PAPER 55

MAGNETIC FIELDS IN RADIO SOURCES

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ABSTRACT

Recent work has suggested very strongly that most non-thermal radio sources emit by the synchrotron mechanism—the radiation of relativistic electrons and positrons in magnetic fields. In this paper a summary of calculations of the total energy in particles and magnetic field in a number of radio sources has been given. Magnetic fields estimated in this way for the Crab, Cassiopeia A, our Galaxy, M 87, NGC 5128, NGC 1316 and Cygnus A are tabulated.

Apart from the method of detection of stellar magnetic fields by measuring the Zeeman effect on stellar spectrum lines, which has been carried out extensively and exclusively by H. W. Babcock, the only other method of measuring cosmical magnetic fields so far devised has been very indirect. In particular, measurements of the polarization of starlight in our own Galaxy have been made by Hiltner [1], Hall (Hall and Mikesell [2]) and Mrs Smith [3]. Polarization measures in extra-galactic nebulae have been made for NGC 5055 and NGC 7331 by Mrs Elvius [4, 5]. If the polarization is attributed to scattering by interstellar grains which have been aligned by an interstellar magnetic field, some idea of the direction of the field and its strength can be obtained from these results if a theory of grain alignment is used. The most plausible theory is that of Davis and Greenstein [6] which suggests that in spiral systems the gross structure of the magnetic field is such that the lines of force lie along the spiral arms, and that the mean field strength is near 10^{-5} gauss.

Two other methods of estimating the strengths of cosmical magnetic fields have now become available. The first of these which we shall briefly mention has recently been suggested by Bolton and Wild [7]. They have proposed that it may be possible to measure the Zeeman splitting of the 21-cm line radiation emitted by neutral hydrogen in the interstellar gas. They estimate that, using present techniques, and a radio telescope with an aperture of 150 ft (several instruments as large as this are under construction) it may be possible to detect magnetic fields as weak as 3×10^{-6} gauss. This method clearly has great potentialities.

The second method which we wish to discuss in the remainder of this paper is that of estimating magnetic field strengths in radio sources. This again is an indirect method, but it does afford some possibility of obtaining information about magnetic fields in very distant extra-galactic nebulae.

Recent work has strongly supported the original suggestion of Alfvén and Herlofson [8] that the mechanism of radio emission, in most strong discrete sources (with the possible exception of the sun), is the synchrotron mechanism in which electrons (and positrons) emit acceleration radiation while spiralling in magnetic fields. The strongest confirmation of this theory has come following the work of Shklovsky [9, 10] who suggested that the high degree of polarization associated with acceleration radiation might be detectable in the Crab Nebula, and in the jet in M 87 (NGC 4486) in the strong optical continua which both of these radio sources emit. The attempts to detect this polarization in the Crab by Vashakidze [11], Dombrovsky [12], Oort and Walraven [13] and Baade [14] and in M 87 by Baade [15] proved entirely successful, thus providing very strong confirmation of the theory.

The theory underlying this type of radiation is well known (Schott [16], Schwinger [17]). If the spectrum of the radiation and the total power emitted have both been measured, it is a fairly straightforward matter to compute the total energy which must be currently present, both in the electron-positron flux and in the magnetic field, as a function of the mean magnetic field strength H. If the frequency spectrum of the radiation is determined sufficiently accurately, a value for the index of the assumed particle energy spectrum ($N(E) \propto E^{-n}$) can be deduced. However, the value of the total particle energy does not depend very sensitively on n. These calculations have been done in detail for the Crab (Oort and Walraven [13],) for M 87 (Burbidge [18]), and for NGC 5128 and NGC 1316 (Burbidge and Burbidge [19]). In all of these cases a series of magnetic field strengths have been assumed and the corresponding total energies have been calculated. To give some idea of the ranges of energies involved we reproduce in Table 1 a portion of Table 4 given in the paper on M 87 (Burbidge [18]) for the radio emission (here a value of n has been deduced from the observed radio frequency spectrum). To obtain the most probable value of the mean magnetic field strength a further postulate has to be made. The most reasonable further condition which may be imposed is to demand that the total energy (particle energy + magnetic energy) is a minimum.

