CONTINUUM RADIO EMISSION AND GALACTIC STRUCTURE

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Abstract. Recent studies of high latitude brightness have shown that in several regions a significant proportion of it is due to loop features. The largest of these are now thought to be local (within a few hundred parsecs) and perhaps to be due to supernova events.

Aperture synthesis maps of 45 external spiral galaxies have shown large-scale continuum nonthermal features in the disks of some and, in general, an absence of spherical halos around the galaxies. This supports the view that the radio emission from our Galaxy can best be described as coming from a thick disk. Any large-scale spherical component could not have a volume emissivity greater than 1.5% of the average volume emissivity of the disk at meter wavelengths.

A comparison of the disk radiation with new disk models suggests that the galactic plane radiation has two components: a base disk and a spiral component. Each of these contributes $\sim 50\%$ of the total power output of the disk at 150 MHz.

I. Introduction

At meter wavelengths, most of the radio emission from within our Galaxy has its origin in synchrotron radiation from relativistic cosmic ray electrons radiating in the magnetic fields of the Galaxy. Only a small percentage of the brightness temperature observed at meter wavelengths is due to the thermal emission from H II regions. This paper deals only with the nonthermal (synchrotron) emission. For a discussion of the distribution of H II regions the reader is directed to Burbidge (1967), Burke (1968), and Reifenstein *et al.* (1970). (The nonthermal emission regions located near the center of our Galaxy are not discussed in this review.)

In order to estimate the locations of nonthermal emission regions in our Galaxy, we can utilize detailed studies of radio brightness distribution at both high and low galactic latitudes. We can also learn much about the expected distribution of nonthermal emission in 'normal' spirals from high-resolution aperture synthesis observations of external spiral galaxies.

Finally, we must combine data from these studies with model fitting to arrive at reasonable estimates of the distribution of the nonthermal radio emission regions (i.e., galactic magnetic field and cosmic ray electrons) within our Galaxy.

II. General Features of the Radio Sky

A map of the brightness distribution on the sky at meter wavelengths (e.g., Landecker and Wielebinski, 1970) is shown in Figure 1. On this map three notable characteristics are apparent.

(i) The radiation is strongly concentrated to the galactic equator.

(ii) Loops or spur features are visible in many portions of the sky, often appearing to 'come out of' the plane. These features are seen even at galactic latitudes higher than 60°.

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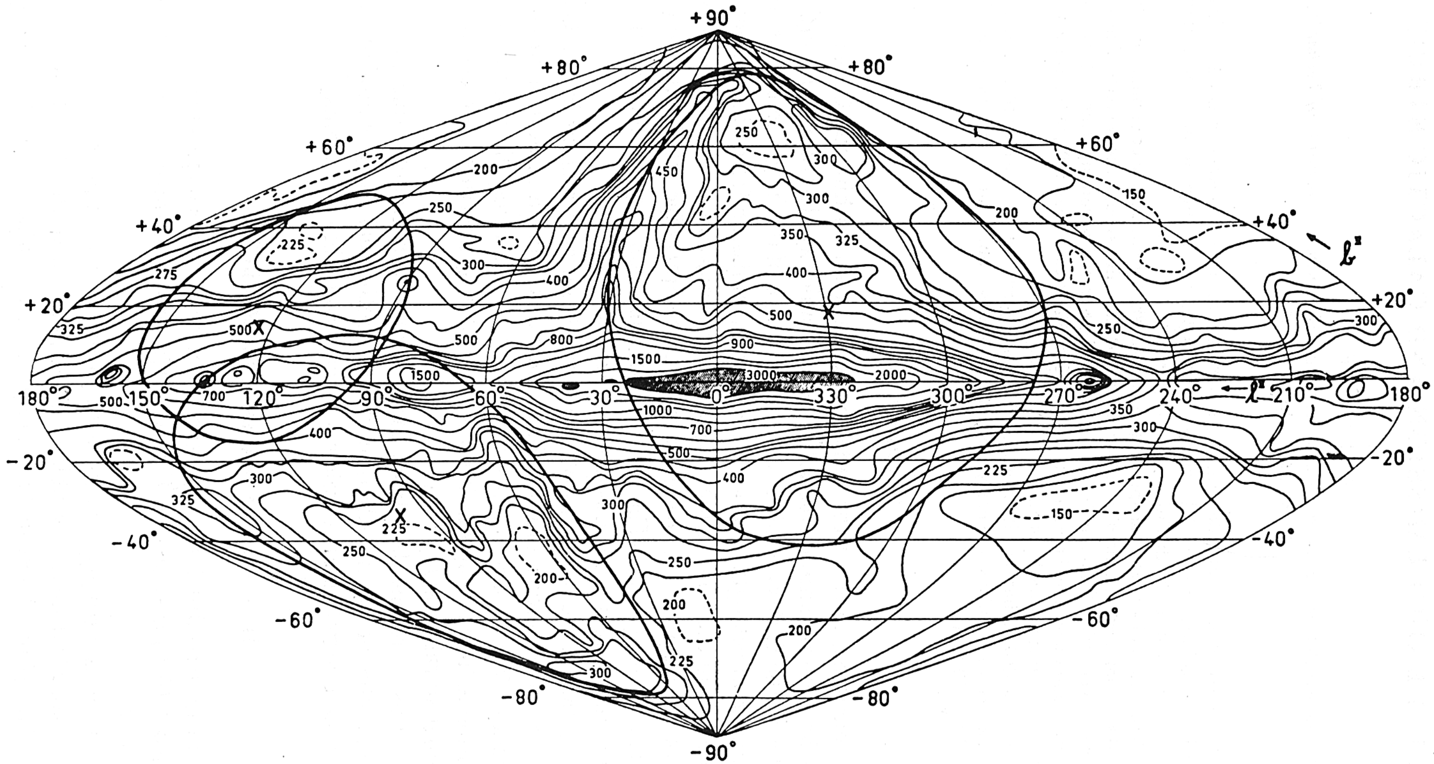

