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27 Astrophysical Plasmas

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27.1 INTRODUCTION

It is not possible in one short chapter to discuss all of the problems in astrophysics in which plasmas play an important role. The most that can be done is to outline the wide range of conditions which are found in different parts of the Universe and to discuss an arbitrary selection of problems in somewhat more detail. In no sense can the problems that are discussed be regarded as necessarily the most important ones.

It is, of course, true that to the best of our present knowledge most of the matter in the Universe is in the form of an ionized gas, so that in a sense almost all astrophysical problems involve plasmas. However not all of the problems are ones in which specifically plasma phenomena play an important role. It is for example possible to study the structure and evolution of most stars without taking much account of plasma physics; this is true because in stellar interiors collision frequencies and the frequency at the maximum of the Planck radiation curve are usually much greater than the plasma frequency and the particle gyration frequencies.

Magnetic fields appear to occur throughout the Universe, so that we are usually concerned with magnetised plasmas and many problems involve magnetohydrodynamics. Many of the plasmas with which we are concerned are highly ionized and, as hydrogen is more abundant than all of the other elements combined in most objects, it is often convenient to refer to fully ionized hydrogen in an approximate discussion of plasma properties. However there are important situations in which ionization is incomplete and in these cases the electrons present may be supplied by atoms of lower first ionization potential than hydrogen. In the interstellar medium it is often radiation by these impurity ions which determines the local temperature just as was the case in some early laboratory thermonuclear experiments.

One obvious property of plasmas in the Universe is the wide range of physical conditions which is encountered.* Thus consider the range of particle density. There is no definite proof that a general intergalactic medium exists but indirect evidence suggests that it could have a density in the range 10^{-1} to $10\,m^{-3}$. Inside clusters of galaxies there does appear to be intergalactic (or intracluster) gas with densities of order $10^2\,m^{-3}$. Inside a typical galaxy, the interstellar gas density is about $10^6\,m^{-3}$ although there are dense gas clouds with $10^{12}\,m^{-3}$. The visible surface of a star such as the Sun has number density $\sim 10^{22}\,m^{-3}$, but much lower densities occur in the outer solar atmosphere (corona). A typical number density in a stellar interior is $\sim 10^{30}\,m^{-3}$, but in a white dwarf we have $10^{36}\,m^{-3}$ and in a neutron star up to $10^{45}\,m^{-3}$. Although the main constituent in a neutron star is the neutrons, there is a residual number of protons and electrons which can have a number density $\sim 10^{42}\,m^{-3}$, which means that plasma properties may be important.

A wide range of magnetic field strengths is also encountered. In our Galaxy, and presumably in other similar galaxies, there appears to be a general interstellar magnetic field of $\sim 10^{-10}$ T. It is likely that there is a somewhat weaker field in intergalactic space but there is good evidence for the existence of stronger fields of order 10^{-8} to 10^{-7} T in some radio galaxies. The Sun has a magnetic field with an overall dipolar character corresponding to a surface field of about 10^{-4} T. However the actual field at the solar surface does not have such a simple form. Fields of several times 10^{-1} T are found in sunspots and the remainder of the solar surface flux is very far from being uniformly or smoothly distributed. It is not possible to measure magnetic fields of the strength of the general solar field in other stars, but some stars are known with average surface fields of order 10^{-1} to 1T. Fields of at least 10^4 T have been measured in some white dwarfs and fields of order 10^8 T appear to exist in neutron stars. All of these stellar fields are surface fields and it is possible that much stronger fields may exist inside stars, as will be mentioned below.

Inside stars, except in the outermost surface layers, conditions are usually very close to thermodynamic equilibrium, so that there is a well-defined temperature which governs all processes. Temperatures inside stars range from about 10^3 K at the surfaces of the coolest stars to 10^{10} K or even 10^{11} K in the central regions of a highly evolved star at the time of a supernova explosion or in a neutron star immediately after it has been formed as a result of such an explosion. The internal temperatures of most stars are in the range 10^7 K to 10^8 K. In the interstellar medium (and even more so the intergalactic medium, if it exists) conditions are in contrast very far from thermodynamic equilibrium and there is no uniquely defined 'temperature'. Even so, in many cases the particles (and particularly the electrons) do have a Maxwellian distribution and hence a kinetic temperature. This 'temperature' tends to lie in the range 10^2 K to 10^4 K in the interstellar gas; in fact for reasons concerned with the heating and cooling processes of the gas, the medium is effectively divided into two phases, a dense (almost) neutral gas at about 10^2 K and a diffuse ionized gas at 10^4 K, in approximately pressure equilibrium. There is also a third even hotter and more diffuse component at $\sim 10^6$ K, which is believed to be produced by supernova explosions. The intercluster gas, which we have already mentioned, emits X-rays and has a temperature of order 10^8 K.

