RADIO CONTINUUM EMISSION OF THE MILKY WAY AND NEARBY GALAXIES

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ABSTRACT: The radio continuum emission of the Milky Way and nearby galaxies can be decomposed into a central region, a clumpy "thin disk", concentrated in the spiral arms, and a smooth "thick disk" (or flattened "halo"). The emissivity ratio of the two disks seems to be related to the magnetic field properties: Galaxies with strong radio spiral arms reveal a highly ordered field following the arm direction, while galaxies with diffuse disks contain a less ordered, smoothly distributed field. The degree of uniformity of the field seems to correlate with the total optical luminosity. The average magnetic field in the Milky Way is weak and turbulent compared to most of the nearby galaxies observed so far.

1. THE MILKY WAY

Our unfavourable position inside the Milky Way requires all-sky surveys in order to derive the general shape and structure of our Galaxy. Following the tradition of the "Bonner Durchmusterung" by F.W. Argelander more than 120 years ago, surveying the radio sky is being continued by radio astronomers at Bonn. An all-sky survey was completed recently at 408 MHz (λ73 cm) (Haslam et al., 1982) as well as the northern part of a companion 1420-MHz (λ21 cm) survey (Reich, 1982). Further studies at 2700 MHz (λ11 cm) have been started which concentrate on the galactic-plane region ($|b| \leqq 20°$).

Radio continuum emission is a probe of the high-energy component of the interstellar medium. The 408-MHz survey reveals various components: the central region, the disk, spiral arm complexes, loops, spurs, supernova remnants, and HII regions. The separation of these components requires spectral-index information, e.g. from the 408-MHz and 1420-MHz surveys which match in angular resolution and sensitivity. The global spectral index of brightness temperature is close to 2.7. Loop structures, however, show a steeper spectral index. A local feature in the Perseus-Cassiopeia region ($115° \leqq \ell \leqq 165°$) exhibits a high-frequency spectral break which correlates with the bend at $\sim$10 GeV in the local cosmic-

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ray electron spectrum (Kallas et al., 1983). If spectral breaks frequently occur in our Galaxy, they would influence the global radio spectrum and affect the separation of thermal and nonthermal emission.

Surveys of the galactic plane need higher resolution in order to separate small-scale from large-scale structures (e.g. Altenhoff et al., 1978; Haynes et al., 1978; Kallas and Reich, 1980; Sofue et al., 1985). The Effelsberg 100-m telescope is involved in further sensitive surveys. Several old supernova remnants have been discovered so far (e.g. Reich et al., 1979; Reich and Braunsfurth, 1981). Improved SNR statistics are needed to compute their direct contribution to the total radio emission of the Milky Way.

The 408-MHz survey has been analyzed to obtain the large-scale structure of our Galaxy by Phillipps et al. (1981a,b) and by Beuermann et al. (1984) (see also Kanbach, 1983). The face-on view is in agreement with a 2-arm or a 4-arm spiral model with a pitch angle of 12 - 13°. The magnetic field strength is ∿ 5 μG on average, with about equal contributions of uniform and random fields. The radial scale length is ∿ 2 kpc for the thermal and ∿ 5 kpc for the nonthermal component (see Berkhuijsen and Klein, 1985). The edge-on view is differently modelled by the two groups: Phillipps et al. (1981b) use a thin disk plus a flattened, box-shaped "halo", while Beuermann et al. (1984) prefer a thin disk with a full width between half-intensity points increasing with distance from the Galactic Centre (250 - 690 pc) plus a thick disk with increasing full width (2 - 6 kpc) (Fig. 1). A similar two-disk model had already been suspected by Yates (1968) and discussed in detail by Ilovaisky and Lequeux (1972). The thin disk contains contributions from

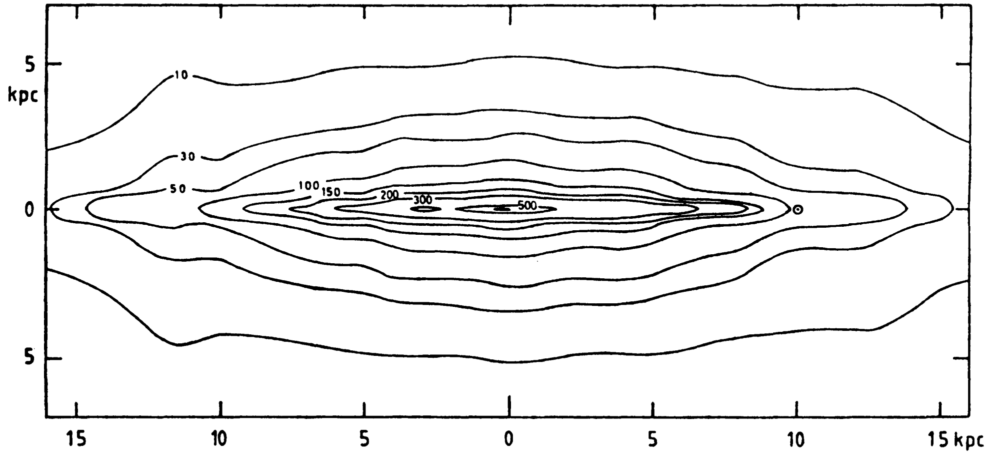

Fig. 1: Edge-on view of the Galaxy at 408 MHz as seen from the direction ℓ = 90°. The picture includes the emission from the thin and thick disk. The contour intervals are given in degrees K; the 30 K level corresponds to about 1 K at 1415 MHz (from Beuermann et al., 1984)