Table 1

H (gauss)	E (electron-positron energy) (ergs)	$\mathfrak{M}$ (magnetic energy) (ergs)
10^{-2}	5.6×10^{51}	4.7×10^{61}
10^{-3}	1.8×10^{53}	4.7×10^{59}
10^{-4}	5.6×10^{54}	4.7×10^{57}
10^{-5}	1.8×10^{56}	4.7×10^{55}
10^{-6}	5.6×10^{57}	4.7×10^{53}

The question now arises as to whether the total particle energy involved is simply the electron-positron energy, or whether a contribution is also to be expected from a proton flux which may be associated with the electrons. This question can only be settled if the mechanism by which the flux of particles has gained its energy is understood. There appear to be three possibilities.

(1) The electrons have been accelerated after being produced at very low energies. In this case a corresponding number of protons will have been accelerated with them, and if any induction-type mechanism of the Fermi type is responsible, the protons will gain kinetic energies M/m times those of the electrons. Since at very low energies (below ~ 100 MeV) the energy losses of the electrons by atomic processes are very large under most astrophysical circumstances, and in most cases those energy losses will overcome the energy gain by any type of Fermi mechanism, however efficient it may be, it appears that this mode of electron production is unlikely.

(2) The electrons and positrons have been produced following nuclear collisions between the quiescent interstellar gas atoms and a flux of high-energy protons. In this case the electrons and positrons are already produced at high energies (10^8–10^9 eV are entirely possible for protons with high enough energy), so that the difficulties inherent in process (1) are avoided. Theoretical work on the radio emission from our own Galaxy (Burbidge [20, 21, 22]) suggests, for example, that the total power emitted may be accounted for by the flux of electrons and positrons produced by the known cosmic ray flux interacting with the interstellar gas.

(3) The electrons and positrons may be produced following the annihilation of protons and anti-protons in the sources. This possibility has been explored elsewhere (Burbidge [18], Burbidge and Hoyle [23]). The advantage obtained by postulating that some anti-matter is present in the sources, is that it provides a very large energy supply with electrons and positrons already having energies of the order of 10^8 eV, and in this case the total energy is just the electron-positron energy without any proton flux.

Table 2. *Estimates of total energies and magnetic field strengths in radio sources*

	Total energy (I)* (magnetic + particles) (ergs)	Total energy (II)† (magnetic + particles) (ergs)	$\bar{H}$ (I) (gauss)	$\bar{H}$ (II) (gauss)
Crab	$1{\cdot}5 \times 10^{48}$	6×10^{49}	10^{-3}	10^{-2}
Cassiopeia A	6×10^{47}	$1{\cdot}7 \times 10^{49}$	3×10^{-4}	2×10^{-3}
Galaxy (disk)		$\sim 10^{55}$		10^{-5}
(halo)	$\sim 10^{55}$			$1\text{–}2 \times 10^{-6}$
M 87 (NGC 4486) (optical jet)	2×10^{55}	4×10^{56}	10^{-3}	10^{-2}
(radio source)	5×10^{55}	10^{57}	10^{-4}	10^{-3}
NGC 5128 (central region)	10^{55}	10^{57}	10^{-6}	10^{-5}
(halo)	10^{57}	10^{59}	10^{-5}	2×10^{-4}
NGC 1316 (central region)	10^{55}	10^{57}	10^{-6}	10^{-5}
(halo)	10^{57}	10^{59}	10^{-5}	2×10^{-4}
Cygnus A	$10^{58}\text{–}10^{59}$	10^{60}	5×10^{-5}– 5×10^{-6}	5×10^{-4}

* Assuming that only electrons and positrons are present.

† Assuming that a primary proton flux produces electrons and positrons in nuclear collisions.

The results which are given in Table 2 have been computed by supposing that either (2) or (3) is operative. For (2) it is found, in general, that the energy in the total proton flux is about 10^2–10^3 times greater than that in the electron-positron flux. Thus the magnetic fields may vary between the two assumptions in some cases by factors ~ 10. Though our final values of H are somewhat uncertain they do show that it is probable that magnetic fields ranging from 10^{-2}–10^{-3} gauss in the Crab Nebula and in M 87 to 10^{-5}–10^{-6} gauss in the halo regions of NGC 5128 and in our own Galaxy, are present. Details and descriptions of most of the sources listed in Table 2 have been given by Baade and Minkowski [24, 25] and Pawsey [26]. The dimensions and hence the volumes of the extra-galactic sources have been estimated by using a value of the Hubble constant $= 180$ km/sec/megaparsec. Estimates for the Crab have been taken with some modifications from the paper of Oort and Walraven [13]. The others have been taken from work of the author (Burbidge [18, 20, 27] and Burbidge and Burbidge [19]). When more radio astronomical data become available, estimates of fields in a large number of radio sources may be made.

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