The statement that the particles have a Maxwellian distribution is not quite correct. In addition to the thermal particles with a well-defined kinetic temperature, there exist suprathermal or relativistic particles, small in number but possessing a large amount of energy. Thus in our own neighbourhood there are cosmic rays whose individual energies are typically of order 10^{10} eV but with values which range up to at least 10^{20} eV. Their energy density is comparable with the kinetic energy density of the interstellar gas and with the energy density of the interstellar magnetic field and as a result they play an important role in galactic structure. Radio emission from objects such as supernova remnants in our Galaxy and from radio galaxies is also attributed to radiation by relativistic electrons moving in magnetic fields.

The interstellar radiation field is far from thermal. One component is starlight, which may have an approximately black body spectrum (at $\sim 10^4$ K), but which is diluted by a factor of about 10^{14} in energy density. Another component is the cosmic microwave background radiation, which apparently fills the whole Universe and which appears to be blackbody with a temperature of 2.7 K and which therefore has an energy density about the same as that of the dilute starlight. This mention of the microwave radiation serves as a reminder that our view of the Universe is somewhat unusual. We are not looking at the entire Universe as it is today. Light reaching us from the most distant galaxies and radio

* In what follows I shall quote values of physical parameters such as density, temperature and magnetic field without explaining how the values are obtained or how reliable they are.

sources which we observe has taken a time to reach us which is a significant fraction of the time since the 'Origin of the Universe', if the Universe is described by a cosmological theory of the 'big-bang' type. Conditions in these radio galaxies and their environment may be very different from conditions in our neighbourhood today. The most unusual plasma which we can discuss is the high temperature dense plasma which is supposed to have been the state of the entire Universe after the 'big bang'.

An important property of most astrophysical plasmas is their extremely high electrical conductivity. More specifically what is very high is the characteristic time for decay or diffusion of magnetic fields, which has the form

$$\tau_R = L^2/\eta \qquad (1)$$

where η is the electrical resistivity and L is the scale of variation of the magnetic field. This time is usually very large, even compared with the time available for astronomical phenomena, because astronomical lengths are so great. Thus two results calculated from formula (1) and the standard electrical resistivity of fully ionized hydrogen are:

$$\begin{array}{llll} \text{Stellar interior} & L \sim 10^{9}\,\text{m} & T \sim 10^{6}\,\text{K} & \tau_R \sim 2\times10^{9}\ \text{yr}, \\ \text{Hot interstellar gas} & L \sim 10^{19}\,\text{m} & T \sim 10^{4}\,\text{K} & \tau_R \sim 2\times10^{24}\ \text{yr}. \end{array} \qquad (2)$$

These examples, and other similar ones suggest that magnetic flux is frozen into astronomical plasmas for times at least comparable with the ages of the objects that we are considering and often for times greatly in excess of the believed age of the Universe. Even the cold lightly ionized interstellar gas is a good conductor in this context.

Although this simple calculation suggests that magnetic flux can scarcely be created or destroyed during the present life of the Universe, there are reasons for being suspicious of the result, at least in its most extreme form. The result may be invalid if there is some form of anomalous resistivity which increases the denominator of (1) or if motions of the gas significantly reduce the length scale of magnetic field which enters in the numerator. Consider specifically the process whereby stars are formed from the interstellar gas. If magnetic flux is conserved while a gas cloud of number density $10^{6}\,\text{m}^{-3}$ is converted into a star of number density $10^{30}\,\text{m}^{-3}$, an initial field of $10^{-10}\,\text{T}$ is converted to a field of $10^{6}\,\text{T}$ if the contraction is spherical. In fact the gravitational field of the star would not be able to contain a field quite that strong. As a result the collapse cannot be spherical all the way.

However, if it is only the magnetic field which is preventing quasi-spherical contraction, the magnetic field may be expected to have a value which is comparable with the maximum which can be contained by a star. All stars may be expected to be very strongly magnetic but that is not what is observed. Thus it appears that some significant magnetic flux loss must occur during the process of star formation or shortly afterwards.

