ON THE EXISTENCE OF THE GALACTIC RADIO HALO

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Abstract

Radio astronomical data available on the galactic background radiation has been carefully examined to deduce information on the existence or otherwise of a Galactic Radio Halo. It is shown that, though considerable doubt has been recently expressed by some regarding its existence, no convincing and quantitative reasoning has been so far advanced towards this; on the other hand, there are substantial arguments in its favour.

1. Introduction

The existence of a galactic Halo of near spherical shape, glowing in the radio region by synchrotron radiation emitted by cosmic electrons spiralling in weak magnetic fields existing therein, was first postulated by Shklovsky in 1952.[1] This suggestion was made credible by Baldwin,[2] who, on the basis of cosmic background radio observations, attributed a diameter of about 20–30 kpc for this Halo. By definition a radio halo is also a cosmic ray halo. The existence of the Radio Halo which received a large measure of support from observational radio astronomers, astrophysicists and cosmic ray physicists for about ten years,[1–7] and was sometimes acclaimed as one of the most important discoveries of our times, is being increasingly questioned during recent years. Being much concerned over these developments, we have carefully examined the many arguments that have been proposed in favour of the Halo and the recent reasonings against it. Though the existence of the Halo has direct implications in matters relating to the dynamics of the Galaxy and cosmic ray storage, much of the arguments so far advanced against its existence has been drawn from recent observations on the galactic background radio emission. In this paper we critically examine these arguments and show that while on the one hand there are certain features which are in favour of a halo, those which have been so far suggested against its existence are not convincing enough.

2. DATA USED

In order to develop our arguments we make use of the following information:—

(*a*) The Solar system is situated at a distance of 8 kpc from the Galactic centre and about 10 pc north of the Galactic plane; the edge of the Disc is another 4 kpc from the Sun while the thickness of the Disc itself is $\approx$ 500 pc. Further, the Sun is located close to the inner edge of the Orion spiral arm, with the Perseus arm lying still beyond in the general Anticentre direction. The spiral arms have a flattened cross-section with the major axis along the plane of the Disc. (For a schematic representation of these, *see* Fig. 2.) These numbers seem to be acceptable to the vast majority of the workers and are unlikely to be in serious error. (For references *see* Refs. 8–10.)

(*b*) Radio brightness distributions are now available from sky surveys for three general galactic directions of interest to us here; these are the Northern Halo (H) avoiding the North Pole Spur, the North Halo Minimum (M) which is the coldest region of the sky, and the Anticentre (A). The best curves fitted to the experimental data for these three cases in the frequency range 10–400 MHz are shown in Fig. 1. (For details of the compilation of the data, etc., *see* Refs. 11 and 12.) From this Figure one finds that, *firstly*, the radio spectra for H and M have identical shapes within errors, whilst that for A seems noticeably flatter at lower frequencies. *Secondly*, at a frequency of about 10 MHz the relative intensities in the three directions have the following values $A/H = 1{\cdot}15$ and $A/M = 1{\cdot}45$; at 85 MHz the corresponding values are 1·3 and 1·7. All three spectra have slopes close to 0·8 at the high frequency end.

(*c*) The interstellar electron energy spectrum required to explain the background radio brightness in the direction of the Anticentre, and fitted to the cosmic ray electron spectrum measured at energies > 2 BeV in the neighbourhood of the earth, has been reliably deduced recently.[11] At energies > 2 BeV, this spectrum fits a power law in energy with an exponent of 2·6 [13]; at lower energies the spectrum continues to flatten upto about 200 MeV.

3. Arguments Favouring the Existence of Halo

3.1. We will now process the information in 2 (*a*) through 2 (*c*) suitably to bring out the feautures in favour of the existence of the Radio Halo. The background radio brightness distribution in the galactic plane ($b \approx 0$) should consist of radiation from the Radio Disc and the isotropic radiation from the Metagalaxy, while that towards high galactic latitudes, as in the direction of H and M should, if the Halo exists, include the radiation from the Halo as well. Therefore a convenient way of attempting to demonstrate the existence of the Halo is to determine first the magnitudes of the components from the Metagalaxy and the Disc in the direction of high latitudes and then see whether there will be any significant residual radiation left for the Halo.

