. Disproving the Program Committee’s skepticism, radio continuum waves from M31 could be detected already in 1972 (Figure 1), shortly after the telecope’s opening, by Richard Wielebinski, director at MPIfR from 1969 to 2004, and Elly M. Berkhuijsen, working at MPIfR since 1970. “M31 accompanied my whole scientific life. Once M31, always M31”, says Elly, remembering a forecast by Gerard de Vaucouleurs made to her around that time. The first complete radio continuum survey of M31 at 11.1cm wavelength was conducted by Elly and Richard in 1972-1973 and published in 1974 (Figure 2), followed by further surveys at 21 cm and 6.2 cm.

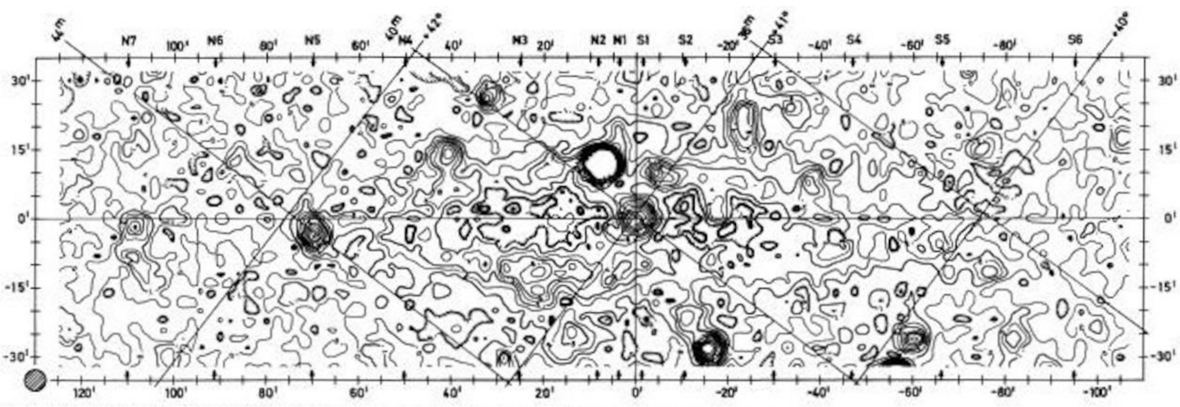

Figure 2: Total radio continuum emission from M31, observed with the Effelsberg telescope at a wavelength of 11.1 cm telescope at an angular resolution of 4.8 arcminutes, scanned parallel to the major axis of M31. The extent is about 3.9° x 1.1°. The arrows at the top edge of the plot mark the positions where the optical spiral arms cross the major axis (from Berkhuijsen & Wielebinski, Astronomy & Astrophysics 34, 173 (1974)).

In 1977, PhD student Rainer Beck discovered high degrees of linear polarization of the 11.1 cm radio emission from M31 as part of his doctoral thesis, supervised by Richard and Elly. This showed that the magnetic fields in M31 are highly ordered, which came as a surprise in view of the turbulent interstellar gas. Obviously, some process is able to generate order out of chaos.

In the following decades the receiving systems of the Effelsberg telescope were continuously improved. Between 2001 and 2012, two students at MPIfR, René Gießübel and David Mulcahy, supervised by Rainer Beck and Elly M. Berkhuijsen, conducted mapping of the total and linearly polarized emission of M31 at three radio wavelengths (3.6 cm, 6.2 cm, and 11.3 cm). The galaxy was scanned in strips many times to increase the sensitivity, which took more than 300 hours of observation in total. Worldwide, only the Effelsberg radio telescope is suited for such a mammoth task. The radio maps were first presented in René Gießübel's PhD Thesis and in David Mulcahy's Master Thesis. The detailed evaluation took several more years of work. The results were published in Astronomy & Astrophysics 633, A5 (2020) (https://www.aanda.org/articles/aa/pdf/2020/01/aa36481-19.pdf).

Figure 3 shows the intensity of the radio emission at 3.6 cm wavelength in colour and the orientation of the magnetic fields as white lines. The intensity is concentrated in a broad ring that is seen almost edge-on (inclined by about 75°) and extends between about 20,000 and 50,000 light years distance from the centre. With a ring thickness of only about 1,500 light years, the shape is that of a playing quoit. The field lines follow the ring almost everywhere, though slightly twisted with a systematic pitch angle of about 20°. If M31 would be seen face-on, its magnetic field would appear as a tightly wound spiral. According to Figure 3, the region close to the center hosts its own spiral field, but with a more open winding than that of the ring.

