Chapter X - Cosmic Magnetic Fields

A new chapter in astronomy was begun in 1962 with the discovery that radio techniques had reached the stage where detailed studies of magnetism in a distant galaxy were possible. Astronomers had found it increasingly necessary to suppose that magnetic fields were present in order to explain, for example, the impressive and ordered spiral structure so characteristic of the xmmmxxm increase of remote galaxies, but there was no means of demonstrating their existence nor of determining their characteristics. Discovery of the peculiar properties of the "loadstone" from magnesia which caused it to align itself in a direction fixed in relation to the Earth, and the subsequent development of the magnetic compass has hmx been of inestimable benefit to mariners over the centuries. There is no reason to suppose that Earth is alone in having its built-in magnet xm but it was not until the discovery of the Zeeman effect in 1908 that evidence for the existence of magnetic fields as far away as the Sun was first obtained. Zeeman found that the characteristic optical lines emitted by atoms are split into symmetrical doublets or triplets xitk in the presence of a magnetic field: the recognition of such splits in the spectrum of light from the Sun revealed the presence of magnetic fields on the Sun, particularly in the neighbourhood of sunspots. It has also been possible to show by the same means that some stars possess unusually strong magnetic fields; and by observations of the polarization of light waves that the grains of interstellar dust are aligned in a preferred direction through the influence of the magnetic field which, apparently, pervades the whole Milky Way system. In recent years, of course, space probes and manned vehicles have provided direct and incontrovertible evidence of the magnetic fields which exist within the solar system, but the countless star systems with which the whole of space is studded, and which owe their present form and structure to their built-in magnetic fields, are forever beyond the reach of such means of exploration. We are therefore completely dependent upon indirect methods, one of the most promising of which is study of the imprint indelibly stamped by their magnetic fields on the radio frequency signals we can now detect from them.

A clear indication that some at least of the extraterrestrial radio waves originated in a magnetic field comes from the fact that their variation with frequency is quite different from that for thermal sources. (See Chapter). A consequence of such an origin is that the waves should be polarized. Early attempts to detect polarization however were unsuccessful, largely due to the use of long wavelengths and wide bandwidths which might be expected to smear out any polarization unless it were high and constant over a wide area. Westerhout and his group at Leiden were the first to demonstrate that polarization due to galactic fields could be detected at 408 MHz. Surveys of a large part of the northern skies showed that there were three regions in which the polarization was high: for the remainder of the northern sky it was extremely low. The observed results were consistent with a magnetic field aligned along the galactic plane, in agreement with the interpretation of optical results. Further radio measurements made it clear that the field in our vicinity is directed along the spiral arm in which the solar system is located.

Apart from these manifestations of the existence of a general field in the Galaxy the radio observations were able to identify local fields in a number of sources, and it was in confirming the optically-observed polarisation from the Crab Nebula that the reality of the synchrotron process as the origin of radio frequency emission from non-thermal sources was firmly established. Observations of other discrete sources, principally by Gardner and his colleagues with the Australian 210-foot radio telescope, have shown detectable polarization from Vela X, another supernova remnant and from several others also suspected of being the remains of supernovae.

A major expansion of magnetic horizons came late in 1961 when Mayer and his colleagues at the U.S. Naval Research Laboratory in Washington D.C. noticed that the radio waves being recorded at a wavelength of about 3 cms from the very powerful but distant source Cygnus A varied in strength as the plane of polarization accepted by their radio telescope was rotated. In most sources oscillations of the electrons causing the emission are not organized in any particular way and cover all possible directions, so that the electric fields in the radio waves we receive from them likewise cover all possible orientations. Under these conditions the signals are unpolarized (or randomly polarized) and do not vary as the feed is rotated. The observations of Mayer et al. showed that the electrons in Cygnus A are vibrating in a preferred direction which can only be due to an enveloping magnetic field. Thus, even though this island galaxy is near the limit of the horizons currently attainable with optical telescopes, we now have a means of verifying the existence of fields and perhaps of tracing them out in some detail.