The Metagalactic Radiation

There could be two subcomponents to this radiation. (*a*) The diffuse radiation, radiated by electrons moving in very weak magnetic fields in the Metagalactic space : From considerations of the steepening of the equilibrium electron spectrum in the Metagalaxy, it seems most natural to expect that this component should have a spectral index of 1·3.[14] If this were so, then it can be shown (for details *see* Ref. 12) that the upper limit of this contribution at 10 MHz is only 20% of the observed radiation from the Anticentre; this inference is possible from a consideration of the shape of the residual radio brightness from the Anticentre after allowing for the Metagalactic contribution, and the shape of the electron spectrum that is required to exist in this region of the Galaxy in order to give rise to this residual radiation. (*b*) The second component arises from the integrated radiation from all galaxies. Spectral measurements so far carried out show that (i) between 38 and 1417 MHz most of the sources have power law spectra[15, 16] of which the majority show a steepening only beyond 1417 MHz, (ii) below 38 MHz, the survey at 26·3 MHz[17] shows that more than 80% of the sources do not show any departure from a single power law and (iii) even at 10·3 MHz there is still no appreciable flattening of the spectra for the majority of the sources.[18] It is also seen that all these power spectra have indices between 0·2 and 1·3 with a very prominent maximum between 0·7 and 0·8. Furthermore, there is no evidence that the spectral distribution depends on the apparent luminosity down to about 2 flux units at 178 MHz.[19] The Metagalactic component[20–24] from discrete sources estimated by using a spectral index of 0·75 is also shown in

Fig. 1, and it is found that its contribution is about 25% at 20 MHz and about 15% at 400 MHz of the North Halo brightness.