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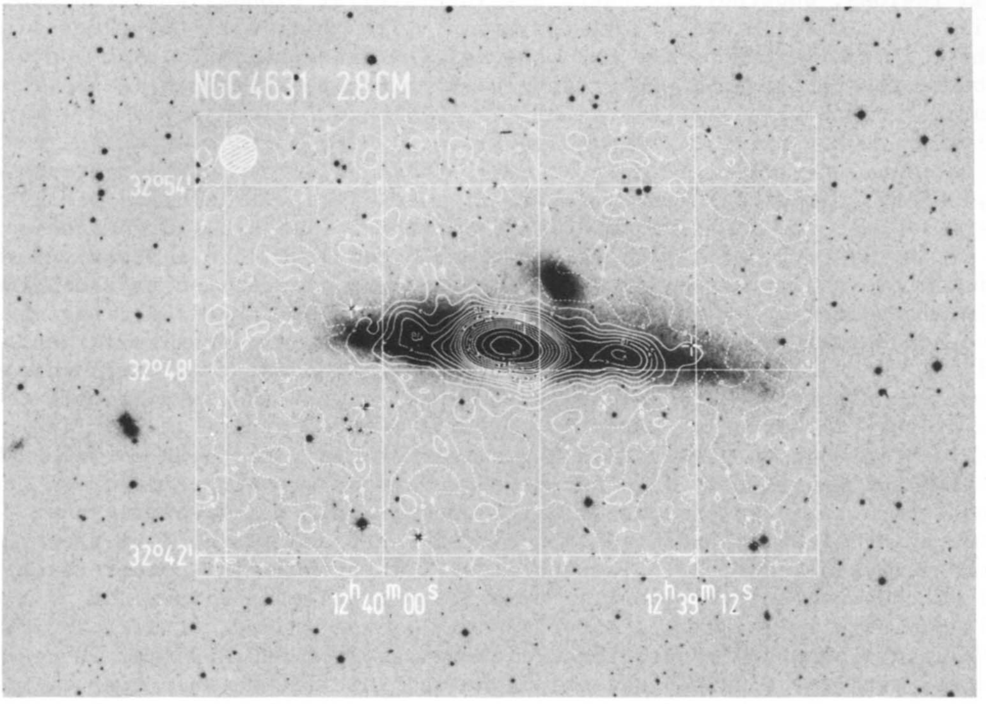

Fig. 2: Effelsberg map of NGC 4631 at 10.7 GHz (λ2.8 cm), superimposed onto an optical PSS plate. Contour levels are: 0 (dashed), 2, 4, ..., 10, 13, ..., 40, 50, 60 mJy/beam area (1 mJy/b.a. ≙ 1.9 mK). The angular resolution is 71 arcsec (hatched circle) (from Klein et al., 1984).

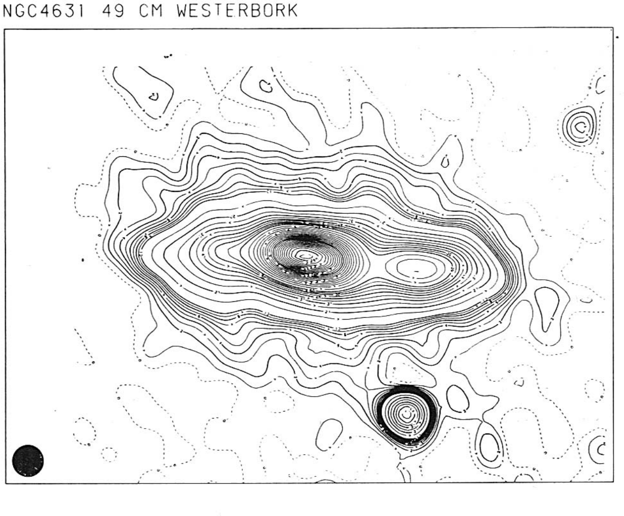

Fig. 3: New Westerbork map of NGC 4631 at 610 MHz (λ49 cm) by W. Werner. Contour levels are in mK. The map has been smoothed to the same angular resolution as in Fig. 2.

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HII regions, supernova remnants and interstellar clouds, while the thick disk emits diffuse nonthermal radiation. The thick disk coincides with the volume occupied by the hot phase of the interstellar medium and by cosmic rays which are accelerated in supernova shock fronts (e.g. Axford, 1982; Bogdan and Völk, 1983).

