RESULTS FROM RADIO OBSERVATIONS IN GALACTIC MAGNETIC FIELDS

Results from Radio Observations

Magnetic Field Strengths in Galaxies

Total magnetic field strengths can be determined from the intensity of total synchrotron emission, assuming energy balance (*equipartition*) between magnetic fields and cosmic rays. This assumption seems valid on large spatial and time scales, but deviations occur on local scales in galaxies. The typical average equipartition strength for spiral galaxies is about 10 μG (microGauss) or 1 nT (nanoTesla). For comparison, the Earth's magnetic field has an average strength of about 0.3 G (30 μT). Radio-faint galaxies like M 31 (Fig.3) and M 33, our Milky Way's neighbors, have weaker fields (about 5 μG), while gas-rich galaxies with high star-formation rates, like M 51 (Fig.1), M 83 and NGC 6946 (Fig.2), have 15 μG on average. In prominent spiral arms the field strength can be up to 25 μG, in regions where also cold gas and dust are concentrated. The strongest total equipartition fields (50-100 μG) were found in starburst galaxies, for example in M 82 and the *Antennae*, and in nuclear starburst regions, for example in the centers of NGC 1097 and of other barred galaxies.

Galactic fields are sufficiently strong to be dynamically important: they drive mass inflow into the centers of galaxies, they modify the formation of spiral arms and they can affect the rotation of gas in the outer regions of galaxies. Magnetic fields provide the transport of angular momentum required for the collapse of gas clouds and hence the formation of new stars.

The degree of radio polarization within the spiral arms is only a few %; the field in the spiral arms must be mostly tangled. The ordered (regular or anisotropic) fields traced by polarized synchrotron emission are generally strongest (10-15 μG) in the regions between the optical spiral arms. This can be explained by a dynamo wave which is phase shifted with respect to the density wave producing the spiral arms.