It was originally suggested that the flux loss was produced by an increase in the classical resistivity. In the process of star formation the interstellar gas may cool and recombine to such an extent that ambipolar diffusion allows the neutral component to slip through the ionized component and to form a star with very reduced flux. Although ambipolar diffusion may sometimes be effective it does not seem likely that this is generally the case. If flux loss does not occur because of an increase in electrical resistivity, it must happen as a result of a reduction in the scale of the magnetic field. Such a reduction can be produced by small scale fluid motions. These may initially increase the strength of the magnetic field without altering the magnetic flux but eventually, if the scale of the field is suitably reduced, flux reduction may occur. Conversely such fluid motions may lead to the creation of magnetic flux by a dynamo process and it may not be necessary to assume that most astronomical magnetic fields are the relics of a primaeval field which existed in the early Universe and which should still be present in intergalactic space. If fluid motions are to lead to a reduction in scale of the magnetic field, some cause must be found for the fluid motions. They may arise as a result of instabilities which may be magnetohydrodynamic in nature or which could be thermal instabilities. It has been hypothesised that the destruction of magnetic flux in interstellar gas clouds or stars could be due to magnetohydrodynamic instabilities of a type which is well known in laboratory confinement experiments. The idea that instabilities can lead to an anomalous resistivity is certainly very familiar.

It has been mentioned previously that there are situations in which specifically plasma effects are relatively unimportant but even those may lead to observable effects because of the great sizes of astronomical objects, It is well known that, in the presence of a plasma containing a magnetic field, the speed of propagation of electromagnetic waves depends on both the frequency of the wave and its sense of polarization. The effects are only large if the frequency, ω, of the wave and the plasma frequency, ω_p, and the electron gyration frequency, ω_{ce}, are comparable in magnitude. If they are, the effects become apparent in a small number of wavelengths. In astronomical contexts, the distance travelled by the waves from source to observer are so large that interesting effects can be obtained even if $\omega \gg \omega_p, \omega_{ce}$. Thus the observation of both dispersion and Faraday rotation in the radiation from pulsars has given useful information about both the electron density and the magnetic field in interstellar space.

Another property of electromagnetic fields which has recently been found to be of at least potential importance in astrophysics (and also in some laser problems) is the existence of strong electromagnetic waves. It is usually supposed that waves whose frequency is below the plasma frequency cannot propagate in a plasma. Propagation is prevented because the electrons in the plasma screen out the field of the wave. This presupposes that the electrons are capable of screening out the field and this will not be possible if the wave field itself is sufficiently strong. It is easy to show that screening is impossible if

$$\omega\,\omega_{ce} \gtrsim \omega_p^2 , \tag{3}$$

where ω is the frequency of the wave and ω_{ce} is the electron gyration frequency in the magnetic field of the wave. Wave fields satisfying criterion (3) may well exist in low frequency waves produced by rotating neutron stars (as in pulsars) or in more massive rotating magnetised bodies in the centres of galaxies. When the plasma cannot prevent such a wave from propagating, the wave instead raises plasma particles to relativistic energies. This process may play a role in the origin of cosmic rays and relativistic electrons in radio sources.

Laboratory studies of plasmas are dominated, as you will already have learnt in earlier chapters of this book, by instabilities of many types. This is also true in astrophysics where it is not possible to demand that a rare stable configuration is realised by chance. Instead we must expect unstable configurations to arise frequently as will become clear when I discuss specific examples. It should be noted that there may be great difficulty in the interpretation of observations in distinguishing between instability and the failure to achieve a genuine equilibrium; this is also true in many laboratory experiments. Note also that in studying astronomical systems we are often forced to consider the nonlinear behaviour of instabilities: if a system is unstable, we cannot repeat the experiment with slightly different parameters in the hope

that we shall find a stable configuration. Some of the radio emission also appears to involve strongly nonlinear processes; as it is too intense to be attributed to incoherent emission by individual particles it must involve a coherent process.

There is at least one plasma process which has no analogue in laboratory experiments. According to the presently accepted theory of weak interactions, it is possible for a plasma oscillation (plasmon) to decay into a neutrino-anti-neutrino pair. In dense stars at a moderately high temperature ($\sim 10^8$K), the density of plasmons is sufficiently high for there to be a considerable production of neutrinos which escape essentially freely from the star in which they are produced. This plasma neutrino process may be the main mechanism of energy loss from some highly evolved stars (very much greater than the photon loss from the surface), because the neutrinos are produced in the region where the stellar temperature is highest.