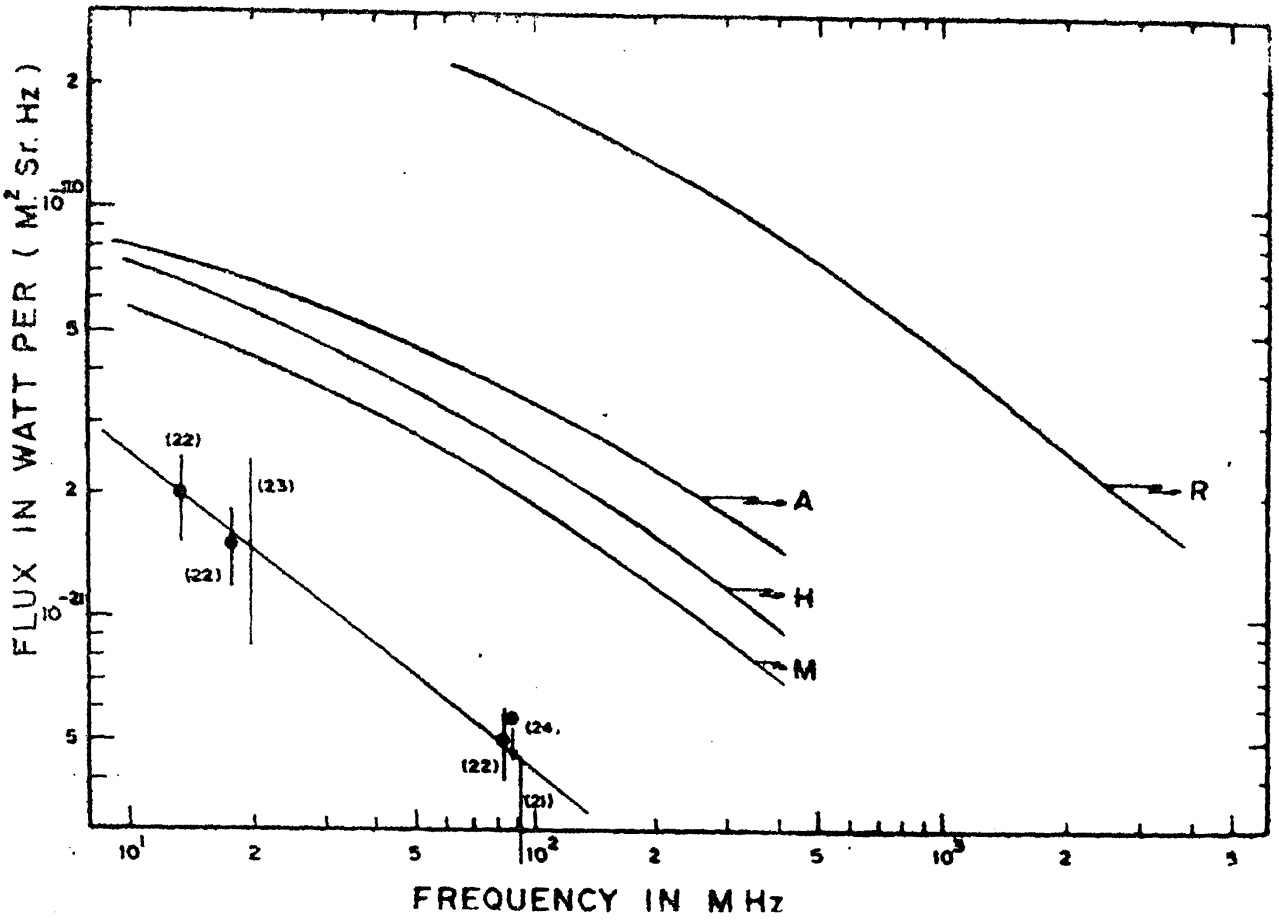

FIG. 1. Radio brightness distributions observed in the galactic directions of North Halo (H), North Halo Minimum (M), Anticentre (A) and the Ridge $l = 0$; $b = +3{\cdot}6$ or $-3{\cdot}6$ (R). The data points and the straight line fit refer to estimates of metagalactic component. (Numbers in parenthesis are the relevant references.)

The Disc Radiation

The contribution of radio brightness from the Disc in the direction of high latitudes can be estimated using the following assumptions: (i) The radio spur features observed in various sky surveys are mainly large-scale galactic phenomena: (The alternative proposal that these are local in character is discussed under Section 4). (ii) The background radiation from the Disc is uniform within the Disc at least in the directions of A, H and M. In support of this assumption we would like to refer to the irregular shapes of the spiral arms and the existence of spiral arm spurs and interarm links.[9] Assumption (ii) means that the Disc contribution in the direction of A and H (or M) should be in the ratio of the corresponding emitting distances, namely, 16 : 1. This would imply that the Disc radiation contributing to the total brightness in the directions of H and M is unlikely to be greater than 10% of the Disc radiation from the Anticentre direction. Even if one assumes

that the Disc radiation arises exclusively from the spiral arms, the spiral arm contribution in the direction of H and M is unlikely to be greater than 20% of that from the direction of A because of the special location of the Sun with respect to the Orion and Perseus arms and the flatness of the spiral arms (*see* Fig. 2).

