this formation is not from the same locality as any of the palæomagnetic sites, hence no correlation is possible.

It may be assumed that the 'reversed' polarities observed in Hawaiian rocks are caused by reversal of the Earth's magnetic field. This is supported by the observation that rocks of each polarity occur in discrete stratigraphic zones, and that in each of these zones the composition of the lavas ranges from picrite basalt to trachyte. In addition, there is no evidence of self-reversal in specimens examined in the laboratory. However, these observations do not refute the possibility of self-reversal, and it is necessary to compare the results from Hawaii with results from rocks of similar age in other parts of the world if the hypothesis of reversal of the Earth's field is to be substantiated.

Our data are consistent with the change from 'normal' to 'reversed' polarity observed[10] in California (Fig. 1) at about 1 m.y., but suggest that a return to 'normal' polarity occurred between 2·5 and 2·75 m.y., rather than at about 2 m.y. as inferred by Cox *et al.*[10]. They recorded 'normal' polarity in a rock dated at 2·6 ± 0·1 m.y. and refer to Rutten[15], who reported 'normal' polarity in a sequence in Italy dated at about 2·4 m.y. These data, combined with our measurements, suggest that the change from 'reversed' back to 'normal' polarity occurred at 2·5 ± 0·1 m.y. The 'reversed' polarity found in a rock from the Waianae Series with a measured age of 2·95 m.y. indicates that the behaviour of the magnetic field is more complex than has been suggested previously. Owing to the lack of data it is not possible to state whether 'normal' polarities found in rocks dated at 3·3 and about 4·5 m.y. belong to the same magnetic epoch or whether a zone of 'reversed' polarity occurs during this period. Our results are consistent with varying frequency of change in the polarity of the Earth's magnetic field in the Upper Cainozoic, rather than a regular change about every 1 m.y.[10].

Roche[16,17] showed that in France lavas of Upper Pleistocene age are normally magnetized, and that lavas of Villafranchian (Lower Pleistocene) age have 'reversed' polarity. Hence, the change in polarity at about 1 m.y. found in the Hawaiian Islands and in California may be correlated with that found in France. The stratigraphic position of the return to 'normal' polarity has not been established in France; but it is either in the lower part of the Villafranchian or in the Astian[18], although Rutten[19] suggested that it occurs at the base of the Villafranchian. Clearly it is of importance to establish the position of this boundary in order that correlations may be made with greater certainty throughout the world. Fourteen polarity zones were reported by Khranov[20] from sequences of Upper Cainozoic age in Russia, but at this stage it would be premature to attempt direct correlations.

The evidence from Hawaii supports, but does not prove, the hypothesis of changes in polarity of the Earth's magnetic field. Further study on rocks of similar age clearly is necessary to confirm the hypothesis, and to place closer limits as to the times when polarity changes occurred. The present work suggests that models of the Earth's magnetic field should account for irregular periodicity of reversal.

We thank E. Irving for his advice.

1 Brunhes, B., *J. Physique*, **5**, 705 (1906).
2 Mercanton, P., *C.R. Acad Sci., Paris*, **151**, 1092 (1910).
3 Hospers, J., *Proc. Kon. Ned. Akad. Wet.*, B, **56**, 467, 477 (1953).
4 Hospers, J., *Proc. Kon. Ned. Akad. Wet.*, B, **57**, 112 (1954).
5 Neel, L., *Adv. Phys.*, **4**, 191 (1955).
6 Verhoogen, J., *J. Geophys. Res.*, **61**, 201 (1956).
7 Tarling, D. H., *Nature*, **196**, 882 (1962).
8 McDougall, I., *Nature*, **197**, 344 (1963).
9 McDougall, I. (in the press).
10 Cox, A., *et al.*, *Nature*, **198**, 1049 (1963).
11 Stearns, H. T., *Hawaii Div. Hydrog.*, *Bull.* 8 (1946).
12 Thellier, E., and Rimbert, F., *C.R. Acad. Sci., Paris*, **239**, 1399 (1954).
13 Irving, E., *et al.*, *Phil. Mag.*, **6**, 225 (1961).
14 Macdonald, *et al.*, *Hawaii Div. Hydrog.*, *Bull.* 13 (1960).
15 Rutten, M. G., *Geol. en Mijnb.*, N.W., 21e Jaarg., 373 (1959).
16 Roche, A., *C.R. Acad. Sci.*, *Paris*, **233**, 1132 (1951).
17 Roche, A., *C.R. Acad. Sci.*, *Paris*, **243**, 812 (1956).
18 Roche, A. (personal communication).
19 Rutten, M. G., *Geol. Rdsch.*, **49**, 161 (1960).
20 Khranov, A. N., *Palaeomagnetism and Stratigraphic Correlation* (Gostoptechizdat, Leningrad, 1958).