There are some interesting analogies and differences between self-gravitating systems and plasmas, which I shall not be able to discuss in detail. The similarities occur because of the inverse square nature of both the gravitational and the electrostatic force; the differences arise because the gravitational force is always attractive and cannot be screened out. Both properties are shown in the comparison between the dispersion relation of electromagnetic waves propagating in a uniform plasma.

$$\omega^2 = \omega_p^2 + k^2 c^2 , \tag{4}$$

and that for sound waves in a uniform gravitating medium

$$\omega^2 = -4\pi G\rho + k^2 c_s^2 . \tag{5}$$

In (4) and (5), k is the wave number, c_s the speed of sound and c the speed of light. G the constant of gravitation and ρ the density. Because there is a minus sign in (5), sound waves of large enough wavelength can be unstable; this is known as Jeans' instability and it is important in the formation of stars and (possibly) galaxies.

27.2 DOUBLE EXTRAGALACTIC RADIOSOURCES

One type of object whose structure and evolution is not completely understood but in which plasma processes certainly play an important role is the double radio source. These appear schematically as shown in Fig. 1. A central galaxy (usually a giant elliptical) has two strong sources of radio emission approximately equally spaced around it. There are often

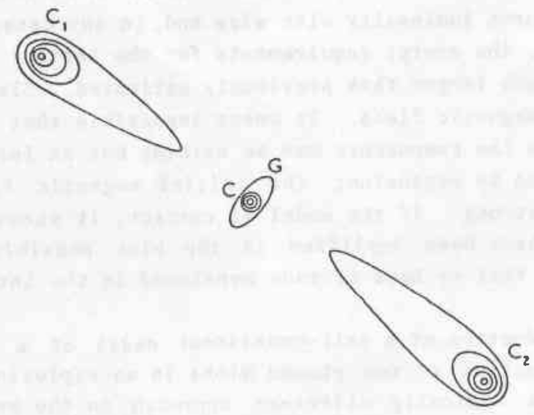

Fig. 1 *A galaxy G has two large radio components C_1, C_2 on either side of it. There may in addition be a central component C. Apart from the ellipse representing the galaxy, the curves are contours of equal radio brightness.*

particularly intense regions of radio emission furthest from the Galaxy, a trail of weak emission extending back towards the galaxy and a central radio source on the galaxy itself.

It is believed that the radio emission is synchrotron radiation from relativistic electrons moving in a magnetic field. It was soon shown (Burbridge, 1959) that this model implies that a considerable amount of energy is present in the radio components. The observed radiation can be produced by very energetic electrons moving in a weak magnetic field or by less energetic electrons in a stronger field, but it is possible to show that there is a minimum total energy of field and particles to give the observed radiation. The minimum energy occurs when the particle and field energies are approximately equal (equipartition solution) and energies of at least 10^{53} J are required for a strong source. This ignores the energy of possible relativistic protons and of non-relativistic matter of all types and some authors believe that this may increase the total energy by a factor of 100. 10^{53} J is the rest mass energy of about 10^6 solar masses, so that it is certainly a large energy.

I believe that it is instructive first to consider a model proposed for the double radio sources which is no longer believed to be valid because it gives a good idea of the types of problem involved. It was originally suggested that the radio source was created by an explosion in the centre of a galaxy and that this resulted in the ejection of two

blobs of plasma. It was necessary for the plasma to be largely relativistic and for it to contain a magnetic field. There are many problems with this model which I shall now describe. For a time it was hoped that they could all be overcome but now this seems unlikely.

We have no direct observation of the speed with which the components are moving but an obvious property of most of the sources is that the components have a size which is very small compared with their separation. This immediately tells us that the blobs are expanding much less rapidly than they are moving apart. If the blobs contained only relativistic particles and magnetic fields, they would expand freely with the speed of sound, which is close to the speed of light, unless they were restrained by the intergalactic medium. We are therefore forced to ask what is the mechanism which determines the size of the blobs.