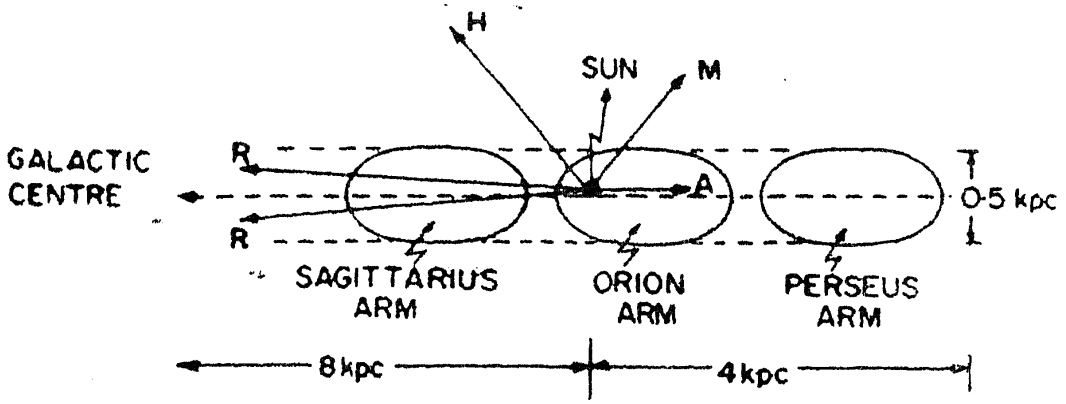

FIG. 2. A simple minded representation of the location of the solar system in the galactic Disc. The four directions for which the background radio spectra are given in Fig. 1, are also indicated.

The Halo Radiation

We can now subtract the contributions arising from the Metagalaxy and the Disc from the observed radio brightness for the directions of H and M and deduce the residual brightness which should be due to the Halo; such values are given for 80 MHz in Table I. These calculations have been made by assuming that 10% and 20% of the radio brightness from the direction of A to be present in the brightness observed from H and M. The values obtained for H/M in Table I clearly indicate that they are insensitive to the magnitude of the correction for the Disc contribution. Indeed, in case the spiral arms are the main radio emitting regions, the effective Disc distance along H is likely to be smaller than that along M because of the special location of the Sun as summarised in Section 2 *a* and would therefore result in increasing the ratio of H/M further. Since this ratio seems significantly greater than 1, one can attribute it as arising from the existence of a Halo. It seems a ratio of 1·5 would be consistent with a Halo of radius 6–10 kpc along the polar direction, as can be seen from a geometric representation of the Galaxy. Furthermore, from what we have discussed above, it is also clear that the magnitude of the Disc *plus* Metagalactic contributions from H is very unlikely to be greater than about 50% of the total radiation from H. Hence the residual radiation amounting to the remaining half of the radiation from H will have to be attributed to the Halo.

3.2. A further argument which we believe offers support to the existence of a Radio Halo is the internal consistency which we find in the analysis of data on non-thermal radio emission and the cosmic electrons. Two important examples for this are the following: (i) It is seen from Fig. 1 that

TABLE 1

Different components of the radio brightness towards H and M at 80 *MHz*

	Anticentre (A) Watts/m.^{2} sr.Hz	North Halo (H) Watts/m.^{2} sr.Hz	Halo Minimum (M) Watts/m.^{2} sr.Hz	H/M
1. Total radiation	$3\cdot7\times10^{-21}$	$2\cdot8\times10^{-21}$	$2\cdot2\times10^{-21}$	..
2. After subtracting the Metagalactic component	$3\cdot1\times10^{-21}$	$2\cdot2\times10^{-21}$	$1\cdot6\times10^{-21}$	..
3. After subtracting the Disc component (10% of A from H and M)	0	$1\cdot9\times10^{-21}$	$1\cdot3\times10^{-21}$	1·45
4. After subtracting the Disc component (20% of A from H and M)	0	$1\cdot6\times10^{-21}$	$1\cdot0\times10^{-21}$	1·6

while the emission from the North Halo and North Halo Minimum directions have the same spectral shape, that from the Anticentre seems to be flatter at low frequencies; this would be a natural and necessary consequence, if the bulk of the radiation from all three directions are of galactic origin and result from the same electron spectrum mentioned in Section 2 *c* but with a mean magnetic field which is significantly higher in the direction of A. (ii) *Secondly*, the fact that in each of the four directions, including that from the galactic Ridge[12] in Fig. 1, a single value of the magnetic field for each direction (which varies by a factor of 4 between the Halo and the galactic Ridge) could generate the corresponding radio spectrum in exceedingly good fit with the experimental observations, and the fact that these mean magnetic fields agree well with those deduced through other methods, provide further confidence to the procedure adopted, and assumptions made.

