PAPER 107

CONCLUDING LECTURE by

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Undoubtedly the outstanding advance of the last few years in theoretical radio astronomy has been the widespread recognition of the importance of synchrotron radiation by relativistic electrons. The possibility that high-speed electrons might be of importance in the solar problem was mentioned by Giovanelli [1] and by me [2] in 1948. But real quantitative development in this direction dated from the well-known paper of Schwinger [3] published in 1949. Schwinger's results were put into a form suited to the problems of radio astronomy by Alfvén and Herlofson in 1950, still from the point of view of emission from stellar surfaces, however. In 1953, Ginzburg [5] and Shklovskiĭ [6] took the additional step of suggesting that relativistic electrons exist in space and that they give rise to the emission from nonthermal sources.

As an indication of the very marked swing of opinion that has taken place in the last five years, I might mention that a similar proposal, made in ignorance of the Russian papers, at the 1954 Washington Conference on Radio Astronomy [7] was generally thought at the time to be decidedly speculative. The turning point really came with a most remarkable suggestion from Shklovskiĭ that even the optical emission from the Crab nebula and from the jet of M 87 is caused by synchrotron emission. The predictions of the existence of optical polarization in these sources was subsequently confirmed by Dombrovskiĭ and Vashakidze [8] for the Crab nebula and by Baade [9] for M 87. This great success carried immediate conviction, so that the important role played by the synchrotron process has scarcely been questioned since.

Indeed the trend is now to examine the applicability of the synchrotron process to all cases of nonthermal radio emission including even solar bursts, particularly of type IV. The existence of bursts on two nearly discrete frequencies in harmonic relation with each other provides the strongest evidence of the importance of plasma oscillations—as opposed to synchrotron emission. But even here the possibility has been mentioned that the phenomenon is the result of tuning between the synchrotron frequency and the plasma frequency. The notion is that a bunching of electrons then takes place, and that the synchrotron emission is enhanced by coherence effects, a process that probably occurs in the synchrotron itself, as Gold has pointed out in paper 104.

In an interesting paper (101) Dr. Takakura showed that the electrons responsible for solar synchrotron emission probably have kinetic energies of a few hundred kilovolts. It is perhaps of interest that this is the order of energy

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possessed by positrons emitted in beta decay processes following (p, n) reactions. Such reactions may well occur in great abundance during flares (there being perhaps 10^{18} to 10^{19} reactions per cm^2 of the solar surface). The possibility of a strong positron flux is clearly of interest since the sense of positron gyration in a magnetic field is opposite to that of the ordinary low energy electrons of the solar atmosphere.

It is clearly of importance to establish whether or not similar bursts are emitted by other dwarf stars. Dr. Schatzman (paper 99) gave us a list of stars that might be worth watching from this point of view.

Before returning to the large-scale problems, it may be mentioned that our ideas on the cause of bursts from Jupiter are still rudimentary, to say the least. Volcanoes were mentioned officially, hydrogen warfare was whispered unofficially. In the latter connection it may not be entirely absurd to point out that radio astronomy provides the only remotely feasible method of detecting life on other planetary systems. It would, for instance, be possible with present-day techniques to build a powerful, highly directional transmitting system that would enable us to send detectable signals to a distance of several parsecs. Moreover, it can readily be calculated that such signals would be distinguishable against the background of the sun, except during the most intense of solar bursts.

Mrs. Marshall reminded us of difficulties associated with the galactic magnetic field. The relation of the form of spiral structure to the differential velocity curve is manifestly a problem that needs consideration in relation to the whole field of galactic research.

The next outstanding point concerns the constancy of the form of the spectra of the nonthermal sources. It is well known that this remarkable property is elegantly explained in its broad features if the relativistic emitting electrons possess the same distribution law with respect to energy as do the cosmic rays. Two possibilities then arise. One is that accelerating processes in all cases possess the same property of yielding the same energy distribution irrespective of whether the accelerated particles are electrons, protons, or heavy nuclei. The other possibility, proposed by Burbidge [10], is that the electrons are secondaries, produced in nuclear collisions of the cosmic rays with interstellar matter (and perhaps with intergalactic matter).

