K.C. Freeman: *"How many unambiguous S0s have double radio sources?"*

R.D. Ekers: *"None! But how many unambiguous S0s are there?"*

Discussion I.5

THE LARGE-SCALE RADIO CONTINUUM STRUCTURE OF SPIRAL GALAXIES

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1. INTRODUCTION

This review concerns the large-scale structure of radio continuum emission in spiral galaxies ("the smooth background"), by which we mean the distribution of radio surface brightness at scales larger than, say, 1 kpc. Accordingly the nuclear emission and structure due to spiral arms and HII regions will not be a major topic of discussion here. Already the first mappings of the galactic background suggested that there is indeed a distribution of radio continuum emission extending throughout the Galaxy. This conclusion has been reinforced by the earliest observations of M31 by showing that the general emission from this object extended over at least the whole optical image. More recently, van der Kruit (1973a, b, c) separated the radio emission from a sample of spiral galaxies observed at 1415 MHz with the Westerbork Synthesis Radio Telescope (WSRT) into a nuclear, spiral arm and "base disk" component, showing that the latter component usually contains most of the flux density. This latter component is largely non-thermal and extends over the whole optical image (see also van der Kruit and Allen, 1976). Clearly it is astrophysically interesting to discuss the large-scale structure of the radio continuum emission.

The study of the spatial and frequency dependence of non-thermal radio continuum surface brightness aims at a number of questions, the most important ones being: (a) Where do the relativistic electrons, which are one component of the cosmic rays originate? (b) How strong are the magnetic fields and what is their distribution, orientation and origin? (c) Can the electrons be contained in the galaxy and if so, how?

From the observational point of view there are a number of difficulties which are partly the reason for the relatively slow progress in these areas. The first is one of observational selection in the sense that the best studied galaxies have a larger brightness temperature in the disk and are usually giant spirals. The effects of this selection are unclear but should always be kept in mind. A second problem is that even though our interest is in the smooth background we do need high-resolution observations. This is because we not only want to correct,

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if necessary, for smaller-scale structure (nucleus, background sources, bright HII regions) but we also want to study the background emission on scales of -say- the optical scale length. On the other hand, the severe requirements on the surface brightness sensitivity restrict effective studies to lower frequencies, where beamwidths are larger. This poses the problem that at some frequencies at least there are serious effects owing to the absence of short spacings in the synthesis observations required to attain the necessary resolution.

It also is important that the observations have a large dynamic range, since the outer disk features or the halos often have surface brightnesses of one percent or less of the brightest parts. A dynamic range of at least a factor 100 seems usually attainable at the synthesis instruments. Finally, a most serious problem is the necessary separation of thermal and non-thermal emission especially when variations of non-thermal spectral index with radius and hence origin and diffusion models for the electrons are studied. In fact, Baldwin (1976) has indicated that in the galactic background at 1.4 GHz as much as 30% is probably thermal.

2. RADIAL DISTRIBUTIONS OF NON-THERMAL RADIO EMISSION

2.1. Spiral galaxies with relatively bright disk emission

Of the larger Sc galaxies in the northern sky M51 and NGC 6946 have the highest brightness temperatures at radio wavelengths and have consequently been studied in most detail. Van der Kruit, Allen and Rots (1977) studied NGC 6946 with the WSRT at 610, 1415 and 4995 MHz (in wavelength respectively 49, 21 and 6 cm). Their maps showed that the galaxy exhibits large-scale structure, but that details are also present. Combining the measurements at the three frequencies they were able to show that most of the small-scale structure is due to thermal emission from large HII complexes and a relatively strong background source.

A main objective in that study was to obtain an accurate radial distribution of continuum emission and its spectral index and consequently much attention has been paid to corrections for absence of small baselines and for the different beam shapes at 21 and 49 cm. Although often done in practice it is in theory not sufficient to use a similar set of baselines at the two frequencies when there is a change of spectral index. This is because the morphology changes as a function of frequency and hence the visibility function at the two frequencies is different. One should therefore be careful when interpreting large variations in spectral index if they derive from this procedure.

Van der Kruit et al. referred the observations of NGC 6946 to an identical (Gaussian) beam after decomposing the maps into point sources, correcting in this way also for missing short spacings. The maps were averaged in rings which are circular in the galactic plane using orientation parameters from a kinematical HI study. The resulting distribution, which at 49 cm extends to 1.2 Holmberg radii, could be fitted well by exponential functions with a scale length quite similar to that of the optical light.