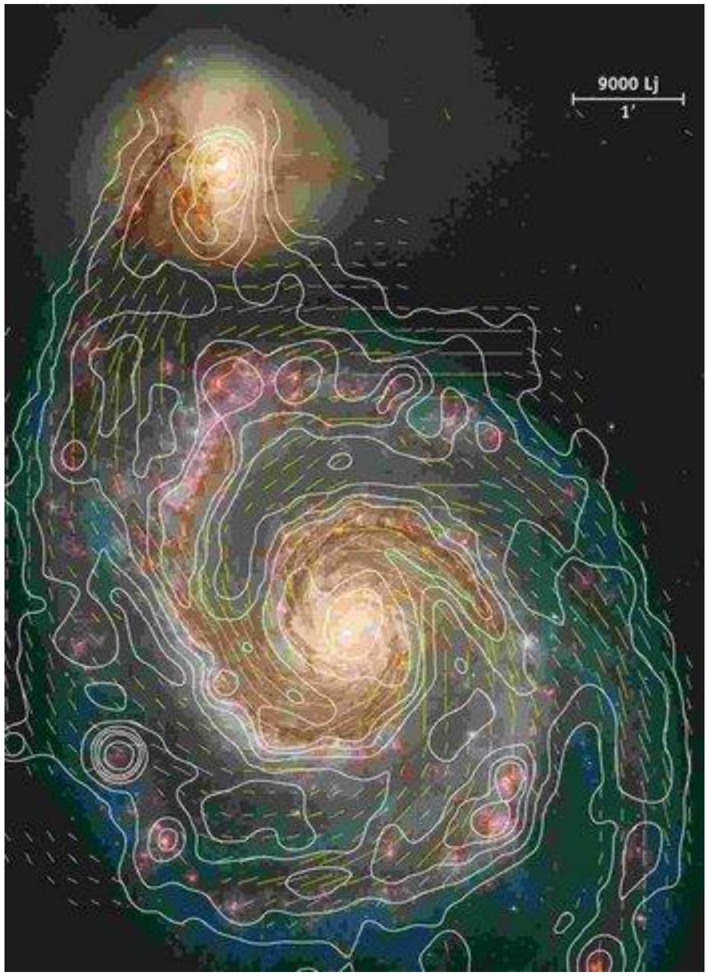

Figure 1: Optical image of the spiral galaxy M 51 obtained with the Hubble Space Telescope (from Hubble Heritage), overlaid by contours of the total radio intensity and polarization vectors at 6cm wavelength, combined from radio observations with the Effelsberg and VLA radio telescopes (from Fletcher et al. 2011). The magnetic field follows well the optical spiral structure, but the regions between the spiral arms also contain strong and ordered fields. The bar in the top right corner indicates a scale of 1 arcminute or about 9000 light years (about 3 kiloparsecs) at the distance of the galaxy. Copyright: MPIfR Bonn

Magnetic Field Structure in Galaxies

The magnetic field forms nice spiral patterns in almost every galaxy, even in flocculent and bright irregular types which lack any spiral optical structure (Beck & Wielebinski 2013). This is regarded as a strong argument for the action of galactic dynamos. Spiral fields are also observed in the central regions of galaxies and in circum-nuclear rings of gas. In galaxies with massive spiral arms, the magnetic field lines run mostly parallel to the optical arms, but are concentrated at the inner edge of the spiral arms or between the spiral arms (as an example, see Fig.1). In several galaxies, the field forms independent *magnetic arms* between the arms, as in NGC 6946 (Fig.2). In galaxies with massive bars, the field pattern seems to follow the gas flow. As the gas rotates faster than the spiral or bar pattern of a galaxy, a shock occurs in the cold gas which has a small sound speed, while the warm, diffuse gas is only slightly compressed. As the observed compression of the field in spiral arms and bars is also small, the ordered field is coupled to the warm gas and is strong enough to affect the flow of the warm gas.

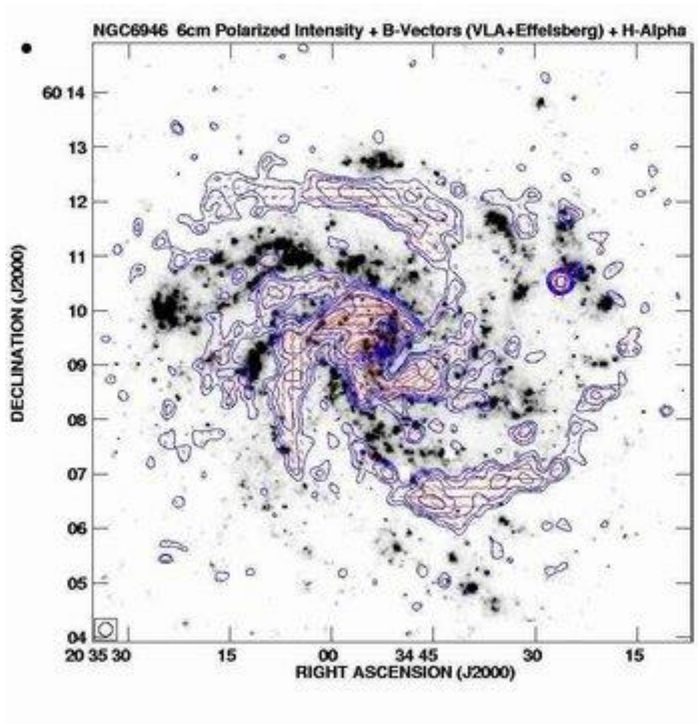

Figure 2: Optical image of the spiral galaxy NGC 6946 in the Hα line (from Ferguson et al. 1998), overlaid by contours of the polarized radio intensity and radio polarization vectors at 6cm wavelength, combined from observations with the Effelsberg and VLA radio telescopes (from Beck and Hoernes 1996). This galaxy shows strong regular fields between the optical spiral arms. Copyright: MPIfR Bonn

