DISTRIBUTION OF NON-THERMAL EMISSION IN GALAXIES

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INTRODUCTION

The properties of the radio continuum emission from spiral galaxies have been reviewed by Van der Kruit and Allen (1976) and by Van der Kruit (1978). In more recent years the major developments in the understanding of the radio continuum properties and the underlying physical conditions of galaxies have come from a number of surveys of large samples of objects. Some of these surveys (e.g. Hummel, 1980a) have good sensitivity and sufficiently high angular resolution to allow for the first time a clear separation of central sources and disk emission and a study of the properties of these components in a large number of galaxies. As a consequence some results already found, suggested or only suspected in previous detailed investigations of a limited number of objects are put on a firmer basis or entirely new aspects are revealed.

We will summarize here mainly the results on the non-thermal radio emission from disks and halos of spiral galaxies and only make a few remarks on the relation with central sources in general and on the completely different behaviour of SO and elliptical galaxies. The central radio sources are discussed in detail by Hummel (paper in this Symposium).

DISK AND HALO EMISSION

The radio continuum emission from spiral galaxies is mainly non-thermal (synchrotron radiation) and depends on the density of relativistic electrons and on the magnetic field strength. The main new results on the disk emission come from the survey of a large sample of galaxies at 1415 MHz by Hummel (1980a) with the Westerbork Synthesis Radiotelescope, and by the study of a number of nearby galaxies at high frequencies (up to 10.7 GHz) with the Effelsberg radiotelescope (Klein and Emerson, 1980). In these studies the emission from the disk and from the halo region are not separated. Some of Hummel's main results are:

1) The mean radio power of the disk emission is directly proportional to the mean optical luminosity.
2) The disk component gives in general the major contribution (more than

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90 percent) to the total radio power. This contribution increases with morphological type.

3) The radio emissivity of the disk is not related to the radio power of the central source.
4) The radio emissivity per unit light of the disk does not depend on the presence of a bar, on the degree of development of the spiral arms (luminosity class), on the colour or on the presence of a companion. But it does depend on the morphological stage of the galaxy: it has a maximum for the intermediate (Sb-Sc) types and becomes significantly lower for the early (factor 2 to 3) and the late types (almost a factor 2).

These observational results lead Hummel to conclude that in general: i) central sources do not contribute a significant amount of relativistic electrons to the disk component, ii) density waves must play a very unimportant role in determining the radio-continuum emissivity, and iii) the main source of relativistic electrons does not belong to the young extreme population in the spiral arms, but rather to the old disk population, which provides most of the light in a galaxy. This was first suggested by Van der Kruit, Allen and Rots (1977) based on observations of NGC 6946.

The radial distribution - This has previously been discussed by Van der Kruit (1978). The most detailed information on the distribution in the disk of the non-thermal radio emission and of its spectral index comes from the high-resolution, multi-frequency observations of NGC 6946 (Van der Kruit et al., 1977), of M51 (Van der Kruit, 1977) and M31 (see paper by Beck and Klein in this Symposium). The studies of NGC 6946 and M51 indicate, in agreement also with Hummel's conclusions for a larger sample (see above), that the radial distribution of non-thermal emission correlates with the total stellar disk population rather than the extreme population I. It should be emphasized, however, that this does not necessarily prove that the sources of relativistic electrons are to be found mainly in the old disk population. But if the sources of cosmic ray electrons would belong mainly to the young population then there must be some way in which the mass density and total mass of the old disk population control the magnetic field strength and the propagation properties of the particles, and consequently also the distribution of volume emissivity and the total radio power.

The observed spectra of radio emission in these galaxies steepen with radius from the center to the other parts. It is not clear how much of this variation of spectral index is due to mixing with thermal emission in the inner parts, and how much is a real steepening of the non-thermal spectrum, to be explained by energy losses of the relativistic electrons and/or variation of the magnetic field strength. After some tentative correction for the thermal emission the spectrum of the non-thermal component still tends to steepen at the edges of the disk as in the case of M31 studied by Beck (see paper by Beck and Klein in this Symposium).

The thermal contribution - The question of the relative amount of thermal and non-thermal emission in a disk and of their separation is still a matter of debate. Observations at high radio frequencies (> 10 GHz), where the thermal contribution is expected to become dominant are important to settle this question. The recent observations of Klein and Emerson (1980) of a number of nearby normal spiral galaxies at 10.7 GHz indicate that the relative amount of thermal emission from galaxies at radio wavelengths is less than previous work (see Van der Kruit, 1978) had suggested. The galaxies studied show straight-line spectra ($\alpha = -0.70$) over the frequency range at least from 0.4 to 10.7 GHz and none shows the flattening at the higher frequencies which would be expected in the case of substantial thermal emission. Klein and Emerson conclude that the thermal content of the integrated emission at 10.7 GHz must be less than 40 percent (and correspondingly less than 14 percent at 1.4 GHz) and that much higher frequencies would have to be observed before the thermal emission can be unambiguously separated from the non-thermal component and before it becomes dominant. Their conclusion depends critically, however, on the assumption of a straight spectrum of the non-thermal emission at high frequencies.