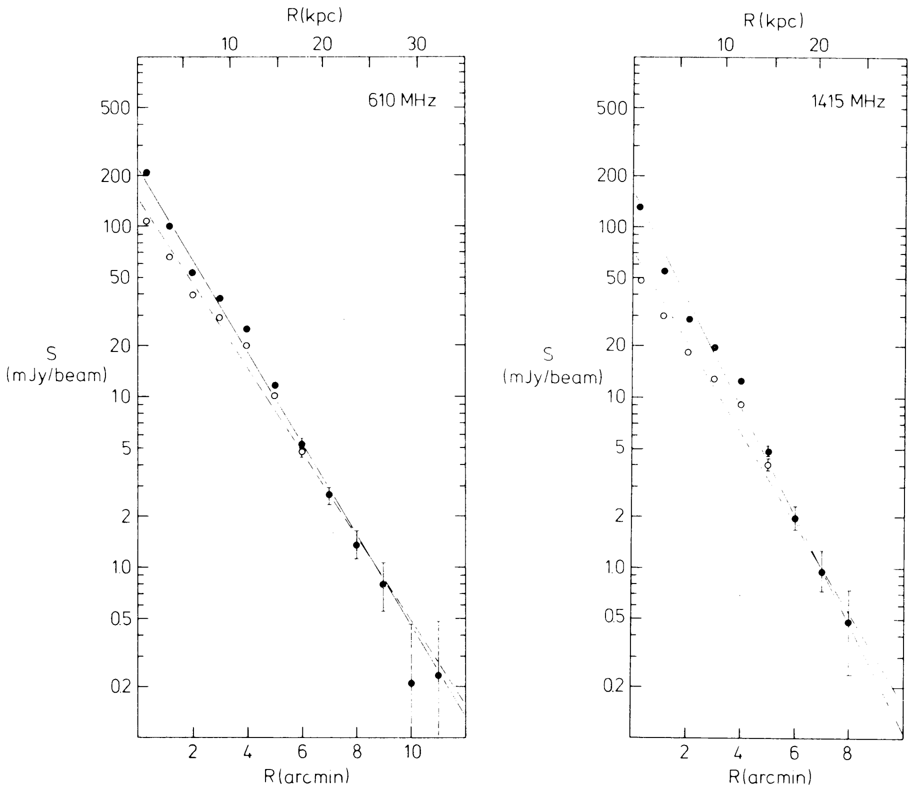

Fig. 1 The radial distribution of radio brightness temperature in NGC 6946 derived after averaging the maps in circular rings in the galactic plane. The open circles are points corrected for the predicted contribution of thermal emission. The HPBW in the maps from which these data are produced was about 1' at both frequencies. (Van der Kruit et al., 1977)

The spectral index varied from −0.5 in the central region to about −1.0 at the last points (see fig. 2). From various lines of arguments they showed that all of this change could be attributed to a radially varying contribution of thermal emission from the HII regions, so that there is no evidence at least over the brighter part of the disk that the spectral index of the non-thermal radio emission changes with radius.

A similar set of observations was obtained by Segalovitz (1976, 1977a) of M51. This system is known to have strong spiral ridges in the radio continuum interpreted as density-wave compression regions (Mathewson et al., 1972). Allen (1975) had earlier pointed out that the general radial fall-off of brightness temperature indicated here also an exponential disk with a scale length typical for late-type spirals.

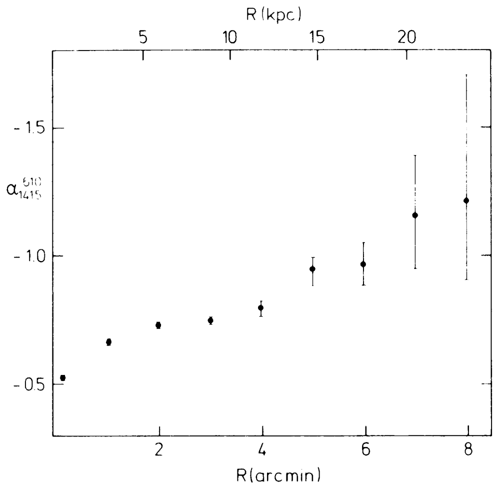

Fig. 2 The radial variation of spectral index in NGC 6946 derived from the points in fig. 1 without correction for thermal emission. As in fig. 1 the error bars relate to uncertainties in the zero-levels in the maps and are therefore not independent (van der Kruit et al., 1977).

Segalovitz (1977a) analysed his measurements in a manner similar to that described above and concluded that there was a real variation of non-thermal spectral index with radius from −0.65 in the central region to −0.8 at the outer edges. Van der Kruit (1977) disagreed with that conclusion and in particular on the basis of Hα flux densities measured by Tully (1974) and of various measurements of Balmer decrements in the HII regions concluded that this change should be attributed to thermal emission. The corrected radial distribution of non-thermal radio emission in M51 would then agree very well with that of the optical light, both being exponential with the same scale length over the main disk.

It should be noted that in NGC 6946 and M51 respectively about 30% and 15% of the total flux density at 21 cm is thermal, which is in agreement with the integrated radio spectra and in particular with recent measurements of the total flux densities at 5 GHz made at Effelsberg (von Kap-herr and Wielebinski, private communication).

An unpublished analysis of the WSRT measurements of M101 (Israel et al., 1975) shows that these observations are consistent with this interpretation but the serious effects of missing short baselines at 1415 MHz make this conclusion very uncertain. Harten (private communication) performed a similar study of IC 342 and found a very strong steepening of the spectrum between 21 and 49 cm with radius. However his maps are derived from similar baseline distributions at the two wavelengths and consequently suffer the difficulties mentioned above. In particular because no attempt could be made to correct for missing short spacings his results may only be correct for small-scale structure.