The power of this new technique was demonstrated shortly afterwards in a remarkable way by Cooper and Price of the C.S.I.R.O. Radiophysics Laboratory in Sydney, using the newly completed 210-foot radio telescope at Parkes in what proved to be its first major achievement. The telescope had been provided with a feed support which could be rotated so that it was well equipped for studies of polarization. The Australians, after noting that the signals from the central (double) source in Centaurus A were certainly polarized, undertook a detailed survey of this source (which was one of those included in the first list of sources published by Bolton). It is associated with one of our nearer neighbour galaxies, NGC 5128 which is a mere 13 million light years away. This nebula has an unusual appearance which does not fit into any of the usual classifications of galaxies, and is shown in Fig. 2. Contours of the radio source at 21 cms and also at 11 cms are illustrated in Fig. 3 in which the directions of polarization of the 21 cm signals from a number of points are xxxx shown by the double-headed arrows, and the position and relative size of the visible galaxy NGC 5128 by the small square at x.

The first impression is of the enormous volume through which the magnetic field extends, whereas the optical source is only some 10 minutes of arc in diameter the radio contours with their associated field spread out 50 times as far and cover about 8° of sky. The second feature to note is that the direction of polarization does not vary markedly over this large region, indicating remarkable uniformity of the magnetic field, and of special significance is the fact that the degree of polarization is high, reaching as much as 40% at 20 cms in some areas. Cooper and his associates found that the direction of the plane of polarization varied with frequency and made many measurements at a number of frequencies between 10 and 75 cms. The results for a central region of Centaurus A are ~~plotx~~ plotted in Fig. 4 and are consistent with a rotation proportional to the square of the wavelength, which is the relationship expected for Faraday rotation, i.e. the rotation produced when electromagnetic waves pass through an ionized medium containing a magnetic field. This is usually expressed in ~~xxxxx~~ terms of a "rotation measure", the constant of proportionality in the relation $\omega = R_m \times \lambda$ (where ω is the rotation of the direction of polarization at wavelength λ) and is given as so many radians per metre^2. The amount of Faraday rotation is easily found from observations at a number of frequencies: it is obviously zero at very short wavelengths but the plane of polarization may be turned through one or several complete 360° rotations at 75 cms. More importantly, the position angle of polarization at the source - obtained by extrapolating the curve relating rotation-to-wavelength to zero wavelength - gives the direction of the magnetic field at the source. (This field is at right angles to the plane of polarization.)

The observations of Cooper and Price show that not only the field but the rotation measure is remarkably constant over the huge volume embraced by Centaurus-A . Where is the Faraday rotation produced: in the outer regions of Centaurus A itself, within the field ~~mx~~ of our own Galaxy, or perhaps even in penetrating the terrestrial ionosphere? The last named can easily be ruled out because the ionisation density of the ionosphere has marked daily and seasonal variations, but no such variations in the rotation measure have been detected. The outer regions of the source itself at first sight may appear the most likely but this would require that the field should be uniform over a distance of half a million light years, because the rotation measured found by Cooper were roughly the same at three points spread over this huge distance. This leaves only the Galactic field as the likely cause, and further observations at Parkes put this beyond doubt. Gardner and Whiteoak studied a number of radio sources both within and outside the Galaxy and found that the rotation is broadly a function of galactic latitude, maximum effects occurring for signals coming from directions in the plane of the Galaxy and very little from the poles. The variation with galactic longitude is more complex however and further observations are needed to define the field in more detail. Fig. 5 summarises the measurements of rotation measure for (a) sources of northern galactic latitude and (b) for southern sources. The general dependence on galactic latitude is clear but the larger scatter for southern sources reflects the effects of fields in the local spiral arm.