Fig. 1. Sky map at 150 MHz prepared by Landecker and Wielebinski (1970). Small circles of Loops I, II, and III are shown (after Berkhuijsen, 1971) with circle centers indicated by ×'s.

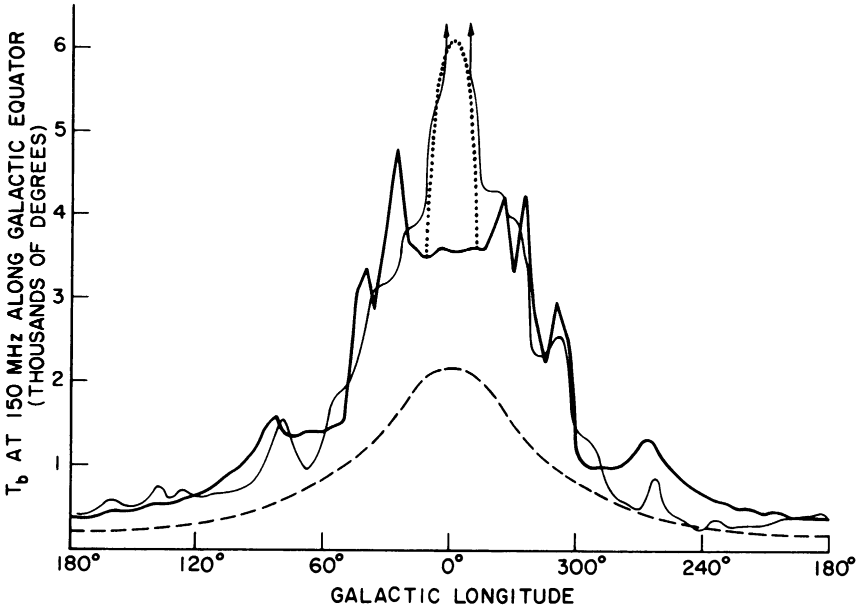

Fig. 2. Profile of brightness temperature at 150 MHz along the galactic equator (Landecker and Wielebinski, 1970) is shown by light solid line. Heavy solid line shows profile predicted by the model of base disk and spiral components (Price, 1974). Dashed curve: base disk component. Dotted line: expected nonthermal contribution from a region with constant volume emissivity and 2000 pc radius located at the galactic center.

(iii) The brightness temperatures at high latitudes are relatively high, as high as 30% of those found along the galactic equator at longitudes greater than 60° from the center.

Information about the distribution of nonthermal emission regions in the galactic disk can be derived from an examination of the profiles of the brightness temperatures along the galactic equator shown in Figure 2. This profile clearly shows that the brightness is highly concentrated within 60° of the galactic center in longitude, regions greater than 60° from the center do not differ greatly in brightness temperature except for two obvious features at $l \approx 80°$ and $l \approx 265°$, and bumps or steps are noticeable on the central concentration.