Except possibly in the case of the Crab nebula, the evidence now seems to favor the second of these alternatives. On this basis, radio astronomy assumes a new dimension of importance, for it now appears as a possible tool of cosmic-ray research, quite apart from its own special problems. If indeed the relativistic electrons are secondaries, then radio astronomy supplies evidence of the existence of cosmic rays, not only throughout our own Galaxy, but in extragalactic systems as well. Although this would be in accordance with the views of most workers in the field of cosmic rays, it is important that radio astronomy supplies observational confirmation of these views.

There still remains the puzzling problem of why the energy distribution of the cosmic rays should be so universal in its form. Two quite different points of view were expressed in the theory session, one by Ginzburg (paper

105) and the other by Gold and me (paper 104). In Ginzburg's paper the cosmic rays are regarded as having their origin in supernovae, the supernovae being taken as substantially identical with each other, so that each makes a similar contribution to the energy distribution. The cosmic rays are thought to escape from the galactic disk into the halo where they become distributed throughout a sphere of some 15 kiloparsecs radius, the total energy in the sphere being of order 10^{56} ergs.

A somewhat similar point of view has been suggested by Biermann, except that he does not regard the current rate of production of cosmic rays as being large enough. He therefore proposes to form the halo of cosmic rays by much more frequent stellar explosions occurring during the early history of the Galaxy. Ginzburg objects to this suggestion on the ground that iron nuclei in the cosmic rays would long ago have been broken up by nuclear collisions. This argument turns on the mean density of matter in the halo. If the density is as low as 3×10^{-28} grams/cm^3, Biermann's point of view can be supported. On the other hand, if the density is as high as the value of 2×10^{-26} grams/cm^3 used by Ginzburg, the implied breakup of the iron nuclei appears to be a decisive argument. Plainly, any observation that yielded a value for the density would have a special importance in settling this difference.

The strength and weakness of this outlook are fairly obvious. The similarity of the spectra of the discrete nonthermal sources in the Galaxy and of the halo itself is an immediate consequence. On the other hand, it is not clear that the highest energy cosmic rays can adequately be confined within the halo, even if the magnetic lines of force are closed within the Galaxy. Nor does it seem possible to understand the intense extragalactic sources. As Burbidge pointed out (paper 98), a source such as Cygnus A must contain an enormous reservoir of energy (magnetic and particle); Burbidge's value of 10^{60} to 10^{61} ergs is greater by several orders of magnitude than the reservoir of cosmic rays in the halo of our Galaxy. If it be claimed that the dynamical energy of collision of two galaxies has been used to increase the energy of previously existing cosmic rays, then we must explain why the form of the energy distribution has not been changed by this new accelerating process; i.e. we have to explain why two quite different processes, the supernovae and an interstellar process, yield the same distribution law.

An almost exactly opposite situation arises from the point of view expressed by Gold and me. Here we regarded magnetic fields, cosmic rays, and relativistic electrons as a universal phenomenon existing everywhere in space. The magnetic fields are normally too low for there to be much emission in the observable radio band, but compression yields a situation where observable radio emission takes place. Thus radio sources arise wherever there is adequate local compression. The magnetic fields are not closed within galaxies or their halos, so that cosmic rays are able to stream more or less freely from galaxy to galaxy.

Without compression the energy density of magnetic fields, cosmic rays, and relativistic electrons is about 10^{-12} ergs/cm^3. In a volume equal to the

Cygnus A source, the total energy before compression would thus be about 10^{59} ergs. A moderate compression of a somewhat greater volume would therefore bring the energy to the value obtained by Burbidge. The difficulty of the energy supply in intense extragalactic sources would accordingly seem much less in this second point of view. But there is a difficulty in understanding the emission from nonthermal sources within the galaxy, unless these sources are simply local regions of compression. In the case of the Cassiopeia source, for example, it seems necessary to argue that the effect of a supernova (if indeed a supernova is involved!) has been to produce a compression within the normal interstellar medium, the energetic electrons being derived from the interstellar medium not from the supernova. Otherwise we again return to the situation in which there are two entirely different sources for the electrons, and we again encounter the difficulty of understanding why two quite different processes should yield the same energy-distribution law.

Enough has been said, however, to show that progress has been made in understanding the theoretical processes that give rise to the emission of cosmic radio waves—perhaps even more progress than seemed possible only a few years ago. Many obscurities still remain, but there is hope that a few years hence at least some of our present difficulties of interpretation will have been resolved. Even more important, the conclusions, whichever direction they may take, seem as if they must be of outstanding interest, not only to astronomy but to physics quite generally.

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