Large-scale patterns of Faraday rotation observed in a few spiral galaxies reveal regular fields with a large-scale constant direction, as predicted by dynamo models. The Andromeda galaxy M 31 (Fig.3) hosts a dominating axisymmetric field, the basic dynamo mode, which extends to at least 15 kpc distance from the centre (one kiloparsec (kpc) corresponds to 3260 light years). Other candidates for a dominating axisymmetric field are the nearby spiral IC 342 and the irregular Large Magellanic Cloud (LMC). The field structures in M 51 and NGC 6946 (Figs.1 and 2) can be described by a superposition of two dynamo modes. However, in most galaxies observed so far no clear patterns of Faraday rotation could be found. Either many dynamo modes are superimposed and cannot be distinguished with the limited sensitivity and resolution of present-day telescopes, or most of the ordered fields traced by the polarization vectors are anisotropic (with frequent reversals), due to shearing or compressing gas flows.

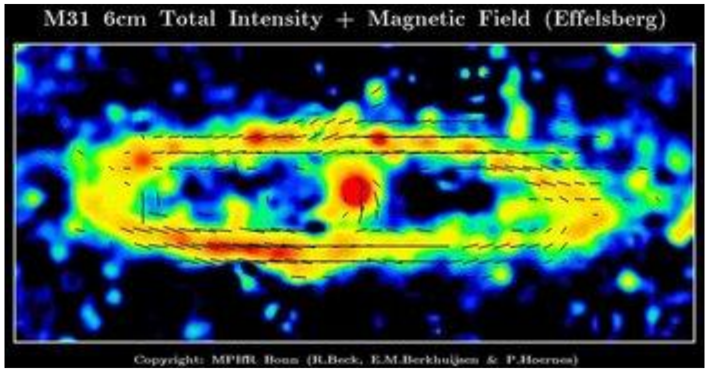

Figure 3: Intensity of the total radio emission at 6cm wavelength (colours) and polarization vectors of the highly inclined Andromeda Galaxy, M 31, observed with the Effelsberg telescope (from Berkhuijsen, Beck and Hoernes 2003). The radio emission is concentrated in a ring-like structure at about 10 kiloparsec radius where the magnetic field is exceptionally regular on scales of several kiloparsecs. Copyright: MPIfR Bonn

Galaxies seen in edge-on view possess radio halos with exponential scale heights of 1-2 kpc. The magnetic field orientations are mainly parallel to the disk near the plane, but vertical components are visible at above and below the plane and also at large distances from the center (Fig.4). A prominent exception is the edge-on spiral galaxy NGC 4631 with the brightest and largest radio halo observed so far, composed of vertical magnetic spurs connected to star-forming regions in the disk. The observations support the idea of a *galactic wind* which is driven by star formation in the disk and transports gas, magnetic fields and cosmic-ray particles into the halo.

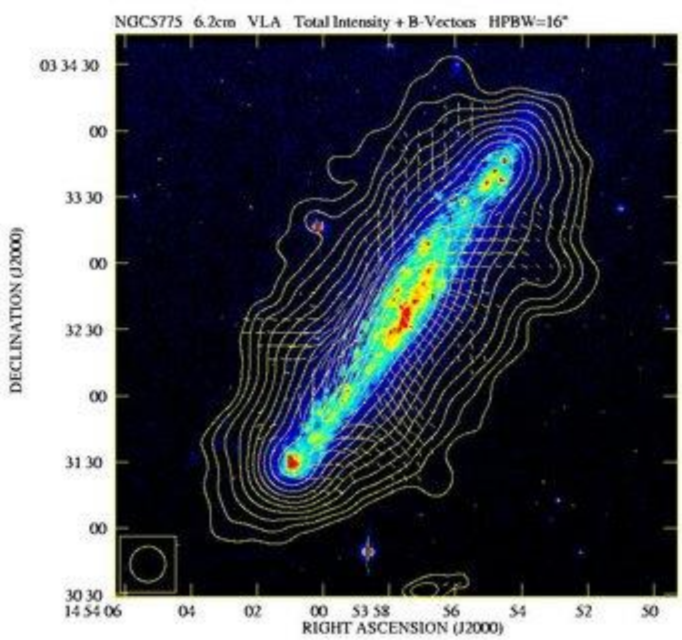

Figure 4: Optical image in the Hα line of the spiral galaxy NGC 5775 which is seen almost edge-on, overlaid by contours of the intensity of the total radio emission at 6cm wavelength and polarization vectors, observed with the VLA (from Tüllmann et al. 2000). The field lines are parallel to the disk near the plane, but turn vertically above and below the disk. Copyright: Cracow Observatory