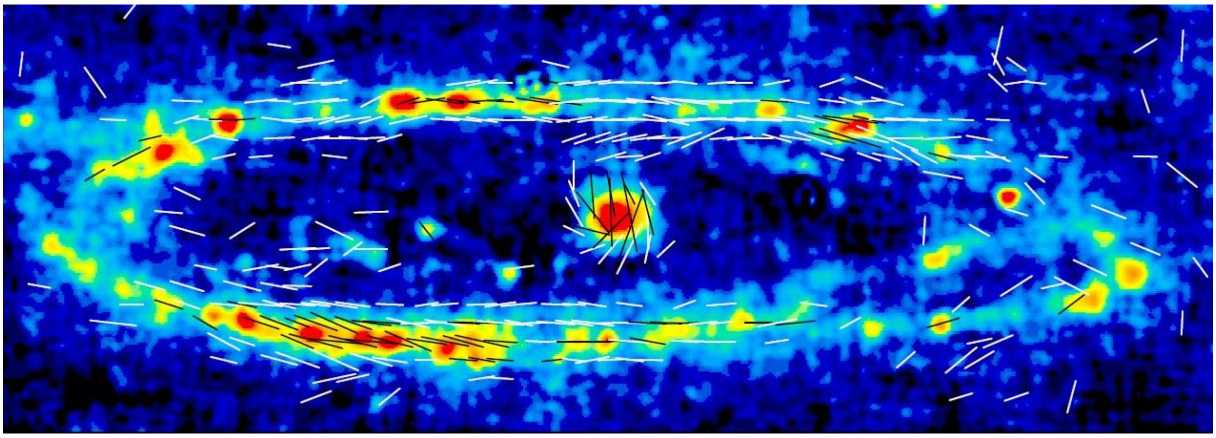

Figure 3: Total and linearly polarized radio continuum emission from M31 at 3.6 cm wavelength, observed with the Effelsberg telescope at an angular resolution of 1.5 arcminutes, scanned parallel to the major axis of M31. The extent is about 1.8° x 0.6°. Colour: intensity of the radio emission; white lines: orientation of the magnetic fields.

The comparison of the polarization angles between the three wavelengths shows a clockwise rotation (positive Faraday rotation) in the left part but a counter-clockwise rotation (negative Faraday rotation) in the right part of the image (Figure 4). This means that the magnetic field points away from us on the left and towards us on right, confirming that the field follows the inclined ring.

A regular magnetic field of such giant dimension seems to be at odds with the disorder in the galaxy's gas motions. Just one theory is able to explain this amazing observation. Fritz Krause and Karl-Heinz Rädler (both at Potsdam, Germany), Eugene Parker (at Chicago), and Anvar Shukurov and Dmitry Sokoloff (both at Moscow) developed the theory of the "galactic dynamo" in the 1960s and 1970s, claiming that within a few billion years, small-scale "seed fields" in the star-forming gas of a galaxy's disk would combine and form a large-scale field in the disk with help of the galaxy's general rotation. This field is described by "modes" with respect to their symmetry. The observations of M31 allow us to identify two modes, a strong axisymmetric one plus a weaker bisymmetric one. This is why the new Effelsberg maps of M31 give the so far most impressive support of this theory, making M31 a prototypical case. Magnetic fields in planets and stars are probably also generated by dynamos, but are much more difficult to investigate because those bodies are not transparent to radio waves.

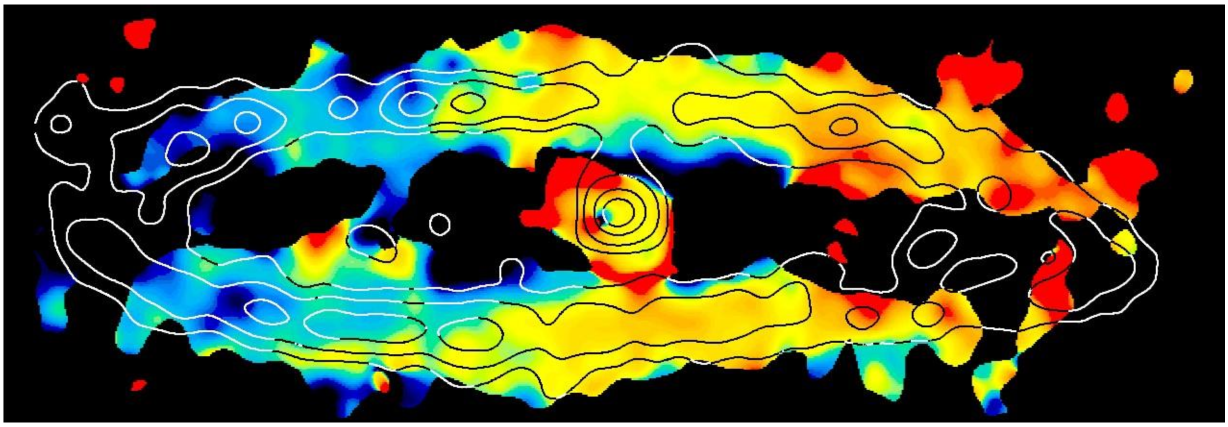

Figure 4: Magnetic field directions in M31, derived from the Faraday rotation of the polarization orientations between 3.6 cm and 6.2cm wavelengths at an angular resolution of 3 arcminutes. ***Blue:*** *clockwise rotation - the field points away from us;* ***red:*** *counter-clockwise rotation - the field points towards us.*

Several other spiral galaxies show dynamo-generated magnetic fields as well, though with more complex structures. Another exceptional property of M31 is the lack of a detectable radio halo. Halos observed around most spiral galaxies seen in almost edge-on view are thought to be generated by "galactic winds" that transport gas, magnetic fields, and cosmic ray particles from the disk into the halo. The wind in M31 is weak or may be lacking at all, which is at odds with the idea that outflows support the action of the dynamo in the disk.

We also found disordered (turbulent) magnetic fields in M31 via the unpolarized radio emission, but these are weaker than in most other spiral galaxies. Turbulent fields are produced by turbulent gas motions energized by supernova remnants and stellar winds. The weakness of turbulent fields in M31 is in line with its low rate of star formation.

Magnetic fields in spiral galaxies are sufficiently strong to affect gas motions, the formation of new stars, and the shaping of spiral arms. There is increasing evidence that magnetic fields also play a role for the formation of galaxies. Numerical models of galaxy evolution are being developed, e.g. with the powerful supercomputers at the astrophysical institutes in Potsdam and Garching.

Published in: Effelsberg Newsletter, Volume 11, Issue 2 (May 2020), p. 5-8