The integrated spectra - A striking result of this study by Klein and Emerson and of their compilation of the best available fluxes is that the spectra of these galaxies between 0.4 and 10.7 GHz are all power-law spectra and all possess a spectral index close to -0.70, with peak deviations of only ± 0.14. This is remarkably similar (same shape and value) to what is found in radio galaxies (see Moffet, 1975), possibly indicating that the same acceleration mechanism is at work.

Polarized emission - Some new results have been obtained recently on the polarized radio emission from the disk of galaxies, which give information on the general distribution and direction of the magnetic fields. The optical polarization of starlight has already been observed in the disks of M31, M51, M81 and some other spiral galaxies. The first detection of polarized radio emission was made by Segalovitz, Shane and De Bruyn (1976) at 21 and 6 cm in M51. Recently Beck, Berkhuysen and Wielebinski (1980) have mapped the polarized radio emission at λ 11.1 cm in M31. This emission is concentrated in a ring around the center of M31 in the same region of the optically brightest arms. The polarization is on average $\sim$ 15 percent and indicates a large-scale regularity of the magnetic field.

The z-distribution - The z-distribution of radio emission has been studied only in a small number of edge-on galaxies. The situation is not significantly changed since the review by Van der Kruit (1978). The two clearest cases with emission at high z-distances from the plane (up to 6 and 8 Kpc) at frequencies around 1415 MHz are NGC 891 (Allen, Baldwin and Sancisi, 1978) and NGC 4631 (Ekers and Sancisi, 1977). More recently Beck, Biermann, Emerson and Wielebinski (1979) have reported detection of emission at large z-distances also in NGC 253 at 8.7 GHz.

These studies have not gone much beyond the detection of a flattened halo (or thick disk) and the discovery that the non-thermal spectrum tends to become steeper with increasing z-distances from the galactic plane. The spectral index changes typically from values of -0.6 near the plane to values of ∿ -1.0, -1.5 at high z. But the shape of the spectral index dependance on the z-distance is certainly not determined accurately enough yet to allow a detailed comparison with theoretical models.

The relative amount of radio flux from the halo and from the disk is not well determined. There is no clear separation of these two components. In the case of NGC 891 a thin component confined to the plane and a broad component of steeper spectrum have been tentatively identified in the observations at 5 GHz (Allen et al., 1978). The broad component, which extends up to 4-6 Kpc from the plane and represents the thick disk or halo emission, contributes about 60 percent of the total emission at 5 GHz and becomes totally dominant at frequencies around 1.4 GHz or lower.

There are also other aspects not clear and questions which are still open:

1) how representative are these few objects for the existence of halos in galaxies in general and for their properties.
2) is the radio emissivity at high z related to the volume emissivity near the plane, as the cases known so far seem to suggest.
3) does the halo emissivity depend on the morphological type of the galaxy and is it related at all with the z-distribution of neutral gas. In NGC 891 (cf. Fig. 1 of Sancisi and Allen, 1979) and in NGC 4631 (compare Fig.1 of Weliachew et al., 1978 and Fig. 1 of Ekers and Sancisi, 1977) the distribution of HI and that of radio continuum emission at 21 cm appear quite different.

These results, in spite of all the uncertainties show that radio halos exist at least in some objects, and therefore support the hypothesis of a radio halo also around our Galaxy. As in NGC 891 and 4631 the halo extent and shape are likely to be dependent on the frequency at which the observations are done. This seems to be consistent with one of the most recent analyses of the radio data in our Galaxy (Webster, 1978).

INTERACTING GALAXIES

A large fraction of the spiral galaxies are members of multiple systems and some of these show peculiarities in their light distribution due to the gravitational interaction (Arp, 1966). There has been some discussion in the past on the effects of such interactions on the radio continuum properties of the galaxies involved. This is clearly relevant also for our Galaxy which is in interaction with the Magellanic Clouds. Stocke (1978) found excess radio emission from close pairs of galaxies, and Hummel (1980b) has shown that the central radio sources in galaxies with close neighbours are on average a factor 2 to 3 stronger as compared to those in isolated spirals, but the disk emissivity is about the same.

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Detailed radio observations of some multiple systems with clear indications of interaction are revealing now an entirely new aspect, namely the existence of radio emission outside the optical images in the regions near or between the systems. Examples of the cases found so far are those of NGC 4038/39 (The Antennae) (Allen, Ekers, Burke and Miley, 1973; Ekers, 1980 private communication), and NGC 4438 (Kotanyi, Ekers and Van Gorkom, 1980 in preparation).

SO AND E GALAXIES

It has already been emphasized (Ekers, 1978) that the continuum emission from SO and elliptical galaxies is completely different from that of spiral galaxies. In the SO's no disk radio emission has been detected. This means that it must be at least a factor 4 weaker than in spirals in general and a factor 1.5 weaker than in early type spirals (Hummel, 1980a; Hummel and Kotanyi, 1980 in preparation).

The radio emission from ellipticals in no case resembles the distribution of light, contrary to spirals, and the range of the ratios of radio to optical luminosity is much larger than that for spirals. In most ellipticals the radio emission is substantially less than in spiral galaxies.

These properties must be related to the absence or the low content of gas, and hence the lower magnetic fields, in these types of galaxies.

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