Part VI

MECHANISMS OF SOLAR AND COSMIC EMISSION

PAPER 98

THE THEORETICAL EXPLANATION OF RADIO EMISSION
INTRODUCTORY LECTURE by

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To discuss the theories of radio emission it is convenient to divide the sources into five different classes: (1) planets, (2) the sun, (3) galactic nebulosities, (4) galaxies taken as a whole, and (5) clusters in galaxies. About (1) and (2) I shall say little. It appears that the temperatures of Venus and Jupiter obtained from the thermal radio emission measures are in reasonable agreement with the temperatures determined by the older astronomical methods. No theories explaining the nonthermal emission from Jupiter have yet been developed, though there has been discussion of the possibility that some type of discharge mechanism leading to plasma oscillations is involved.

As far as solar radio emission is concerned, a considerable body of observational material is now available, and at this Symposium we have heard many papers on various types of solar radio bursts. The theoretical explanation of all the solar nonthermal radio phenomena, however, remains rather confused. Since the Jodrell Bank conference papers have appeared explaining this radiation in terms of plasma radiation, Čerenkov radiation, and synchrotron (acceleration)* radiation. It is probable that all of these mechanisms are at work in different types of solar phenomena. The situation is so complex, however, that a separate review of solar radio physics is really what is required. Since I am not prepared, nor do I have the time, to do that, I shall say nothing further about it here.

In the remainder of this paper I shall give an account of the position we have now reached in understanding the mechanism of radio emission of the objects in categories (3), (4), and (5).

Broadly speaking, within the Galaxy two types of radio source are known. If they are put together under the general heading of galactic nebulosities (category (3)), the two types can be distinguished according to whether they are thermal or nonthermal radio emitters. The thermal radio emitters are the H II regions and the more massive optical emission nebulae. There appear to be no basic difficulties associated with the thermal sources, i.e., the temperatures of the H II regions in the galactic plane obtained by radio methods

* In my opinion, the term "synchrotron radiation" to describe cosmic radio emission should be avoided. It was first used by physicists interested in this phenomenon, which has been a source of trouble in accelerating electrons in synchrotrons. To continue to use a laboratory term in connection with astronomical phenomena does not appear very sensible. Some authors in the U.S.S.R. have used the term "magnetic bremsstrahlung." However, I would like to suggest the term "acceleration radiation," which has the advantage of more closely describing the phenomenon itself.

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are in reasonable agreement with those derived by theoretical arguments based on optical astronomy. Also the surveys of the discrete thermal sources have shown that they can be identified with the larger emission nebulae in the Palomar Atlas (see G. Westerhout, paper 80).

Minkowski (paper 61) has discussed the optical identification of the nonthermal galactic sources (nine in all). It is now certain that many of these, if not all, are the remnants of supernovae of different ages. The best known case is the Crab nebula, and it is from understanding this source that much of the recent development on the theoretical side had its origin. Since most of us now believe that these sources, together with those in categories (4) and (5), emit by means of the same mechanism, I shall now turn to a brief historical sketch of the generation of ideas in this field.

1. HISTORICAL DEVELOPMENT

For a number of years, roughly speaking the period 1948–55, two different hypotheses concerning the nonthermal sources were frequently discussed. The first of these was that the radiation was emitted by plasmas in oscillation. From the very beginning it was realized that there were severe difficulties in such a theory. Apart from those concerning the conditions under which a plasma will radiate at all, the most severe difficulty to my mind always has been that at the low mean density that prevails in both galactic and extragalactic nonthermal sources, the plasma's characteristic frequency is far lower than the frequencies at which sources emit much of their radiation.