Each of these characteristics of the galactic brightness distribution gives information on a different aspect of the distribution of nonthermal emission regions in the Galaxy. These aspects will be discussed separately.

III. Loops

Loops or spurs are a well-known feature of the radio sky. The best-fit small circles to three of the loops are shown in Figure 2. Portions of some of the loop and spur features lie at high galactic latitudes (e.g., the North Polar Spur, which passes near the north galactic pole). They contribute significantly to the observed brightness temperatures away from the galactic equator. There are indications that they contribute not only along their main ridges but also 'inside' the ridges and beyond the outer boundaries of the bright ridges. A complete description of the radio properties of the loops can be found in Berkhuijsen (1971). Information and references concerning these features are listed in Table I.

On the basis of an 820 MHz survey, combined with polarization measurements, Berkhuijsen (1971) has concluded that the loop features have the following properties.

(i) They contribute significantly to the brightness temperature distribution in high latitude regions. Their radiation comes not only from the bright rims of the loop features but also from regions closer to the loop centers and outside of the bright rims.

(ii) They are nearby features, i.e., located within several hundred parsecs in many cases.

(iii) They are probably supernova remnants.

The question of whether some or all of the loops are supernova remnants is very important. The shapes of many of these features favor such a hypothesis. They show a large degree of circular symmetry (over the identifiable arc of the observed feature). In some cases the continuum radio ridges are associated with optically observed filaments or neutral hydrogen features. Spoelstra (1972, 1973) has shown that the observed brightness and polarization distributions are in rough agreement with results of models of supernova remnants in the local magnetic field. Also, Berkhuijsen (1973) has established that five of the loops lie near the $\Sigma - D$ relationship for known supernova remnants.

There are obstacles that raise uncertainty about the supernova origin of the loops.

(i) The low internal velocity of the clouds of neutral hydrogen associated with the North Polar Spur is not consistent with the idea of explosive origin.

(ii) The very large and regular outer envelopes of the loops (~ 100 pc) are hard to explain unless the interstellar medium is exceedingly homogeneous, of low density, and has a larger scale height above the galactic plane than is estimated at present.

(iii) Similar features have not been identified in other regions of the Galaxy. This can be a very difficult observational identification to make because of the low surface brightness of loop objects and the confusion at lower latitudes at which the more distant loops would be expected.

Other suggestions have been offered to explain the loop features. Brandt and Maran (1972) have suggested that they might be fossil Strömgren spheres produced by supernova outbursts. Kafatos and Morrison (1973) have estimated the radio and X-ray emission that might be expected from such an object and conclude from available observational information that such an origin is consistent.

Mathewson (1968) has suggested that the loops are 'radio tracers' of the helical component of the local magnetic field, but more recent studies of the magnetic fields in the vicinity of the sun do not appear to support this hypothesis (e.g., Manchester, 1972).

TABLE I

Galactic loop features

Feature	Center		Diameter	Estimated distance	Additional data		Discussion of objects, References
	l	b		(pc)	H I	Optical	
Loop I North Polar Spur	329 ± 1°.5	+17.5 ± 3°	116 ± 4°	130 ± 75 (1)	2		1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Loop II Cetus Arc	100 ± 2°	−32.5 ± 3°	91 ± 4°	110 ± 40 (1)	13	14, 15, 16	1, 3, 4, 5, 7, 11, 12, 14, 16
Loop III	124 ± 2°	+15.5 ± 3°	65 ± 3°	150 ± 50 (1)	17	18	1, 3, 4, 5, 7, 11, 12
Loop IV	315 ± 3°	+48.5 ± 1°	39.5 ± 2°	250 ± 90 (1)	19		1, 3, 4, 7, 20
Origem Loop	194°.5	+0°.5	5°	1000 ± 500 (1)			1, 20
Lupis Loop	330°.1	+15°.1	4°.5	400 (21)			20
Monoceros Loop	205°.7	−0°.1	3°.5	600 (21)	22		20, 23