There are only tentative results for a few more galaxies. For example in NGC 2841 the spectral index is roughly constant with radius, but in NGC 7331 it steepens somewhat with radius (Hummel and Bosma, private communication). The spectrum of NGC 4736 also steepens somewhat with radius (de Bruyn, 1977a), while changes in spectral index are also evident across the disk of NGC 4258 (de Bruyn, 1977b). In all these systems the observations are at least consistent with the view that the change in spectral index is due to thermal emission and that the non-thermal emission is distributed like the optical light. We stress this similarity and not the approximate exponential nature of the distributions in M51 and NGC 6946. Observations of edge-on systems are in general agreement with this conclusion (see section 3a). It has been noted before (Lequeux, 1971; van der Kruit, 1973a, b) that radio continuum distributions are qualitatively similar to the optical appearance.

2.2. Spiral galaxies with weak disks

For galaxies with faint disks information can only be obtained for those with a large angular size, because then the signal-to-noise ratio can be improved by smoothing the maps. However, especially for Sc galaxies the problem of contamination by thermal emission becomes much more serious. The emission of M33 at 21 cm is dominated by thermal emission (Israel and van der Kruit, 1974) so that present studies of this system may be irrelevant to the matters discussed here.

The best remaining galaxies with faint disks suitable for study then are the Sb galaxies M31 and M81. (Note that our Galaxy also has a faint radio disk with a surface brightness similar to these two systems (see also Baldwin, 1976).) Pooley (1969) first mapped M31 and found that the emission at 408 and 1417 MHz was strongly concentrated towards the broad ring of HII regions although the spectrum was clearly non-thermal. This behaviour was studied in more detail at 2.7 GHz (11 cm) with the Effelsberg telescope (Berkhuijsen and Wielebinski 1973, 1974). The radial profile is characterized by a minimum at about 4 kpc followed by a broad maximum at 9 kpc with an exponential fall-off in the outer regions (Berkhuijsen, 1977). The HII regions also peak radially at about 9 kpc.

The same behaviour is found in M81 (van der Kruit, 1973a; von Kapherr et al., 1975; Segalovitz, 1977b) with the minimum at 2 kpc and the maximum at about 5 kpc. The radial distribution of HII regions and possibly also of non-thermal emission in our Galaxy qualitatively behaves similarly.

The full-resolution Westerbork map of M81 (Segalovitz, 1977b) at 21 cm shows radio emission near the spiral arms which Segalovitz attributes to shocks in a galactic density wave. He notes that the spectral index is rather uniform starting in the inner minimum to the outer regions. The radio spectrum is clearly non-thermal. The same general characteristic follows from the detailed work by Berkhuijsen (1977) on M31. From this study it also follows that the thermal contribution to the radio emission in the arm regions is not negligible.

In the outer regions beyond the broad maximum the radio continuum and blue light fall-offs in M31 can both be described by exponential functions with similar scalelengths (Berkhuijsen, 1977). This same property approximately holds for Segalovitz's radial distribution in M81. From this it seems that the major difference between these galaxies and those described above lies in the deficiency of radio emission and HII regions in the central regions. It has been noted by Berkhuijsen and by Segalovitz that this may be related to the low density of neutral hydrogen in the same inner regions. In this respect our Galaxy also behaves similarly, even when the distribution of CO and that of H_2 inferred from this is added.

2.3. The origin of the cosmic rays

Lequeux (1971) suggested on the basis of the general similarity of the radio continuum extent in external spiral galaxies with that of the extreme population I (in particular the HII regions) that the supernovae of type II associated with this young population are the prime source of cosmic rays. Van der Kruit and Allen (1976) however pointed out that a relation with the general optical light rather than the HII regions seemed more likely.

The detailed analysis of NGC 6946 (van der Kruit et al., 1977) and M51 (van der Kruit, 1977) clearly indicate that the non-thermal emission is in the radial direction distributed similarly as the total stellar component and certainly different from that of the HII regions. Indeed, if the observed change in spectral index is due to mixture with thermal emission it follows that the thermal and non-thermal emission cannot be distributed in the same way. It also is a general property of spiral galaxies that the HI falls off much slower than the radio continuum brightness, so the non-thermal emission certainly does not correlate with the extreme population I. Van der Kruit et al. noted that the radial distributions of non-thermal emission and optical light are also similar to those derived statistically for supernovae (irregardless of type!) in galaxies. They concluded that it is then reasonable to take the view that indeed supernovae, their associated remnants and/or pulsars are important sources of cosmic rays but that then supernovae of <u>both types</u> have to be considered.

The above discussion then argues against a unique relation of the non-thermal radio emission and the young population I. It is evident from discussions of supernova statistics (e.g. Tammann, 1977) that only supernovae of type II (SNII) belong to the young population I. The progenitors of SNI are part of the older disk population (possibly in binaries). They may not be related to recent star formation unless in the interarm regions star formation deficient in the most massive stars occurs (Tinsley, 1977). The occurrence rates and energetics of the two types of supernovae by themselves already indicate that if the origin of cosmic rays is associated with supernova activity, there is no reason to presume an exclusive relation to the young population I. On the other hand the evidence discussed here is also consistent with the view that cosmic rays originate in any constituent of the disk that is distributed like the total stellar disk population (e.g. flare stars). It is of course also possible that the distributions of magnetic field, lifetimes of the electrons and cosmic-ray sources conspire in such a way that a spurious relation with total star light results.