2. NEARBY GALAXIES

The discrepancies between the present models will not be solved within the near future. Nearby galaxies are better suited to study the global radio properties of spiral galaxies. In M31 (NGC 224), thermal and nonthermal radio emission are concentrated in a ring-like structure with ∿1 kpc full width (Beck and Gräve, 1982). No extended disk emission has been observed. Any halo emission must be weak and is difficult to separate from confusing Galactic emission (Gräve et al., 1981). The only known edge-on galaxy with a prominent thick radio-disk is NGC 4631 (Ekers and Sancisi, 1977). Recent observations with the Effelsberg and Westerbork radio telescopes (Figs. 2 and 3) confirm a spectral-index steepening with increasing distance from the plane and will be used to test galactic-wind models (Werner et al., in prep.). All other thick disks observed so far reveal an emissivity of only a few percent of the disk emissivity and a full width of only ∿1 kpc (Hummel et al., 1984). The significantly stronger thick-disk emission of NGC 4631 may be connected with the finding that its magnetic field in the thin disk is more ordered than in other edge-on galaxies, e.g. NGC 253 (Klein et al., 1983).

In face-on galaxies two components can be distinguished in radio continuum: a clumpy component (thermal and nonthermal), concentrated in the spiral arms, and a smooth nonthermal component. They can be identified as the thin and thick disks observed edge-on. The ratio of emissivities of these components determines whether radio arms dominate (e.g. in M31 and M51) or strong diffuse disks (e.g. in NGC 6946; Klein et al., 1982). The different ratios between thin- and thick-disk emissivities have to be considered as the result of the interstellar magnetic field interacting with the processes of cosmic-ray acceleration and propagation.

The energy sources for the acceleration of cosmic-ray electrons must belong preferentially to the spiral-arm population (e.g. type II supernovae), because correlations were found between the radio-to-optical-flux ratio and the optical colour (Klein, 1982) and between the total radio and Hα fluxes (Kennicutt, 1983). The different radial scale lengths of the thermal and nonthermal radio emission (Sancisi and Van der Kruit, 1981; Berkhuijsen and Klein, 1985) require diffusion lengths for cosmic-ray electrons of a few kiloparsecs. If cosmic rays are scattered by magnetic-field irregularities, they cannot stream faster than with the Alfvén speed. Our understanding of this interaction demands better observational data about interstellar magnetic fields.

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3. MAGNETIC FIELDS

The linearly polarized emission of a few nearby galaxies has been mapped with the Effelsberg telescope (Beck, 1982; Klein et al., 1982, 1983). Magnetic field lines follow spiral arms, but their overall structure is probably closed, in agreement with the theory of turbulent interstellar dynamos (Beck, 1983). The average degree of alignment of the field correlates with total optical luminosity (Fig. 4), indicating a connection between star formation and field ordering, e.g. by density-wave shock fronts. The average magnetic field strength, on the other hand, does *not* correlate with total luminosity. Strongest fields occur in galaxies with massive spiral arms. Hence, introduction of magnetic fields into the theory of stochastic star formation (Seiden, 1985) is promising.

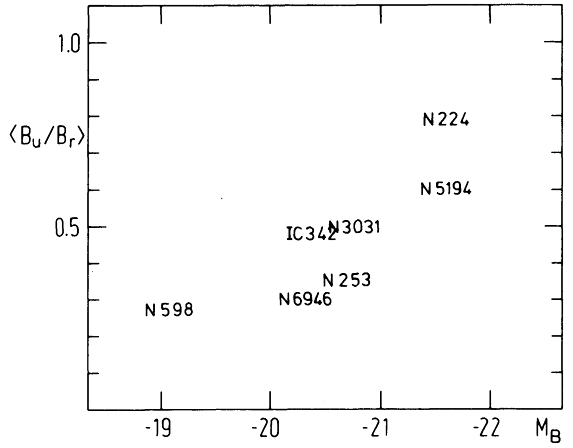

Fig. 4: The correlation between the average ratio B_u/B_r of the uniform and random magnetic field strengths and the total optical luminosity M_B. B_u/B_r refers to similar linear resolutions of ~ 3 *kpc.*

The Milky Way fits into these relations: Its moderate luminosity ($M_B \cong -20$) indicates a low degree of alignment of the magnetic field, in agreement with the observations; its intermediate luminosity class (L ≅ II) is in accordance with the low magnetic field strength observed. The field structure, however, is still under debate. A bisymmetric model was proposed by Simard-Normandin and Kronberg (1980) and Sofue and Fujimoto (1985) on the basis of rotation-measure data, while a closed configuration is favoured by Inoue and Tabara (1981) and Vallée (1983).

Radio observations of nearby galaxies have proved to be fertile to understand the physics of the interstellar medium in the Milky Way. In particular, the role of magnetic fields for the formation of disks and spiral structures has to be considered seriously.

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