ABSORPTION IN RADIO SOURCES OF HIGH BRIGHTNESS TEMPERATURE

By P. J. S. WILLIAMS

Mullard Radio Astronomy Observatory, Cavendish Laboratory, University of Cambridge

THE discrete radio sources have continuous spectra which generally follow a power law, $S \propto \nu^{-\alpha}$ (S = flux density, ν = frequency), and the usual graph of log S against log ν is a straight line. It is generally believed that most sources are galaxies and that the radiation is synchrotron radiation from relativistic electrons; the straight radio spectrum then implies a population of relativistic electrons with an energy distribution which also follows a power law: $N(E) \propto E^{-(2\alpha+1)}$. However, there are sources the spectra of which deviate significantly from a straight line, and it has been noticed[1] that these sources tend to have high surface brightness.

Recently, improved measurements at 38 Mc/s have shown that, in a few sources, the flux density actually falls at low frequencies (Fig. 1), and these sources also have the smallest known angular diameters and the highest known surface brightness. In the case of 3C 147, the decrease in flux density between 81·5 Mc/s and 38 Mc/s is so rapid that no cut-off in the electron energy spectrum, however sharp, would account for it. These circumstances suggest that we may be observing synchrotron self-absorption.

In Fig. 1, the high-frequency data are taken from Conway, Kellermann and Long's paper[1] on the spectra of 160 sources. The 38-Mc/s points are taken from a survey by J. E. Baldwin, S. Kenderdine, and me, using the instrument described in ref. 2. Flux densities at 81·5 Mc/s (3C 48, 147, 295, 298) and 85 Mc/s (3C 298) have been taken from refs. 3 and 4 respectively; correction factors (0·85 and 0·75 respectively) have been applied to the

Table 1

Assuming that T_e for H II region = 10,000° K
$B = 10^{-4}$ gauss.

Source	Galactic latitude b	Emission measure necessary for thermal absorption cm^{-6} × parsecs	θ_p necessary for synchrotron absorption	θ_0
3C				
48	29°	2,450	0·4″	1·0″
119	04°	2,450	0·3″	1·5″
147	10°	5,000	0·2″	2·0″
295	61°	1,400	0·6″ double; components	1″ × 1·7″
298	61°	3,200	0·6″	4·0″
299	67°	1,250	0·2″	2·0″
CTA				
21		34,000	0·01″	—
102		20,000	0·01″	—

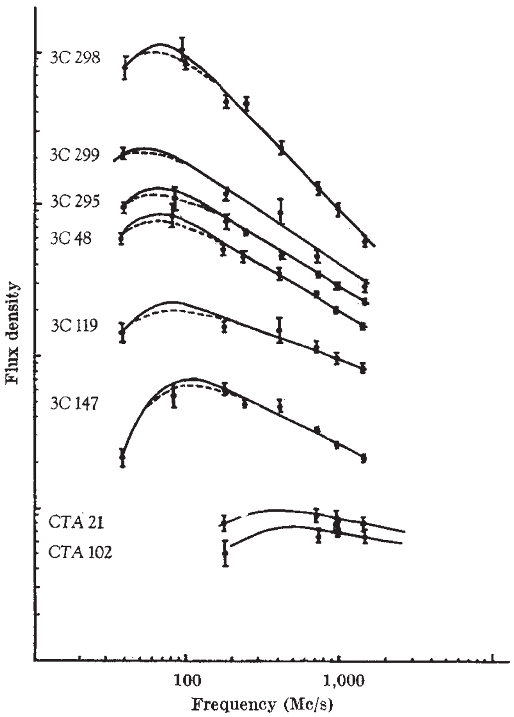

Fig. 1. —, synchrotron absorption; – – –, thermal absorption

catalogue values of flux density, the factor being determined by a comparison of the flux densities of the strongest 'Class S' sources[1] with the values interpolated from the spectra given[1].

Two mechanisms of absorption could be held responsible for the cut-off in the spectra at low frequencies:

(*a*) *Thermal Absorption*. This occurs if a layer of H II of appropriate optical depth, τ, lies between the source and the observer. The spectrum would be:

$$S = k.\nu^{-\alpha} \exp(-\tau) = k.\nu^{-\alpha} \exp(-A/\nu^2)$$

If a spectrum of this shape is scaled in both frequency and flux density to fit the observed values, we can calculate the emission measure of the H II layer necessary to cause the absorption. The values quoted in Table 1 are $\int N_e^2 \,.\, ds$, where $N_e =$ No. of electrons/c.c., and ds is distance through the layer, measured in parsecs.

(*b*) *Synchrotron Self-Absorption*. This occurs if the brightness temperature of emission is of the same order as the mean kinetic temperature of the relevant relativistic electrons, and so we should expect to observe this in sources of high enough brightness temperature.