We now have to discuss how the radial profiles of the galaxies discussed in section 2.2. fit in the picture outlined above. From that discussion it follows that these systems deviate only in the central regions where a minimum in radio continuum, HI and HII is found. In these central minima the HI density is very low; much lower than found at comparable radii in e.g. NGC 6946 and M51. Segalovitz (1977b) in his study of M81 suggested that in these regions the extremely low gas density inhibits star formation but is not preventing shocks from forming (thin dust lanes are observed). This already might lead to reduced production of cosmic rays. Also Ekers (private communication) has suggested that the broader z-distribution of mass at these radii due to the bulge component might allow the cosmic rays to expand quickly in the z-direction. Finally in these regions of very low gas density the magnetic field could also be weaker than elsewhere in the disk.

The difference of these systems therefore is restricted to a relatively small central region and possibly related to extremely low gas densities. Note that in our Galaxy there appears a minimum in SNR's in the central region (e.g. Berkhuijsen, 1977), although there are obvious selection effects. It should be noted that those electrons that radiate in the minimum are probably accelerated there rather than diffusing from the nucleus or from the maximum further out. This follows from the observation of Segalovitz in M81 that the spectrum in the minimum is not steeper than that in the broad maximum (a significant thermal contribution would make the spectrum even steeper in the maximum).

An important inference from this model has to do with the diffusion of the cosmic rays in galactic disks. Clearly a systematic change of spectral index with radius is most easily interpreted as due to energy losses of the electrons while diffusing through the disk. The correction for thermal emission discussed above is therefore very critical. After concluding that thermal emission is negligible in M51 and that the observed variation of spectral index is entirely due to the non-thermal emission, Segalovitz (1977c) has constructed detailed models fitting the observations in M51. In his model the diffusion coefficient is $\sim 10^{29}$ cm^2 sec^{-1}, the leakage time of electrons out of the disk and its associated magnetic field is $\sim 3 \times 10^7$ years and the slope of the energy injection spectrum of the electrons $\gamma_o \sim 2.2$, while the source function is strongly concentrated towards the inner regions.

Van der Kruit (1977) has constructed similar models for the case of

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constant spectral index assuming that the sources of the cosmic rays varied as an exponential disk with the optical scalelength and a constant magnetic field strength. Then the diffusion coefficient is $\sim 10^{29}$ cm^2 sec^{-1}, the leakage time has to be $\sim 10^7$ years or less and the injection spectrum has $\gamma_o \sim 2.6$. Note that these parameters do not differ much from those of Segalovitz in spite of the two greatly different geometries, and cannot alone be used to choose between the models. However, since the case for the observed change of spectral index being due to thermal emission is very good the last mentioned model is strongly preferred. The parameters derived are reasonable compared to what they are estimated to be in our Galaxy (Parker, 1976). Unfolding of galactic γ-ray observations also gives evidence that the distribution of relativistic electrons closely follows that of total stellar mass and of supernovae (Dodds et al. 1975; Stecker, 1977). Note that in both models the electrons escape from the disk in about 10^7 years.

Some comments will be made on the general brightness of disk emission. This can vary considerably from galaxy to galaxy (at 21 cm from T_b = 10 K to T_b < 0.1 K) and is not strongly correlated with Hubble type and colour and correlates only weakly with integrated optical magnitude (van der Kruit, 1973c; Ekers, 1975). Although severe selection effects exist there still is an apparent relation between the power of the nuclear radio source and the average brightness temperature of the disk emission (see for example van der Kruit and Allen, 1976). The evidence mentioned above that the spectral index of the disk emission does not change with radius is good evidence against a model in which the nuclei contribute significantly to the cosmic rays in the disk, since such a model would be qualitatively very similar to the one developed by Segalovitz for M51.

Also the above discussed association of the origin of cosmic rays with the total disk population suggests that the simple assumptions in Biermann's (1976) calculations are not justified, since he directly links the strength of the radio continuum emission to the very recent formation of massive stars. The absence of correlation of disk strength with Hubble type (and colour index) furthermore argues for at least another parameter to control the synchrotron volume emissivity. Since the latter depends most sensitively on the magnetic field strength this might in fact be a dominant factor. In this respect Pacini's (1975) suggestion that pulsars are a source of galactic magnetic fields is important to note, but difficult to quantify in the models.

3. Z-DISTRIBUTIONS AND RADIO HALOES

3.1. Observations of some edge-on galaxies

The most detailed investigation at present has been that of NGC 891 with the WSRT (Allen, Baldwin and Sancisi, 1977). They observed at the three wavelengths of 6, 21 and 49 cm and were also careful to produce maps with identical beam shapes and to correct for missing spacings. They separated the emission into two components. There is a thin disk in the equatorial plane of which at least two-thirds is non-thermal at 6 cm