Some of the most extensive surveys of polarization have been carried out by Australian radioastronomers at Parkes, Gardner, Morris and Whiteoak having observed a total of 366 sources at three frequencies 2650, 1660 and 1410 MHz (11, 18 and 20 cms wavelength). This total included 64 quasi stellar objects, 119 radio or normal spiral galaxies and 31 galactic objects, the remainder being unidentified or of doubtful identity: they were mostly taken from the Parkes Catalogue of Radio Sources. For a proportion of the quasars the results support current ideas that these strange objects consist of two components one of which is of small size and radiates only at high frequencies while the other is larger, behaves like a radio galaxy, and contributes the polarized emission. Results for the galaxies confirm a relationship suggested from the preliminary observations, namely that the highest degrees of polarization occur in objects which are physically large and have relatively low surface brightness. This is indicated in Fig. 6. The unidentified sources show characteristics that closely parallel radio galaxies and, as has been suggested by Bolton, probably represent galaxies that are beyond the limits of the Palomar Sky Survey plates used in searching for identifications. The rotation measure is proportional both to the electron density and to the longitudinal magnetic field and if either or both of these vary appreciably within an area comparable with the beam of the radio telescope then the net polarization measured will be reduced and may be smeared out altogether. This effect is known as depolarization and is increasingly evident at longer wavelengths, which accounts for the negative results obtained in some of the first attempts to detect polarization, made before techniques for observing at very short wavelengths had been developed.

Another feature that has emerged is that in the case of extended sources of low brightness the direction of the magnetic field (which is always at right angles to the plane of polarization at the source) lies roughly at right angles to the direction in which the source is elongated. This is evident for NGC 5128 (see Fig.) and it also appears in the case of several other sources examined by Gardner which were large enough to be resolved by the aerial beam. The intensity contours for Fornax A are shown in Fig. 7; this source is associated with the peculiar galaxy NGC 1316 which lies midway between the two components of the radio source. Another interesting example is the extragalactic source 13-33 which at a wavelength of 11 cms is resolved into three components, all of which are polarized, the central one coinciding closely in position with the galaxy IC 4296 (11.9 magnitude). For this source the direction of the magnetic field is remarkably uniform across the source - a distance estimated at one million light years - and closely aligned with the line of centres of the three components. (See Fig. 8). These observations are consistent with the suggestion that x some radio sources are the outcome of an explosion in the optical galaxy with which they are associated, the magnetic lines of force being compressed by the expansion of gas which followed the initial explosion. For extended sources of high brightness temperature however such as Cygnus A, the field tends to be more nearly along the major axis mx of the source. Intensity contours for this source obtained by aperture synthesis at Cambridge are shown in Fig. 9. The data available from some 20 extended extragalactic sources indicates that the field tends to be either generally parallel to or at right angles to the major axis.

The Evolution of Radio Sources

The knottiest problem in present day astronomy is how galaxies originate and why there should be different kinds: monster galaxies, like our own, with a mass 100,000 million times that of the Sun, when the average size is only about 10,000 million solar masses; and quasars and radio galaxies, emitting radio waves so powerfully that we cannot visualise the processes by which so much energy can be made available for so long.

We do not know the origin of the original magnetic field but it clearly plays a major role along with gravitational and relational forces, in shaping the structure of the condensing gas cloud, and any theories of the evolution of radio galaxies must be able to account for the observed polarization. The fact that many such galaxies consist of two radio sources symmetrically placed on either side of an optical galaxy suggests that the latter consist of plasma ejected from the parent galaxy following a violent explosion. The plasma carries magnetic field with it which becomes compressed and wound up as a result of rotation, and electrons spiralling around the lines of force emit the synchrotron radiation which our radio telescopes can detect. Initially the magnetic field in the plasma will remain linked with the parent body and it is possible to imagine a model in which the signals come from two groups of electrons radiating with their fields predominantly parallel to and perpendicular to the axis of rotation. At the stage indicated in Fig. 10 the A group would predominate and the polarization would be at 90° to the major axis. As expansion proceeds the radio source would become more spherical in shape and the C group of electrons become progressively more important until the polarization is predominantly parallel to the major axis. An evolution of this type implies that the degree of polarization would pass through zero at one stage, and it is possible that it is this stage that we see in one component of the central (double) source of Centaurus A which is virtually unpolarized.

It seems that in each component of a source there are two regions from which polarized radio waves originate, one emitting in a plane parallel to the major axis of the source and the other perpendicular to it, with the former usually predominating. At this stage however there is a need for more detailed information about the distribution of polarization in a range of sources of different brightness temperatures, and of the rotation and general motion of the galaxies with which they are associated.