4. An Examination of Radio Astronomical Data on Radio Spurs and Structures

Perhaps the most important argument which has been advanced against the existence of the Halo is that the structures and spurs that are seen in the background radiation are of local nature (*i.e.*, within about 300 pc from the Sun) and that when this and the metagalactic contribution are corrected for, almost nothing will be left for the Halo. In this, the evidence used in support of the local nature of the spurs is the existence of polarisation at the outer edges of the North Polar Spur which indicates that the spur is within about 100 pc and is probably the remnants of a supernova.[25]

Though the local nature of the spurs has been often referred to in the literature, to our knowledge, there have been only two papers with relevance to the existence of the Halo, in which the authors have attempted to look into this problem in a quantitative way. Of these the first is by Yates[26] who has very critically assessed the various contributions to the background radiation. The general approach followed by Yates is to start with an assumption of a very small (or no) radiation from the Halo—this he calls a "Minimum-Halo Model"—and symmetry in the high latitude radiation with respect to $l \approx 0$; thereafter in his attempt to explain the observed radiation to be of metagalactic and local origin only, he finds he has to invoke further conditions which seem to be questionable. The second is a preprint by Wielebinsky and Peterson[27] in which they try to show that there is no Halo when account is taken of the spurs. We will therefore examine these two papers in further detail to identify and point out the general weaknesses of such arguments.

Yates,[26] in his detailed paper, has studied the background radiation in the North and South hemispheres of the Galaxy at 85 MHz and is able to establish first the spur features by attributing them to be local in nature and demanding symmetry in the high latitude radiation. He then removes the spur contributions from the observed radiation contours and still finds the remaining radiation to be not very symmetric about $l \approx 0$. This was then explained as due to the effect of the radiation from the local arm. In order to estimate this contribution, Yates has proposed a model for the local arm with the Sun at the centre but slightly displaced towards the anti-centre, a magnetic field of $1{\cdot}2 \times 10^{-5}$ Gauss which slightly expands about the axis $l \approx 250°$ and an electron energy spectrum which obeys a power law upto the lowest energies. However, it is found that these assumptions and the ensuing deductions do not lead to a complete understanding of the

observed patterns in the background radiation; in fact they lead to many difficulties which are summarised below. (i) The local hypothesis of the observed spurs leads to a high emissivity in a region close to the Sun, an exceptionally high radio to optical luminosity and the requirement that the Sun has to be in a very special position in the Galaxy; it also cannot explain the pronounced features which are observed mainly in the direction of the galactic nucleus and the rapid decay of the intensity with latitude. (ii) The optical and radio observations suggest that the Sun is located close to the inner side of the Orion arm and not in the centre. (iii) For $b < 30°$ the effect of nearby spiral arms (the Sagittarius and Perseus arms) and their interlinks which have been neglected by Yates would lead to radio profiles different from what he has obtained. (iv) Recent analyses described in Section 2 (c) show that the interstellar electron spectrum deviates from a power law below about 2 BeV; this spectral flattening would demand a much higher magnetic field to exist in Yates' model of the spiral arm than the value of $1{\cdot}2 \times 10^{-5}$ Gauss used by him.