A detailed calculation by Le Roux[5] has shown that for a source in a uniform cube of side l, in a magnetic field of strength B,

$$S = l^2 \frac{\bar{\varepsilon}}{\chi} (1 - \exp(-\chi l))$$

where χl, the optical thickness,

$$= \frac{\mu a e^2 c l}{16\pi m_0} (\gamma + 2) \left(\frac{eB}{2\pi m_0}\right)^{(\gamma+2)/2} F'(\gamma) \nu^{-(\gamma+4)/2}$$

and $\bar{\varepsilon}$, the mean emission per unit volume,

$$= \frac{\mu a e^2 c}{8\pi r^2} \left(\frac{eB}{2\pi m_0}\right)^{(\gamma+1)/2} F''(\gamma)\, \nu^{(1-\gamma)/2}$$

If $N(E)\,dE =$ No. of particles/unit vol. with energies between E and $E + dE$,

$$= \text{const. } E^{-\gamma}\, dE;$$

$$a = (\gamma - 1) \int_{m_0 c^2}^{\infty} N(E)\, dE;$$

r = distance of the source from observer.

$F'(\gamma)$ and $F''(\gamma)$ are numerical factors weakly dependent on γ. If γ is determined by the spectral index at high frequency, the predicted spectrum can be scaled in flux density and frequency to fit the observed values and so indicate ν_m, the frequency at which the flux density is greatest.

If synchrotron self-absorption is taking place, the predicted angular diameter of the source is then given by:

$$\theta_p^2 = \frac{S_{400}}{(400 \cdot 10^6)^{(1-\gamma)/2}} \left(\frac{eB}{2\pi m_0^3}\right)^{1/2} \frac{(\gamma + 2)(1 + z)^{1/2}}{\nu_m^{(\gamma+4)/2}}$$

The 'observed' angular diameter, θ_0, is largely based on a single interferometer measurement at a spacing of 61,100 λ (ref. 6), assuming that the source is single with a simple Gaussian brightness distribution. However, very few sources have such a simple brightness distribution, many being made up of two separate components. In such a case, θ_p corresponds to the sizes of individual components, while θ_0 corresponds to the dimensions of the source as a whole, and can only be used as a generous upper limit. For example, a single interferometer measurement for $3C$ 295 would only give $\theta < 12''$; more detailed measurements[7] have indicated that it is made up of two components 4″ of arc apart. Each component is less than 1″ of arc wide on the line joining them, but 1·7″ of arc in length perpendicular to this line. These dimensions give much better agreement with θ_p.

The one clear and outstanding fact is that the six sources selected from the available data on the basis of their unexpectedly low flux-densities at 38 Mc/s all belong to the very small fraction of sources with angular sizes $< 5''$ of arc and exceptionally high surface brightness. The high surface brightness suggests that synchrotron self-absorption may occur; but it is also possible that a source of such small size may lie entirely within the associated galaxy so that thermal absorption may take place.

For both mechanisms, the observations can be fitted by calculated spectra representing reasonable physical conditions. It is unlikely that improved spectral measurements will be able to distinguish between the two proposed mechanisms as the predicted spectra are based on very simple models, and will not apply in detail to a real source.

In the case of $3C$ 295, however, the two components are separated by more than 16 kparsecs, and it is probable that the radio emission occurs too far outside the galaxy to be absorbed appreciably by ionized hydrogen. In this case, at least, synchrotron self-absorption seems the more probable mechanism.

The two sources CTA 21 and CTA 102 are also included because they, too, have spectra with a maximum, but at much higher frequencies. If these maxima are to be explained by synchrotron self-absorption, the sources must have linear dimensions of less than 150 parsecs (again assuming $B = 10^{-4}$ gauss, but making no assumptions about their distances).

While the known upper limits on angular diameters are consistent with synchrotron self-absorption, it is clearly desirable that more detailed measurements of brightness distribution should be made, if possible, so that a quantitative comparison can be made.

I thank H. van der Laan and P. A. G. Scheuer for useful discussion of the synchrotron absorption mechanism.

[1] Conway, R. G., Kellerman, K. I., and Long, R. J., *Mon. Not. Roy. Astro. Soc.*, **125**, 261 (1963).
[2] Costain, C. H., and Smith, F. G., *Mon. Not. Roy. Astro. Soc.*, **121**, 405 (1960).
[3] Shakeshaft, J. R., Ryle, M., Baldwin, J. E., Elsmore, B., and Thomson, J. H., *Mem. Roy. Astro. Soc.*, **67**, 106 (1955).
[4] Mills, B. Y., Slee, O. B., and Hill, E. R., *Austral. J. Phys.*, **11**, 360 (1958).
[5] Le Roux, E., *Ann. Astro.*, **23**, 1010 (1960); **24**, 71 (1961).
[6] Allen, L. R., Anderson, B., Conway, R. G., Palmer, H. P., Reddish, V. C., and Rowson, B., *Mon. Not. Roy. Astro. Soc.*, **124**, 477 (1962).
[7] Anderson, B., Palmer, H. P., and Rowson, B., *Nature*, **195**, 165 (1962).