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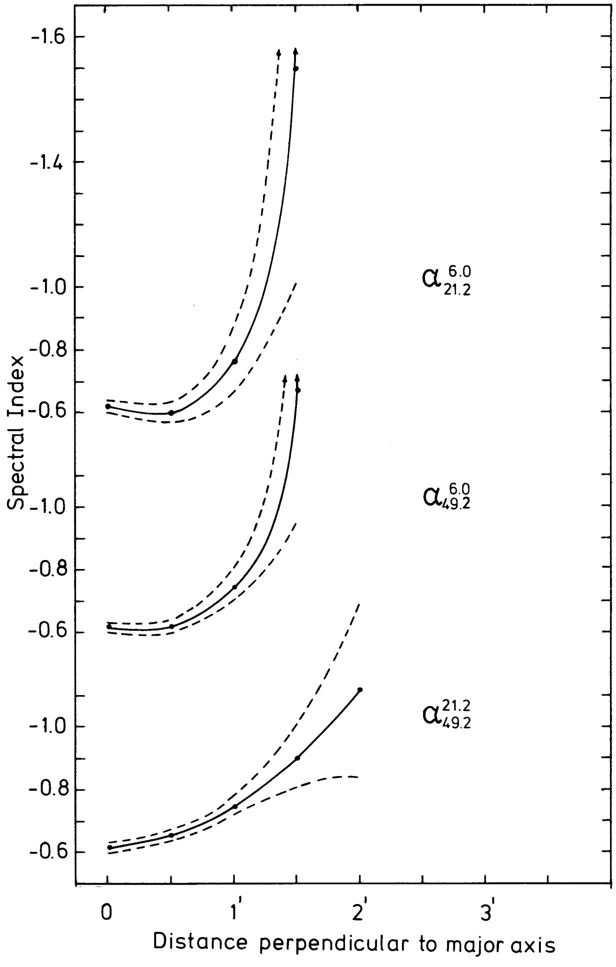

Fig. 3. The variation of spectral index with z in the edge-on galaxy NGC 891. The HPBW in this direction was 1' in all maps and the wavelengths of observation are indicated. At the assumed distance of 14 Mpc, 1' corresponds to 4 kpc. (Allen et al. 1977.)

and a "thick disk" with axis ratio 3.5 : 1 which is non-thermal. The emission has been detected up to about 6 kpc above the plane. In the plane the spectral index where measurable is constant with radius (up to 12 kpc from the centre, which is only half the optical extent), but the spectrum steepens at distances of more than 2.5 kpc out of the plane (see fig. 3).

The steepening of the radio spectrum with z is also found in a few

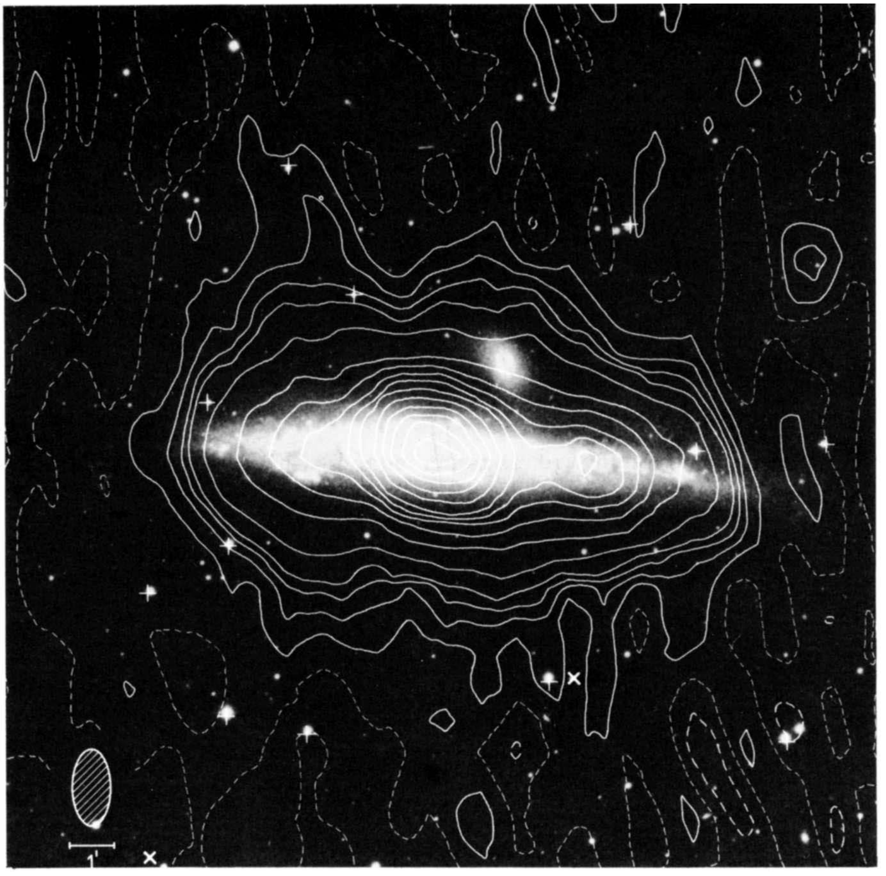

Fig. 4. The radio halo in NGC 4631 observed at 610 MHz (49 cm). The scale and HPBW are indicated in the lower-left corner. (Ekers and Sancisi, 1977.)

more edge-on galaxies observed in Westerbork such as NGC 3556 (de Bruyn and Hummel, private communication), where the emission apparently extends to at least 2 kpc above the plane (see also van der Kruit, 1973b). The spectrum in the disks of NGC 3556 and 5907 steepens with radius which can conceivably be explained by mixture with thermal emission.

Ekers and Sancisi (1977) presented evidence for a flattened radio halo in NGC 4631 with an axis ratio of about 2 : 3 (see Fig. 4). The volume emissivity is comparable to that for the proposed halo in our Galaxy. There is a definite spectral steepening with distance above the plane. Since steepening occurs in all cases still at $z \gtrsim 1$ kpc, mixture with thermal emission cannot be invoked here as an explanation.