Wielebinsky and Peterson[27] have examined the background radiation from the southern hemisphere at 85 and 150 MHz in the direction $l = 0°$; $b = -45°$ and $l = 180°$; $b = -45°$ according to a simple test suggested by Baldwin[28] for the existence of the Halo. After removing the spur contributions in the direction $l = 0$; $b = -45°$, they estimate the ratio of the intensities from the two directions and conclude that a spherical Halo cannot be fitted to the observed radiation and that it can be explained by Disc and spur radiations only. However, it is seen that (i) the remaining radiation in these two directions after removing the spur and metagalactic contributions is still too large to be accounted for as due to the Disc and (ii) the coldest part of the southern hemisphere as shown in Yates' paper[26] occurs at about $l \approx 240°$; $b \approx -32°$ where the observed temperature is $\approx 900°$ K at 85 MHz and not at $l = 180°$; $b = -45°$ as used by these authors. For these reasons the conclusion drawn by them becomes questionable.

5. To summarise we are of the opinion that though frequent references are recently made, seriously doubting the existence of the galactic Radio Halo on the basis of radio astronomical data, no convincing and quantitative reasoning has so far been advanced towards this, to our knowledge. On the other hand there are substantial arguments in its favour.

5. REFERENCES

1. Shklovsky, I. S. .. *Ast. Zh.*, 1952, **29**, 418.

2. Baldwin, J. E. .. *M.N.*, 1955, **115**, 690.

3. Spitzer, L. .. *Ap. J.*, 1956, **124**, 70.

4. Pikelner, S. B. and Shklovsky, I. S. .. *Ast. J. (USSR)*, 1957, **34**, 145.

———— .. *Ann. d'ap.*, 1959, **22**, 913.

5. Woltjer, L. .. *Stars and Stellar Systems*, University of Chicago Press, 1965, **5**.

6. Parker, E. N. .. *Ap. J.*, 1965, **142**, 584.

7. Ginzburg, V. L. .. *I.A.U. Symp.*, 1967, **31**, 365.

8. Allen, C. W. .. *Astrophysical Quantities*, published by Athlone Press, University of London, 1963, 268.

9. *Galactic Structure*, Edited by Blaauw, A and Schmidt, M., pp. 167–202.

10. Bok, B. J. .. *Observatory*, 1959, **79**, 58.

11. Anand, K. C., Daniel, R. R. and Stephens, S. A. *Nature*, 1968, **25**, 217.

12. ———— .. *Proc. Ind. Acad. Sci.*, 1968, **67**, 267.

13. ———— .. *Phys. Rev. Let.*, 1968, **20**, 764.

14. ———— .. *Proc. Symp. Cosmic Rays*, Aligarh, India, 1967.

15. Convey, R. G., Kellermann, K. I. and Long, R. F. *M.N.*, 1963, **125**, 261.

16. Long, R. F., Smith, M. F., Stewart, P. and Williams, P. J. S. *Ibid.*, 1966, **134**, 371.

17. Erickson, W. C. and Cronyn, W. M. *Ap. J.*, 1965, **142**, 1156.

18. Galt, J. A., Purton, C. R. and Scheuer, P. A. G. *Publs. Dom. Obs.*, 1967, **25**, No. 10.

19. Kellermann, K. I. .. *Ap. J.*, 1966, **146**, 621.

20. Turtle, A. J., Pugh, J. F., Kenderdine, S. and Pauliny-Toth, I. I. K. *M.N.*, 1962, **124**, 297.

21. Yates, K. W. and Wielebinski, R. *Aust. J. Phys.*, 1966, **19**, 389.

22. Bridle, A. H. .. *M.N.*, 1967, **136**, 219.

23. Shain, C. A. .. *Paris Symp. Radio Astr.*, 1958, p. **328**.

24. Costain, C. H. .. *M.N.*, 1960, **120**, 248.

25. Davis, R. D. .. *Ibid.*, 1964, **128**, 133.

26. Yates, K. W. .. *Aust. Jour. Phys*, 1968, **21**, 167.

27. Wielebinski, R. and Peterson, C. E. Preprint 1968.

28. Baldwin, J. E. *I.A.U. Symposium*, No. 31, *Radio Astronomy and the Galactic System*, Academic Press, 1967, p. 337.