The alternative hypothesis, that the radiation was emitted by the synchrotron mechanism, was first proposed in its most rudimentary form when it was still thought that radio sources might be stellar, by Alfvén and Herlofson in 1950. However, Shklovskiĭ originally developed this theory and applied it to conditions in the sources as they came to be investigated experimentally. His most important proposal concerned the Crab nebula, which is different from all of the other nonthermal galactic radio sources in that it is a comparatively luminous optical nebula, and it was difficult to explain the continuous optical radiation from the nebula by a thermal mechanism. Shklovskiĭ, therefore, proposed that the continuous optical radiation from the Crab was also acceleration (synchrotron) radiation, the properties of which (total polarization of the radiation in the direction of the velocity vector of the electron) are such that we would expect to observe a high degree of polarization if sufficiently small areas of the nebula could be isolated, and there would also be a net polarization for the nebula as a whole.

Following this prediction, immediate confirmation came from the work of Dombrovskiĭ and others in the U.S.S.R. and then from Oort and Walraven and Baade. The latter work had just been completed at the time of the Jodrell Bank conference. This, then, was the strongest evidence we had that acceleration radiation was being generated in a radio source. Of course, it did not provide direct evidence that the radio-frequency radiation was being generated in this way, though the presumption was very strong. To obtain the polarization effect in radio frequencies that would provide the strongest evidence for the theory it was clearly necessary to go to high frequencies where Faraday rotation was small. Finally, in 1957, the group at the U.S. Naval Research Laboratory detected about 7 per cent polarization at a 3-cm wavelength.

The next important step forward—also based on a prediction by Shklovskiĭ in 1955—was that the well-known optical jet in the extragalactic nebula M 87 (NGC 4486), which is also a powerful nonthermal radio source, was caused by acceleration radiation and should show a high degree of polarization. This was confirmed in 1956 by Baade, who measured the polarization photographically.

Another argument that strongly favors this theory is given by the spectral form of the sources. They are all of the type

$$P(\nu) \propto \nu^{-x} ,$$

where the index x in general lies between 0.5 and 1.5. It does not appear that there is a unique spectrum for any one source type, but there are still observational uncertainties. This type of spectrum, however, is to be expected if a large flux of electrons and positrons, related to what is often described as a cosmic-ray flux, accelerates in a magnetic field.

I have not discussed two other mechanisms that have been proposed to explain nonthermal radio sources: (1) that the continuous optical emission from the Crab nebula is polarized "bremsstrahlung" produced by aligned streams of particles; and (2) that radio frequency radiation is emitted from rotating dust grains. Both of these ideas, though ingenious, can only work under exceptional conditions, and there are severe difficulties in applying them in general.

The situation at this symposium is, to my mind, one in which we should accept the mechanism of acceleration radiation as the mechanism operating in all the galactic and extragalactic nonthermal sources.

2. RESULTS DERIVED FROM THE THEORY

Accepting the theory described above, what can be deduced about the conditions in the radio sources? In the ideal case we might expect to have the following observational data: (1) radio-power measurements at a number of frequencies, (2) spectral index of the emission, (3) high- and low-frequency cut-offs, (4) optical identification of the source, (5) distance to the source, and (6) dimensions of the source.

At present we have a considerable body of (nonhomogeneous) data on (1) and (2), but nothing concerning (3). I shall only discuss sources for which (4) is available, for without it we do not know the answer to (5) which has been determined so far only by optical methods. For many sources few radio data are available concerning (6).

The acceleration radiation theory was first developed by Schott more than 40 years ago. More recently, analyses of energy losses in electron accelerators have been carried out, particularly by Schwinger and Vladimirskiĭ. The application and reduction of their analyses to a form suitable for use in radio sources has been carried out in the last few years by Shklovskiĭ and Ginzburg, Hoyle, Twiss, Oort and Walraven, and me. I shall not discuss the analysis or even the formulas here, since they can be found in the literature under the names above. However, the following points should be stressed. The characteristic frequency near which a highly relativistic electron emits much of its radiation is a function both of its energy and of the magnetic field in which it is accelerating. For a spectrum of particles this means that the two variables involved are the total particle energy and the mean magnetic field in which they move. If we can determine from observation a source's total power and its spectral distribution, then for an assumed value of the mean magnetic field, which we may suppose is distributed uniformly over the source's volume, we can calculate the total energy needed for the particles to radiate at this power level and their spectrum. Unfortunately, we have no independent determinations of magnetic field strengths, either for external galaxies or for galactic sources. Thus we can only determine from the radio measures the most plausible conditions in the source, or, more precisely, the minimum total energy in particles and magnetic field required to explain the observed emission. It is easily shown that this minimum value is obtained when there is equipartition between the magnetic energy and the particle energy. However, this does not mean that the system will necessarily reach this state. Furthermore, this argument says nothing about the kinetic energy of mass motions in the gas.