3.2. The radio haloes of our Galaxy and M31

Historical notes on these haloes can be found in van der Kruit and

Allen (1976). Webster's (1975, 1977) work has produced good evidence of a halo in our Galaxy. In view of what has been mentioned above his assumption that its spectrum is steeper than that in the disk seems well justified. In Webster's models the volume emissivity is about 30 times less than in the disk.

Wielebinski (1976) has recently reviewed the evidence for a radio halo in M31. He compared in particular a recent 408-MHz Bonn map of M31 and surroundings with the distribution of 4C and 5C3 sources. This shows that structure in the contours such as the spurs near the minor axis are due to the distribution of these sources on the sky. The Bonn map however does show a broad region of excess emission around M31, but Wielebinski attributes it completely to the 5C3 sources. This seems invalid because his integrated flux density of the region is derived with respect to a chosen zero level in his map which then already contains the general distribution of background sources. The smooth excess emission can in principle also be due to the galactic background, but the data are also consistent with a smooth halo around M31 with a flux density equal to or less than that of the disk. The question of radio halo versus structure in the galactic background can best be resolved by spectral index studies, especially if a low frequency (maybe 100 MHz) is chosen.

3.3. Containment of cosmic rays

We will briefly discuss the question of containment of cosmic rays in view of the observational material reviewed above. Allen et al. (1977) interpreting the z-distribution of the radio emission in NGC 891 suggested that the observations can be understood in a model in which the electrons diffuse out of the disk. The slope of the electron energy spectrum steepens with z due to the energy losses and this effect plus a fall-off of magnetic field strength with z would indicate a propagation time of 4×10^7 years or more for the electrons to reach a height of 4 kpc above the plane. Note that the models described in section 2 for the radial radio continuum distributions also require the electrons to escape from the disk on timescales of the order of 10^7 years.

As is discussed above whenever a spiral galaxy has a strong radio disk and its orientation is sufficiently edge-on there appear to be z-extensions up to at least 2 kpc accompanied by a steepening of the spectrum with z. The most straightforward conclusion from this is that at least in these brighter systems the electrons are not contained in the disk, but diffuse into the halo. There containment times would be very long and the magnetic fields weak.

4. CONCLUSIONS

It is emphasized that conclusions following from the above discussion should be regarded tentative since they derive from a small and somewhat biased sample. From the observations these are: (a) Often the observed spectra in disks of spiral galaxies steepen with radius, but most of this is probably due to mixture with thermal emission. (b) The non-thermal brightness distribution in the disk correlates with the total stellar disk population rather than the young population I. (c) Extensions in the z-direction are observed to at least 2 kpc and sometimes up to 6 kpc above the plane. (d) The radio spectra steepen with z and this cannot be due to thermal emission. For the origin and diffusion of cosmic rays the conclusions are: (e) Cosmic rays originate in the disk but are not exclusively related to young population I. Sources of cosmic rays can be supernovae of both types, their remnants, pulsars and/or any constituent distributed like the total stellar disk. (f) Relativistic electrons diffuse out of the disks after travelling not very far (say 1 kpc in about 10^7 years) from their places of origin. (g) Nuclei do not appear to be significant contributors to cosmic rays in galactic disks.

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REFERENCES

Allen, R.J.: 1975, La Dynamique des Galaxies Spirales (C.N.R.S.), p.157
Allen, R.J., Baldwin, J.E., Sancisi, R.: 1977, Astron. Astrophys. (in press)
Baker, J.R., Haslam, C.G.T., Jones, B.B., Wielebinski, R.: 1977, preprint
Baldwin, J.E.: 1976, The Structure and Content of the Galaxy and Galactic Gamma Rays, ed. C.E. Fichtel and F.W. Stecker (Goddard), p. 206
Berkhuijsen, E.M.: 1977, Astron. Astrophys. 57, 9
Berkhuijsen, E.M., Wielebinski, R.: 1973, Astrophys. Lett. 13, 169
Berkhuijsen, E.M., Wielebinski, R.: 1974, Astron. Astrophys. 34, 173
Biermann, P.: 1976, Astron. Astrophys. 53, 295
Bruyn, A.G. de: 1977a, Astron. Astrophys. 54, 491
Bruyn, A.G. de: 1977b, Astron. Astrophys. 58, 221
Dodds, D., Strong, A.W., Wolfendale, A.W.: 1975, M.N.R.A.S. 171, 569
Ekers, R.D.: 1975, Structure and Evolution of Galaxies, ed. G. Setti (Reidel), p. 217
Ekers, R.D., Sancisi, R.: 1977, Astron. Astrophys. 54, 973
Israel, F.P., Goss, W.M., Allen, R.J.: 1975, Astron. Astrophys. 40, 421
Israel, F.P., Kruit, P.C. van der: 1974, Astron. Astrophys. 32, 363
Kap-herr, A. von, Jones, B.B., Wielebinski, R.: 1975, Astron. Astrophys. 41, 115
Kruit, P.C. van der: 1973a, b, c, Astron. Astrophys. 29, 231, 249, 263
Kruit, P.C. van der: 1977, Astron. Astrophys. 59, 359
Kruit, P.C. van der, Allen, R.J.: 1976, Ann. Rev. Astron. Astrophys. 14, 417
Kruit, P.C. van der, Allen, R.J., Rots, A.H.: 1977, Astron. Astrophys. 55, 421