1. Berkhuijsen (1973)
2. Berkhuijsen *et al.* (1970)
3. Berkhuijsen (1971)
4. Berkhuijsen *et al.* (1971)
5. Bingham (1967)
6. Bunner *et al.* (1972)
7. Haslam *et al.* (1971)
8. Holden (1969)
9. Large *et al.* (1966)
10. Merkelijn and Davis (1967)
11. Quigley and Haslam (1965)
12. Spoelstra (1972)
13. Hughes *et al.* (1971)
14. Elliott and Meaburn (1970)
15. Meaburn (1965)
16. Meaburn (1967)
17. Fejes and Verschuur (1973)
18. Elliott (1970)
19. Fejes (1971)
20. Spoelstra (1973)
21. Milne (1970)
22. Morgan *et al.* (1965)
23. Gebel and Shore (1972)

Loops or bubbles could also be produced in the galactic magnetic fields by cosmic ray pressure according to the theory of Parker (1965). This theory has not yet been examined in sufficient detail to determine whether the resulting structure would have the observed properties of the radio loops.

Thus the origin and the nature of the loop features is still uncertain. Regardless of their origin, there can be little doubt that the loops with the largest angular size are nearby features and that their contribution to local high latitude radiation must be considered in the interpretation of large-scale continuum radio galactic structure. If we calculate a space density for these objects based on those nearest the Sun, we may also conclude that a significant fraction of the nonthermal disk radiation might come from such objects distributed throughout the galactic disk.

IV. Galactic Plane

Surveys of the brightness distribution at low galactic latitudes (Table II) show the overall structure of the galactic disk.

Detailed studies of particular regions give additional information about the properties of individual sources. Many of the sources are H II regions. Some details of studies of these sources have been given by Goss and Shaver (1970) and by Felli and Churchwell (1972).

TABLE II

Surveys of brightness distribution at low galactic latitudes

Reference	Frequency (MHz)	Beam-width	Longitude range
Mathewson *et al.* (1962)	1440	~50′	256°–0°
Seeger *et al.* (1965)	400	~2°	0°–250°
Komesaroff (1965)	408	~48′	280°–355°
Wielebinski *et al.* (1968)	85	~3°.7	290°–0–60°
	150	~2°.2	
Hill (1968)	1410	~14′	280°–355°
Altenhoff (1968)	2700	~11′	345°–0–240°
Beard and Kerr (1969)	1410	~14′	27°–38°
	2650	~7′	27°–38°
Australian J. Phys.	2650	~7′	288°–307°
Astrophys. Suppl. Ser. No. 11,	2700	~7′	307°–330°
(1969)	2650	~7′	334°–345°
	2650	~7′	345°–0–5°
Altenhoff *et al.* (1970)	1414	~11′	335°–0–75°
	2650	~11′	335°–0–75°
	5000	~11′	335°–0–75°
Goss and Day (1970)	2700	~7′	6°–26°
Day *et al.* (1970)	2700	~7′	37°–47°
Sinclair and Kerr (1971)	1410	~14′	355°–0–5°
Berkhuijsen (1971, 1972)	820	~1°.0	25°–220°
Green (1972)	408	~3′	240°–0–55°
Day *et al.* (1972)	2650	~7′	190°–290°
			46°–61°

As well as H II regions, 150 nonthermal galactic sources, which are presumed to be supernova remnants, have also been catalogued. These sources are discussed by Milne (1970), Downes (1971), Goss and Shaver (1970), and Clark, *et al.* (1973). Careful use of the $\Sigma - D$ relationships derived by using supernova remnents of known distances enables plotting the distribution of these objects in the Galaxy. Ilovaisky and Lequeux (1972a) have used this method to derive a surface density for supernova remnants in the disk.

There are too few catalogued nonthermal sources to obtain an accurate picture of their distribution in longitude. In latitude, they are concentrated to the galactic plane. More than half of the sources between $\pm 2°$ latitude lie within $\pm 0.^{\circ}3$ of the galactic equator. Using the derived distances of all of the catalogued supernova remnants to obtain their distribution in z, we find that more than 75% lie within a disk of 300 pc total thickness.

The unresolved nonthermal disk radiation has a width in latitude of approximately 2° between half-brightness points (Altenhoff, 1968). Baldwin (1967) has pointed out that the equivalent thickness of the nonthermal radio disk is approximately 750 pc. A comparison of the distribution in latitude of the supernova remnants and the disk brightness temperature shows that the major portion of the nonthermal disk emission cannot be due to a superposition of a large number of nonthermal sources of the type now thought to be supernova remnants. From energy considerations Ilovaisky and Lequeux (1972b) also conclude that supernova remnants contribute less than 10% of the nonthermal galactic luminosity at 1 GHz.