Before discussing the calculations that can be made with these ideas, it is necessary to look more closely into what is included in the "total particle flux." The particles described so far are the electrons, and perhaps the positrons, directly responsible for the radiation. It is necessary to look into the ways such a flux can be built up. The simplest assumption generally made is that the electrons have been accelerated from very low energies by some sort of Fermi mechanism in the sources to energies anywhere between 10^7 and 10^{12} electron volts (this range covers the requirements for all the sources I shall list). But it is extremely difficult to accelerate electrons from very low energies, even in a gas of low density, because of their large energy losses, first through atomic and ionic collisions, and second by "bremsstrahlung" losses. On the other hand, in nearly all situations when electron acceleration begins, equal numbers of protons will also be accelerated. These are far less sensitive to atomic energy losses. Also if we suppose that both electrons and protons are initially accelerated from nonrelativistic energies by an induction-type mechanism, the protons will gain far more energy than the electrons; in the limit M/m times as much. Both arguments suggest that the proton flux gains far more energy than the electron flux in an acceleration process.

It must be remembered also that in general the half-lives of the electrons against acceleration radiation losses are short compared with the time scales for the systems involved, so that many generations of electrons must be produced over the lifetime of the radio source. If in each generation of electrons an equal number of protons is produced then clearly the energy of the proton flux will soon dominate.

The only circumstances under which electrons and positrons may be produced without an accompanying flux of protons are when they arise either in the radioactive decays of unstable nuclei, or following annihilation collisons between nucleons and anti-nucleons. The difficulty associated with electron or positron production by radioactivity is that in general a very large amount of nuclear activity in a low-density medium would be required to build the radioactive nuclei. At the 1955 Symposium Greenstein proposed that nuclear reactions might take place in the Crab nebula. More recently Woltjer has supposed that the radioactive nuclei were generated in the Crab, using the idea that this took place during the nucleogenesis when the supernova exploded. It is, however, difficult to account for the source of the particles in this way. A more far-reaching proposal has been made by Gold and Hoyle at this Symposium. They suggest that if neutrons or heavy mesons are being continuously created throughout the universe, the resulting decays will give rise to a continuous flux of electrons.

In 1956 I suggested that the interaction between matter and anti-matter might account for the jet in M 87. Hoyle and I then considered this hypothesis in relation to all radio sources. There have been no developments since this idea to alter its plausibility. The difficulty is that it is impossible to proceed further without fundamental advances in unified field theories. What would give considerable support to our hypothesis would be the discovery in the primary cosmic radiation of a comparatively heavy anti-nucleus.*

Returning now to the theory that there is a large proton flux present together with the electron flux, it appears that such a proton flux can be dissipated only by escape from the source or by nuclear collisions in the gas and dust. When nuclear collisions take place at large energies compared with the rest-mass of the proton a multiplicity of mesons is produced, together with nucleon-anti-nucleon pairs. The mesons decay, and the stable end-products of such a collision will be protons and anti-protons, gamma rays, neutrinos, and electrons and positrons. It is hard to estimate the initial energies, energy spectra, and multiplicities of the electrons and positrons because we still do not have a satisfactory theory of multiple meson production. However, it can be roughly estimated that about 5 per cent of the kinetic energy of the collision will be taken up by the electrons and positrons. Thus, by this mechanism a proton flux provides a source of secondary electrons and positrons. These secondaries will have sufficiently high energies so that if further