Magnetic Fields in the Milky Way

According to radio synchrotron, optical polarization and Zeeman splitting data, the average strength of the total magnetic field in the Milky Way is about 6 μG near the Sun and increases to 20-40 μG in the Galactic center region. Radio filaments near the Galactic center and dense clouds of cold molecular gas host fields of up to several mG strength (Heiles & Crutcher, in Wielebinski & Beck 2005). Outside the central region, the large-scale field is mostly parallel to the plane of the Galactic disk. Faraday rotation measurements from the polarized radio emission of pulsars with known distances allow to investigate the structure of the Milky Way's magnetic field in three dimensions with much higher resolution than in external galaxies. The overall field structure follows the optical spiral arms, like in other galaxies, but additionally one large-scale field reversal in the disk, inside the solar radius, and several distortions near star-forming regions were discovered (Beck & Wielebinski 2013). More large-scale field reversals in the disk have been proposed, but need confirmation by improved observations.

The diffuse polarized radio emission from the Milky Way as observed with radio telescopes and with the WMAPsatellite and the Faraday rotation measures (RM) from polarized background sources were analyzed to obtain an overall model of the Milky Way's magnetic field (Sun et al. 2008, Jansson & Farrar 2012). The field reversal inside the solar radius was confirmed. The sign of the magnetic field in the disk is the same above and below the plane, but a field reversal in the Milky Way halo beyond about 1 kpc (about 3000 light years) height is required. Such a vertical reversal would be very hard to detect in external galaxies. New RM measurements of sources behind the Galactic plane by Van Eck et al. (2011) gave further evidence that the Milky Way hosts a spiral field with one reversal.

Radio polarization surveys of the Milky Way also revealed a wealth of parsec-scale structures in the magnetized interstellar medium (Reich 2006).

Future Radio Telescopes

Present-day radio polarization observations are limited by sensitivity and angular resolution. The best available spatial resolution is 100-300 pc (one parsec (pc) corresponds to 3.26 light years) in the nearest spiral galaxies and 10 pc in the nearest galaxy, the Large Magellanic Cloud. The Jansky Very Large Array (JVLA,https://public.nrao.edu/telescopes/vla) and the Square Kilometre Array (SKA, http://www.skatelescope.org), construction of phase 1 planned for 2018-2023 at two sites (Southern

Africa and Western Australia), will have much improved sensitivity at centimetre and decimetre wavelengths (Carilli & Rawlings 2004, Beck 2010). The SKA will allow to study magnetic field structures at resolutions more than 10 times better than today (Beck et al. 2015). The SKA will discover thousands of new pulsars in the Milky Way which will enormously increase the number of Faraday rotation measurements and hence provide a detailed map of the magnetic field structure.

At long wavelengths of a few metres, a new-generation radio telescope, the Low Frequency Array (LOFAR), has started full operation in 2012. 38 of the 46 stations are operating in the Netherlands (http://www.lofar.org), five in Germany (http://www.lofar.de), and one each in the UK (http://www.lofar-uk.org), in France (http://www.obs-nancay.fr/index.php/en/instruments/lofar) and in Sweden (http://lofar-se.org). Extension to further European countries are planned. Among many other observing possibilities, LOFAR is able to trace radio synchrotron emission from low-energy cosmic rays in weak magnetic fields. This allows us to observe the outermost regions of galaxies which are only accessible via radio waves. The first galaxy observed in detail is M 51 (Mulcahy et al. 2014).

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