Lequeux, J.: 1971, Astron. Astrophys. 15, 42
Mathewson, D.S., Kruit, P.C. van der, Brouw, W.N.: 1972, Astron. Astrophys. 17, 468
Pacini, F.: 1975, Origin of Cosmic Rays (Reidel), p. 371
Parker, E.: 1976, The Structure and Content of the Galaxy and Galactic Gamma Rays, ed. C.E. Fichtel and F.W. Stecker (Goddard), p. 320
Segalovitz, A.: 1976, Astron. Astrophys. 52, 167
Segalovitz, A.: 1977a, Astron. Astrophys. 54, 703
Segalovitz, A.: 1977b, Astron. Astrophys. 55, 203
Segalovitz, A.: 1977c, preprint
Stecker, F.W.: 1976, The Structure and Content of the Galaxy and Galactic Gamma Rays, ed. C.E. Fichtel and F.W. Stecker (Goddard), p. 357
Tammann, G.A.: 1977, Supernovae, ed. D.N. Schramm (Reidel), p. 95
Tinsley, B.M.: 1977, Supernovae, ed. D.N. Schramm (Reidel), p. 117
Tully, R.B.: 1974, Astrophys. J. Suppl. 27, 415
Webster, A.: 1975, Monthly Notices Roy. Astron. Soc. 171, 243
Webster, A.: 1977, preprint
Wielebinski, R.: 1976, Astron. Astrophys. 48, 155

DISCUSSION FOLLOWING REVIEW I.4 GIVEN BY P.C. VAN DER KRUIT

TOOMRE: What spectral index would we <u>expect</u> from synchrotron theory, i.e., if thermal effects were absent?

VAN DER KRUIT: Such a prediction depends on the energy distribution of the cosmic ray electrons and on how fast they escape.

OORT: Do not possible changes in the magnetic field strength play an important part beside the density and propagation of the cosmic ray particles?

VAN DER KRUIT: Of course, the magnetic field must be playing a role, but we can only guess at its strength and at how it may vary across a galaxy. The main point I wanted to make is that the distribution of nonthermal emission seems to correlate with the older population to some extent rather than with the very young population. It would seem to be a mere coincidence if this apparent correlation were caused by a systematically varying magnetic field and a source function following the young population.

BURKE: After correction of the variation of spectral index for HII contamination in the disks of the galaxies you have considered, how uniform is the nonthermal spectral index? It does seem surprising that the injection and loss mechanisms are so uniform throughout the disk.

VAN DER KRUIT: If you correct as well as you can for HII contamination in M51 you find a nonthermal spectral index of -0.80 ± 0.05 at all radii; thus across this galaxy it is constant to within the errors.

VAN DER LAAN: I would like to make two remarks:
(1) The hope of using the continuum intensity distributions to sort out basic questions of cosmic ray physics, concerning their origin and propagation, is frustrated by the R-dependent nonthermal/thermal radiation mix. The prediction of free-free emission from optical line emission data is very uncertain, beset with problems of nonuniformity in absorption, of filling factor uncertainty and of very low brightness emission from large areas. The best way to determine the true nonthermal emission distribution is to measure the continuum emission at $\lambda \sim 2$ cm, where it is almost purely thermal, and subtract it from lower frequency array maps. Only the Effelsberg telescope can make the required thermal emission maps.
(2) The lack of λ-dependence of the nonthermal intensity in the R-direction indicates that cosmic ray production is widespread in the disks and diffusion is primarily in the z-direction. The λ-dependence of intensity in the z-direction is consistent with this. We should keep in mind in any quantitative treatment that the spectral steepening may be enhanced by a decrease of magnetic field strength with increasing z, so that it takes higher and higher energy electrons to emit at a given frequency.

BIERMANN: I would like to make two comments:
(1) You mentioned my models for the radio continuum emission from galaxies. These models were constructed with the assumption that only massive stars make supernovae and supernovae make nonthermal radio radiation, because that is the most simple assumption conceivable. It is obvious that more complicated models could be constructed and the observations may require more complicated assumptions.
(2) The spectral index map of M51 shows quite strong variation across the disk explainable as you say by variation of the thermal contribution. Then the steepest spectral index on the map corresponds to the nonthermal index, according to your arguments constant across the disk after subtraction of the thermal component. However, the outermost spectral index is steeper than about unity which would seem to be consistent with diffusion and losses of cosmic ray electrons being important contrary to your conclusions. In view of the large errors involved I do not see that you can really exclude a variation of the nonthermal spectral index across the disk.

VAN DER KRUIT: No, you cannot exclude that. Both a constant nonthermal spectrum as well as a steepening spectrum is consistent with the data.

BALDWIN: The nonthermal spectral index you deduce for the outer parts of spirals is close to 1. Are the total flux densities at low frequencies consistent with this value?

VAN DER KRUIT: Yes, they are, but the flux densities at low frequencies are rather uncertain. In the literature the total flux densities at high frequencies are also unreliable. However, the well determined values at 6 cm that have recently been obtained in Effelsberg are in full agreement with our predictions based on the observed spectral index and the important contribution of thermal emission.