* Since this was written, Schiff (*Proc. Nat. Acad. Sci.*, **45**, 69, 1959) has shown by an elegant method that the passive gravitational masses of positron and anti-nucleon are positive. He has concluded that it is very likely that all particles and anti-particles have positive inertial and passive gravitational masses and that the equivalence principle is valid at least to very great accuracy. The active gravitational masses of antiparticles are then unknown. However, gravitational separation of stable aggregates of matter and anti-matter on a cosmological scale cannot then be achieved by assuming that they are negative, and the validity of Newton's third law would require them to be positive. These conclusions show that the assumption that there is a widespread distribution of anti-matter in the Universe, while it may still be correct, leads to complications in explaining its occurrence, either within galaxies predominantly made of matter, or elsewhere.

acceleration takes place they will easily overcome the losses due to atomic processes. Depending on the initial proton energies and the magnetic fields, they may already have sufficient energy to radiate in radio or optical frequencies, thus obviating the need for any acceleration process at all.

Ginzburg and I have independently suggested the idea that the electron-positron flux is probably secondary and that the proton flux is all-important. I have described in some detail how secondaries may arise in M 87. If we suppose that a state of equilibrium has been reached, so that the rate of energy transfer from the proton flux to the electrons and positrons is equal to the rate of energy loss due to radio or optical acceleration radiation, we can calculate the total energy of the proton flux as a function of the density of the medium in which it is moving. Such calculations show that in many sources the proton flux will have about 100 times the energy of the electrons and positrons. This ratio or a greater one is borne out by the conditions in our own Galaxy. This is the only system in which we have independent evidence about the proton flux, i.e. the primary cosmic-ray flux. Table II gives the approximate parameters derived for the Galaxy as a radio source. To explain the observed emission, $\mathcal{E}_p/\mathcal{E}_e \simeq 100$. If the magnetic field in the halo is greater than $\sim 2 \times 10^{-6}$ gauss, as Shklovskii and Pikel'ner have recently argued, then $\mathcal{E}_p/\mathcal{E}_e > 100$. I have shown further that the rate of cosmic-ray destruction in the galactic disk is of the right order to produce electrons and positrons at a rate that explains the energy loss by radio emission. The radio observations show that the spectrum of the electron-positron flux is very similar to that of the primary cosmic-ray flux in the Galaxy. However, a detailed understanding of this relationship can come only when we are able to calculate accurately the energy distribution at production of the secondaries, and determine whether further acceleration after production in nuclear collisions is required.

Tables I and II contain the results of calculations, based on the ideas described, for all the nonthermal radio sources for which adequate data could be found prior to this Symposium. The minimum values of the total particle and magnetic energies have been calculated under the assumptions (*a*) that the total particle energy is just twice the electron-positron energy, and (*b*) that the proton flux has 100 times the energy of the electron-positron flux.

The assumed lower and upper frequency cut-offs are 10^7 c/s and 10^{10} c/s, respectively. In the cases in which no spectra were available, a power-level measurement near 100 Mc/s was used and an equivalent frequency band of 10^9 c/s. The general form of the spectra that have been measured suggests that this approximation leads to an uncertainty of a factor about 2 at most. A larger uncertainty exists because few size estimates are available, so that the volume and total magnetic energy are hard to determine. Accordingly, in many cases I have used the sizes of optical galaxies from Sandage's data on galaxies of different types. There appears to be a general tendency for the radio emission to be more widely distributed than the stellar radiation from galaxies. Simple scaling laws can determine new values for the total energy and the magnetic field, if the dimension of the source is redetermined.

TABLE I

MINIMUM ENERGIES REQUIRED FOR SOURCES OF ACCELERATION RADIATION WITHIN THE GALAXY

	Rate of emission (ergs/sec)	Total energy (electrons + mag. energy) (ergs)	Mean Value of H (gauss)	Total energy (protons + mag. energy) (ergs)	Mean Value of H (gauss)
*Crab {Radio	8×10^{33}	$\sim 10^{48}$	$\sim 10^{-3} - 10^{-4}$	$\sim 10^{50}$	$\sim 10^{-2}$
*Crab {Optical	10^{36}				
Cassiopeia A	2.6×10^{35}	4.1×10^{48}	2×10^{-4}	5.7×10^{49}	1×10^{-3}
IC 443	4×10^{33}	8×10^{48}	1×10^{-5}	1.2×10^{50}	4×10^{-5}
*Cygnus Loop	2.5×10^{32}	10^{50} magnetic; 3×10^{46} electrons	—	10^{50} magnetic; 3×10^{48} protons	5×10^{-5}
Galactic center source	1.4×10^{36}	1.0×10^{52}	1×10^{-5}	1.3×10^{53}	4×10^{-5}