There is a strong possibility, however, that supernovae could provide the energetic electrons responsible for the nonthermal disk emission. Lequeux (1971) has discussed this point in greater detail.

A map of the galactic plane by Green (1972) with a half-power beamwidth of approximately 3′ has resolved the disk radiation. From this survey Green reached the following conclusions.

(i) There is only a slight clustering of disk sources (thermal and nonthermal) in longitude. The clustering is generally near the neutral hydrogen tangent points, as might be expected if the sources are weakly concentrated to spiral features.

(ii) The steps in the unresolved (i.e., 'smooth') radiation observed along the plane, first identified at 85 MHz by Mills (1959), are also clearly shown at 408 MHz.

(iii) The observed steps fit some model spirals, the best fits being 7° or 9° two-arm spirals and a 14° four-arm spiral.

V. External Normal Galaxies

The radio continuum structure of spiral galaxies has been studied by Cameron (1971) at 408 MHz with a 3′ half-power beam. Studies have been carried out with the use of aperture synthesis techniques by Pooley (1969a, b), Mathewson, *et al.* (1972), and by van der Kruit (1971, 1973a, b) at 1400 MHz. The results of the studies can be summarized as follows.

(i) Nonthermal radiation exhibits large-scale structure in the disks of some spiral systems. It can be distributed in any or all of the following components: base disk (regular or irregular in distribution), spiral features, and sources or complexes of sources in the nuclei of the galaxies.

(ii) Large-scale halos are seldom associated with spiral galaxies. A possible exception is NGC 891, where some extensions of the nonthermal radiation are seen above the galactic disk. M31 also has a higher single-dish flux density than can be a accounted for by high-resolution measurements. This might be due to a large-scale halo around M31.

(iii) Observations show concentration of neutral hydrogen gas to spiral features in some systems, e.g., M101. This indicates the possibility of a corresponding compression of magnetic field and relativistic particles which would result in nonthermal emission from the spiral features.

The best examples of nonthermal radio spiral features that we now have are those observed in M51 (Mathewson *et al.*, 1972). It should be noted that the emission does not follow a regular spiral pattern; rather, it wanders somewhat, generally on the inner edge of the bright optical arms, also forming spurs or cross links between spiral features. This observation suggests that we should not expect a high degree of regularity in nonthermal spiral features in our Galaxy.

At the present time, there is no simple basis on which to predict the type of large-scale nonthermal emission that might be associated with a given spiral galaxy. This is a strong argument against close direct comparison of the structure of our Galaxy with any particular external system.

VI. Radio Disk and Spiral Features

At the time Mills (1959) first suggested that the steps and bumps observed in the brightness temperature profile along the galactic equator at meter wavelengths might be due to nonthermal radiation from spiral features there was no widely accepted model for the form of the spiral features. The Lin-Shu (1967) density wave theory now provides one method for calculating the form of the spiral patterns in galaxies. On the basis of the nonlinear density wave theory (Roberts, 1969) the relative locations of gas, dust, and young stars can be predicted. The location of nonthermal radio emission can also be predicted, under the assumption of the existence of a large-scale magnetic field and energetic electrons in a galaxy. The theory provides a satisfactory explanation of the observations of the nonthermal spiral structure in M51 (Mathewson *et al.*, 1972).

For our Galaxy, we can compare the observed radio brightness distribution at meter wavelengths with models to help determine the distribution of non-thermal emission regions. The approach suggested by Price (1974) is as follows.

(i) Estimate a base disk component by using a volume emissivity function that accounts for the bulk of the observed brightness temperature along the galactic plane, especially in longitudes toward the galactic center.

(ii) Compare the residuals (observations minus estimated base disk) with the contribution expected from nonthermal emission regions distributed in the form of spiral features.

Such an analysis suggests the following properties of the distribution of nonthermal emission in the disk of our Galaxy.

(i) The volume emissivity of the base disk falls off from the galactic center toward the outer regions of the Galaxy. It has been suggested (Price, 1974) that the volume emissivity follows a function of the form $e^{-\alpha R}$. This base disk component, as shown in Figure 2, contributes approximately one-half of the total power observed from the galactic disk at meter wavelengths.

(ii) Emission from spiral features provides most of the remaining total power emitted from the galactic disk. These spiral features are irregular both in volume emissivity (i.e., compression) and in shape. That is, they do not follow a precise spiral pattern but wander somewhat about some mean best-fit spiral. A comparison of observations with the profile predicted by a model incorporating a base disk and spiral features is shown in Figure 2. It can be seen that there is general agreement in the overall shape of the profile, but not in smaller details.