WIELEBINSKI: THE THERMAL CONTENT OF IC342

The Scd galaxy IC342 is a very good case to demonstrate the presence of significant thermal emission in a normal galaxy. Recent radio continuum observations of Baker et al. (1977, A.A. 59, 261) and Harten (1977, in prep.) give well calibrated high resolution maps at widely separated frequencies as well as total flux values at a number of frequencies. The spectral index for frequencies below 1 GHz is $\alpha = 1.2$ ($S \propto \nu^{-\alpha}$), in fact greater than for any other normal galaxy. The spectral index reduces to $\alpha = 0.7$ for the frequency range 2.7 to 4.8 GHz. The reality of this flattening of the spectrum is further supported by considering the spectral index distribution across the galaxy. The nuclear area of IC342, where optically "fuzzy" emitting regions are seen, has the spectral index $\alpha = 0.6$. Further sources with flat spectra are found directly on the spiral arms where similar "fuzzy" regions are found. Presumably this is a mixture of the nonthermal emission with spectral index $\alpha = 1.2$ and thermal emission with $\alpha = 0.1$. Individual thermal sources account for some 20% of the emission of 4.8 GHz. From studies of the spectral index it can be shown that some 70% of the total flux is nonthermal so that 10% is due to either smaller obscured HII concentrations or distributed in the disk of the galaxy.

The thermal content of a normal galaxy was originally discussed by Segalovitz (1977, A.A. 61, 59), and was recently re-examined by van der Kruit et al. (1977, A.A. 55, 421) and van der Kruit (1977, A.A. 59, 359). The conclusions of the latter authors for NGC 6946 and M51 disagree with the results of Segalovitz and indicate the emergence of thermal emission at f > 3 GHz. Our results on IC342 support these conclusions. New observations in Effelsberg of normal galaxies at a number of frequencies above 5 GHz are in progress, specifically aimed at settling the issue beyond any doubt.

BYSTEDT: M31 has been observed with the Westerbork telescope at 49 cm (Israel, de Bruyn and Bystedt). The HPBW of the synthesized beam is $0\overset{'}{.}9 \times 1\overset{'}{.}4$ and the r.m.s. noise level at the map center about 0.8 mJy/beam. As van der Kruit mentioned, it has been noted by Wielebinski that there seems to be an excess of 5C3 sources approximately in the minor axis direction of M31. Our map gives the impression that the asymmetry is seen also among sources weaker than the 5C3 sources, and that the asymmetry is present even close to the central part of M31.

WIELEBINSKI: A radio telescope with a beam elongated in declination and the point source distribution near M31 gives a very realistic halo around M31. In addition, a galactic spur complicates the issue. I agree with Dr. van der Kruit that renewed investigation of the halo (if any) around M31 should be made, particularly at low frequencies.

PFLEIDERER: DECONVOLVED SINGLE DISH RADIO OBSERVATIONS OF NGC 6946

The problem of finding the true flux density distribution of extended objects if the measurements are smeared out by the finite beam of the observing instrument cannot be solved exactly (Bracewell and Roberts 1954, Austr. J. Phys. 7, 615). The main reason is that the instrument does not transmit higher Fourier components. However, by observing a large enough area it may be possible to make a deconvolution which is fairly unique. An extreme case is a single point source which is effectively deconvolved simply by determining its position and flux density. Högbom (1974, A.A. Suppl. 15, 417) argues on similar lines.

As a cooperation between Dr. Wielebinski's group in Bonn and the Institut für Astronomie, Innsbruck, we have developed a deconvolution procedure in which the true map is replaced by a model of point sources on a grid. The flux density of each point source is chosen such that the convolution with the beam (which must be known) reproduces the observed map within the noise level. The procedure is similar to the first part (deconvolution part) of the CLEAN procedure (with a small loop gain) as described by Högbom (1974). Some smoothing can be achieved by a superposition of the results for different point source grids.

The first completed example is a 6-cm map from Effelsberg (HPBW = 2!6) of NGC 6946 which has an optical extension of about 5' x 8'. Unfortunately, our radio data are markedly distorted by bad weather. Some details become apparent in the deconvolved map which are quite difficult to deduct directly from the observed map: the central source is little or not extended and has only about one quarter of the total flux density. It is surrounded by extended emission which is entirely restricted to the optically visible region of the galaxy. Some resemblance of this emission to the spiral structure is indicated. Both maps and more details will be published in Mitteil. Astron. Ges. No. 43 (1978).

The theory of our procedure is not yet completed. It should, however, be noted that the informational content of the observed and the deconvolved map is the same within the noise level. The question is therefore not so much whether or not the deconvolved map is correct but rather how to interpret it - in particular, how to avoid an overinterpretation. It should be possible to learn how to read these maps, as we have learned how to read observed maps.

VAN WOERDEN: I agree that deconvolution is possible, and may be necessary, provided one has a stable, accurately known instrumental profile and a good signal-to-noise ratio. How precisely is the antenna pattern of the 100-meter telescope known, and is it a function of time, temperature, altitude, azimuth, etc.?

PFLEIDERER: At 6.2 cm the sidelobes do not play an important role. The shape of the main lobe is important but that we know pretty well.

EKERS: I think the right question to ask is how you tell which of the infinite number of possible solutions is the correct one (see Bracewell and Roberts, Austr. J. Phys. ∿ 1962).

PFLEIDERER: It is a trial and error process; the structure must come out the same each time. The solution is unique for the main structure but not for the details.

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