TABLE II

MINIMUM ENERGIES REQUIRED FOR SOURCES OF ACCELERATION RADIATION IN GALAXIES

	Rate of emission (ergs/sec)	Total energy (electrons + mag. energy) (ergs)	Mean value of H (gauss)	Total energy (protons + mag. energy) (ergs)	Mean value of H (gauss)
*Galaxy	$\sim 10^{38}$	$\sim 3 \times 10^{54}$ (electrons); $\sim 10^{56}$ (mag. field)	—	$\sim 3 \times 10^{56}$	7×10^{-6} (disk); 2×10^{-6} (halo)
M 31	1.9×10^{38}	2.1×10^{55}	8×10^{-7}	3.0×10^{56}	3×10^{-6}
Magellanic Clouds	1.3×10^{37}	2.5×10^{54}	1×10^{-6}	3.4×10^{55}	4×10^{-6}
NGC 4038-39	2.1×10^{39}	1.7×10^{56}	2×10^{-6}	2.3×10^{57}	7×10^{-6}
NGC 1068	7.5×10^{39}	3.2×10^{55}	2×10^{-5}	3.6×10^{56}	6×10^{-5}
NGC 5128 (central region)	2.4×10^{41}	3.2×10^{56}	2×10^{-5}	4.4×10^{57}	9×10^{-5}
NGC 5128 (halo)	2.2×10^{41}	5.0×10^{58}	1×10^{-6}	7.0×10^{59}	5×10^{-6}
NGC 1316 (central region)	8×10^{40}	2.1×10^{56}	2×10^{-5}	3.0×10^{57}	6×10^{-5}
NGC 1316 (halo)	1.6×10^{41}	1.8×10^{58}	1×10^{-6}	3.2×10^{59}	5×10^{-6}
NGC 4486 (jet)	2.3×10^{42}	1.7×10^{54}	2×10^{-4}	2.4×10^{55}	7×10^{-4}
NGC 4486 (central radio source)	3.5×10^{41}	1.7×10^{57}	1×10^{-5}	2.4×10^{58}	4×10^{-5}
NGC 1275	6.4×10^{41}	9.4×10^{56}	2×10^{-5}	1.3×10^{58}	8×10^{-5}
NGC 6166	7.8×10^{42}	1.4×10^{57}	3×10^{-5}	1.9×10^{58}	1×10^{-4}
Hydra A	1.5×10^{43}	1.0×10^{58}	8×10^{-5}	1.5×10^{59}	3×10^{-4}
Cygnus A	5.7×10^{44}	2.8×10^{59}	4×10^{-5}	3.9×10^{60}	2×10^{-4}
Coma cluster	1.0×10^{41}	2.9×10^{59}	2×10^{-7}	4.0×10^{60}	7×10^{-6}

* For these sources the equipartition condition has not been used.

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If the dimension R is changed by a factor x, i.e. $R \rightarrow xR$, then the minimum total energy in particles and field required to explain the observed emission is increased by a factor $x^{9/7}$, and the mean magnetic field strength is reduced by a factor of $x^{6/7}$. The characteristic time of the radiation is increased by a factor of $x^{9/7}$.

Table I gives results for some of the galactic nonthermal sources. Some of the estimates for the Crab have been taken from the work of Oort, Walraven, and Woltjer. The calculations for the Cygnus loop have been reported in paper 62. The minimum energy conditions have not been used because they would imply that the magnetic field in this source was less than the normal interstellar magnetic field.