(iii) From the observed width of the concentration of brightness temperatures toward the galactic center, and from the brightness of the emission associated with the local arm (at $l = 80°$ and $265°$), it is inferred that the Sun is located near the inner edge of the local nonthermal radio spiral feature.

(iv) If the Sun is, in fact, located just within the local nonthermal feature, the nonthermal radiation produced locally will account for the relatively high brightnesses observed at high galactic latitudes. Yates (1968) has suggested a similar origin for the high latitude brightness. His analysis, however, requires that the Sun be at the center of the local spiral arm.

In any case, observations at meter wavelengths at high galactic latitudes ($|b| > 30°$) indicate that any large-scale spherical component around our Galaxy could not have a volume emissivity greater than 1.5% of the average volume emissivity of the disk (Price, unpublished).

VII. Observational Needs

The observational requirements listed by Baldwin (1967) have been carried out in part. The information derived from those studies suggests the need for further observational programs.

(i) Observation of more external normal galaxies to determine the frequency of occurrence of nonthermal radio features in their nuclei, disks, and spiral features.

(ii) Search for more distant loop features in the disk radiation of our Galaxy.

(iii) Search for additional nonthermal sources in the galactic plane, and a careful study of the characteristics and distribution of these sources.

(iv) Studies of the distribution of the nonthermal component of the disk at low and medium (to $b \approx 20°$) latitudes.

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DISCUSSION

Yuan: From Davies and Whiteoak we learn that there is a large-scale magnetic field in the direction $l=90°$ and from Mathewson that there is a local magnetic field in the direction $l=50°–60°$. Would you estimate the contribution from the local field in your observations? I feel somewhat uncomfortable with your placing the Sun in different locations with respect to the spiral arms without considering the local field.

Price: It is not possible to determine very much about the structure of the local magnetic fields by continuum brightness measurements alone. Some information can be obtained from polarization of local emission. However, any small rms component of field on top of a uniform field will preclude detection of large-scale synchrotron beaming and polarization effects. Continuum measurements give the integrated line-of-sight brightness, and we must in many cases resort to simple geometrical models to estimate the location of regions where the emission originates.

Mills: Green in her 408 MHz survey investigated different spiral patterns and found that many fitted her results reasonably well, the original 7° spiral being best. Thus the radio continuum results cannot provide a unique model but can be most effective for deciding between competing models.

Shakeshaft: In any dismissal of radio haloes, it is important to make clear the frequency range under consideration since it may be that, as Ginzburg emphasizes, any halo to our Galaxy may have a steep

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spectrum and be detectable only at low frequencies. As radio maps of other galaxies (such as M31 and M51) show, interpretation of the continuum features in terms of simple disks and spiral arms is likely to be misleading. One hopes, of course, to relate the nonthermal emission to the distribution of cosmic-ray electrons, which may in turn be related to the distribution of supernova remnants, or perhaps to whether there has been an explosion in the galactic center. Do you have any views on this?

Price: There is some evidence from the low-frequency work done by Hamilton and Ellis in Tasmania that there could be a halo at low frequencies. This should be carefully looked at. Certainly I would urge caution in the direct comparison of our Galaxy to any specific external galaxy. However, radio observations of external galaxies do provide us with information on what types of large-scale radio continuum emission features are possible and can thereby help us in the interpretation of the observed brightness distribution in our own Galaxy. I agree, no simple model will be comprehensive. We have no direct evidence for the source of the energetic electrons causing the synchrotron radiation. All we know for certain is that there is a definite fall-off in radio volume emissivity in going from the galactic center towards the outer parts of the Galaxy.

Westerhout: I distinctly remember that at the Noordwijk Symposium, Ginzburg started his discussion with the statement that there might not be a galactic halo, but that the galactic plane material must extend several kiloparsecs up. I agree with Price that there is at present no evidence for a halo, even at very low frequencies.

Price: The last phrase is not quite in agreement with what I said. I said there is no evidence for a large-scale radio halo – except there might be some evidence for such a halo at low frequencies, tens of megaherz.

Wielebinski: Maps of M31 at 408 MHz (Pooley) and at 2695 MHz (Berkhuijsen and Wielebinski) with similar resolutions of 4.5′ are remarkably similar. The assertion that a halo is seen at lower frequencies in M31 needs careful reexamination.