Table II gives results for galaxies and for the Coma cluster of galaxies in which it has been assumed that the emission comes from a volume containing the whole cluster. For systems outside the local group the distances have been obtained by using Sandage's value of the Hubble constant, which corresponds to a red-shift constant of 75 km/second/megaparsec.

3. PROBLEM OF THE ENERGY SUPPLY FOR RADIO SOURCES

A study of Tables I and II leads us to the major issue now confronting us in considering radio sources in general; i.e., the initial energy source for the magnetic field and the high-energy particles. As far as the galactic sources are concerned, it appears that the nuclear energy released in supernova explosions may provide an important source, particularly for the magnetic energy. The mechanism that amplifies the magnetic field remains uncertain. The origin of the particle flux is more obscure. If a large proton flux were accelerated soon after the supernova exploded, the gradual depletion of this flux by nuclear collisions would provide a steady flow of electrons and positrons. I, personally, favor this theory, though no one yet has devised a detailed mechanism to give rise to such a proton flux. The recent revival by Ginzburg and Shklovskiĭ of the idea that all the cosmic rays originate in supernovae is closely related to this. Oort and Walraven proposed that the only alternative, particularly for the Crab, is to suppose that electrons and positrons are continuously being generated. Woltjer considered that this might, in part, be caused by radioactivity. Such continuous production might also be related to the bright wisps that are seen moving about in the Crab today at very high velocities, and about which we know little. Alternatively, Hoyle and I suggested that the presence of anti-matter at very low concentration in the Galaxy (1 part in 10^7 or less) could explain the effect, the radiation then appearing from the volume of the Crab simply because its magnetic field after the explosion is sufficiently high so that particles produced in annihilation collisions will radiate in the radio-frequency region. This explanation requires further acceleration within the nebula to give the much higher energies ($\sim 10^{11}$ electron volts) for electrons and positrons to radiate in visible frequencies.

For galaxies the energy problem in some cases becomes more severe. The situation is comparatively satisfactory for systems such as our own Galaxy, M 31, or the Magellanic Clouds. Thus, a cosmic-ray flux of the intensity observed at the top of the earth's atmosphere, with a magnetic field of the order of magnitude that is expected from other arguments in the Galaxy, is sufficient to explain the radio emission from the disks and the halos of galaxies similar to our own. Of course, much work remains to be done, particularly on the structure of the halos of normal galaxies. Other arguments suggest that in our own Galaxy the halo is connected with the radio source at the galactic center.

On the other hand, the much more powerful extragalactic sources present many problems. Table II shows that only the M 87 jet requires the mean minimum magnetic field in the source to be significantly greater than 10^{-4} gauss. If the sources are spread over larger volumes than the dimensions of the optical nebula, the required fields will be smaller. Since we have no a priori knowledge of the distribution of magnetic fields in the universe it is meaningless to argue that such fields are in general "excessively large" or "reasonably small." On the other hand, the total energy in particles and field in some sources is very high for a galactic volume when these energy modes are compared with the kinetic energy of mass motions, or with the available nuclear energy (taking into account the time scales involved). For the Cygnus source $\sim 10^{60}$ ergs is required, which even for this large volume corresponds to an energy density ~ 100 electron volts/cm^3. It should be remembered also that in addition to the flux of high-energy particles giving rise to the radio emission, there may well be an even greater flux of lower-energy particles. It has often been proposed that the Cygnus source and other radio sources are the results of collisions between pairs of extragalactic nebulae, and that the kinetic energy of the collision is the ultimate energy source. This appears improbable for several reasons. In the Cygnus source the efficiency of the process of energy conversion would need to lie between 0.1 and unity, a value that appears to be far too high. In other sources the efficiency might be lower, but still rather improbable. Collisions may certainly amplify the magnetic field in the interacting complex, but the particles can be accelerated only through the intermediary of the macroscopic motions in the gas and dust over a considerable period. Furthermore, in some cases, particularly in the case of M 87, a collision cannot be invoked as the energy source. This leads us to a further complexity. As Ambartsumian (among others) has stressed, we should be careful before accepting the idea that many peculiar objects are two galaxies in collision. The optical data are difficult to interpret and if two previously separate galaxies are involved it is often impossible to disentangle each one's contribution. Even in the cases where we have evidence that there are large velocity differences in the sources (e.g. in NGC 1275), this is still not proof that a collision is occurring, since, whatever the source of the high-energy particles, we should expect large macroscopic motions to accompany, or even to precede, them.

It is of considerable interest that both the Cygnus source and NGC 1275 lie in rich galactic clusters and that the Coma cluster has been detected as a radio source. In rich, highly condensed clusters such as these, many collisions will take place, and the distribution of magnetic field may be high toward the center, where most have occurred, and decrease toward the outer parts. The high-energy particles can be accelerated by a Fermi mechanism among the galaxies and intergalactic clouds in the cluster. In this way the energy reservoir required for radio emission can be built up at the expense of the cluster's internal kinetic energy, which may be $\sim 10^{63}$ ergs.

4. CONCLUSION

There are two final points to be made concerning our acceptance of the theory of acceleration radiation. With this hypothesis the only requirement for a radio source is that there is a flux of high-energy particles and a magnetic field of appropriate strength. Some gas and dust will be associated with the magnetic field, but the relationship between them and the presence of stars is very indirect. Consequently, there will be no simple relationship between the optical and the radio luminosities of an extragalactic system. Some radio sources may be intergalactic clouds containing no stars at all (such is probably the case for the Cygnus source). Thus on this level at least, there is no difficulty in understanding why so few radio sources can be identified with optical galaxies.

The second point concerns the frequency range that is being studied in radio astronomy. The key arguments leading to our theoretical understanding came from predictions and observations of the *optical* radiation from the Crab nebula and the jet in M 87. The lesson to be learned from this is that, though the subject may be defined in the minds of radio astronomers by the word "radio," our understanding of the mechanism involved requires that as much as is possible in the frequency range 10^6 c/s upward to 10^{15} c/s and beyond should be investigated. In particular, strenuous attempts should be made to detect acceleration radiation in the ultraviolet, and in the infrared, where the thermal radiation from stars falls off appreciably.

Discussion

van de Hulst: What are the observational parameters entering into the estimates of the magnetic fields by the method of equipartition as used in your paper? Am I right in assuming that the volume emissivity at one representative radio frequency determines the value of the magnetic field directly?

Burbidge: We use the spectra in many cases. The uncertainties concerning the total emission for different spectra, or using an equivalent bandwidth, are not very large, probably not more than a factor of 2.

Erickson: Soon after the discovery of optical polarization in the Crab nebula, the statement was often made that this discovery constituted a proof of the validity of the synchrotron mechanism. Logically it does not, it merely constitutes a fairly strong piece of evidence in favor of this mechanism. Yet this objection appears rather hollow unless one can point to possible alternative mechanisms. Therefore, I attempted to make two such suggestions even while agreeing that the synchrotron mechanism is by far the most plausible one at present. This should be interpreted as a plea to theoreticians not to close their minds to other possibilities.

The principal problem concerning the synchrotron mechanism, namely the production of large amounts of energy in the form of relativistic electrons, remains unanswered. In this connection I would like to ask Burbidge's views concerning Parker's apparently promising suggestion of an interaction and equilibrium between a relativistic gas and a normal gas moving at near-sonic velocities.

Burbidge: I agree that all other possibilities should be explored.

Denisse: Is the volume emissivity very sensitive to the assumed cut-offs at high and low frequencies?

Burbidge: Only the low-frequency cut-off is important.

Gold: By assuming an electron energy spectrum given by the secondary production from the cosmic-ray flux, can one obtain the magnetic field strength, and its degree of homogeneity in the sources, from their radio spectra?

Burbidge: The difficulty is that, at the moment, we are not able to deduce the energy distribution of electrons and positrons from nuclear collisions because we do not know sufficiently the processes of multiple meson production in nuclear collisions.

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