There are several possibilities. The most obvious one is gravitational confinement, if the blobs contain massive objects which have been ejected from the galaxy. However gravity cannot restrain relativistic particles and the only possibilities are either continuous production of relativistic particles by activity in the massive object or that the magnetic field in the blob is anchored in the massive object and that the charged particles are confined in the magnetic field. There are difficulties in the latter explanation. To possess a magnetic field which produces an average field of $\sim 10^{-8}$ T, which is deduced to exist in some radio source components, the central object would have to be very massive indeed and the energy requirements for the initial explosion would probably become prohibitive. In addition, if the relativistic particles have an energy close to the equipartition value with the field, there could well be instabilities leading to the loss of relativistic particles. We should then, in any case, require the massive object continually to produce new relativistic electrons. Models of radio sources involving massive objects in the components have been discussed in Saslaw *et al.*, 1974.

Another possibility is that the components contain cold gas with a high enough energy density that the velocity of sound in the blob is reduced considerably below c. They could then freely expand much more slowly. How much cold matter is required depends on how rapidly the components are ejected when the source is formed. If the initial ejection is at a relativistic speed, the amount of cold matter needed is much less than if the blobs are ejected relatively slowly. In either case the energy requirements for the explosion are increased above the minimum energy estimate.

A third, and for a long time a very popular suggestion, is that the components are confined by the intergalactic medium. The most obvious idea is that the thermal pressure of the intergalactic gas balances the magnetic and particle pressure in the component. Suppose that a component has the field 10^{-8}T mentioned earlier. Its pressure can only be balanced by thermal pressure if the product of number density and temperature in the intergalactic gas has the value

$$nT \sim 3\times 10^{12}. \quad (6)$$

Such a value requires both the density and temperature of intergalactic gas to be higher near to the radio galaxy than at a typical point in intergalactic space. This model was developed by Gull and Northover (1973). It is not implausible for those sources near the centres of rich clusters of galaxies, where X-ray emission, which is believed to be produced by bremsstrahlung in hot cluster gas (Giacconi *et al.*, 1974), has been observed. One difficulty with the explanation is that there is apparently no morphological difference between double radio sources inside clusters and those outside clusters.

A further possibility is confinement by what is called the ram pressure of the intergalactic gas. In this case ρv^2, where ρ is the gas density and v is the relative velocity of blob and gas, must balance the pressure inside the blob. This process was proposed by de Young and Axford (1967) and it was for a long time believed to be the most likely confinement mechanism.

Although the evolution of individual sources cannot be studied, it is found that sources with small component size usually have small linear extent and correspondingly for large size. It is therefore reasonable to suppose that small sources evolve into large sources and that, if the observed sources from a reasonably homogeneous sample, information about source evolution can be obtained by studying the properties of sources of different size. This was originally done by Ryle and Longair (1967) on the basis of a very limited sample of sources and with relatively poor resolution for the radio observations.

One result that follows from studies of this type is that there must be a continuous injection of relativistic particles into the components. The blobs must originally have been contained within the parent galaxy and as a result they have undergone considerable expansion during their lifetime. However, if a system of relativistic particles expands it loses energy by the so-called adiabatic losses and, if there has been no continuous injection of particles, the components must have been very much more luminous in the past than they are now. There is no evidence for such a decline of source luminosity with size and, in any case, without continuous injection, the energy requirements for the initial explosion would become very much larger than previously estimated. Similar problems arise with the magnetic field. It seems impossible that the present magnetic field in the components can be nothing but an initial magnetic field as weakened by expansion; the initial magnetic field would have been far too strong. If the model is correct, it seems that the magnetic field must have been amplified in the blob possibly by fluid motions in the way that we have already mentioned in the introduction.

Problems with the production of a self-consistent model of a radio source involving the ejection of two plasma blobs in an explosion led Rees (1971) to suggest a radically different approach to the problem. This proposal has subsequently been developed both by him (Blandford and Rees (1974)) and Scheuer (1974). His idea is that the continuous injection is the most crucial part of the source. It has become apparent recently that many, and possibly all, double radio sources possess a central component which provides evidence of continuing activity in the galactic centre. Rees suggested that an intense low frequency electromagnetic wave of the type mentioned in section 27.1 is radiated either by a single massive rotating magnetised object in the galactic centre or by a collection of stellar sized objects. This wave travels down a cavity which it has produced in the intergalactic medium and eventually 'breaks' against the intergalactic medium. At this point particles, which have been accelerated to relativistic energies by the wave field, begin to radiate and produce the hot spot in the radio source component, which is often found furthest from the parent galaxy. The relativistic particles then gradually diffuse out of the head region and produce the emission from the remainder of the component and also the tail of emission back towards the parent galaxy.

This double radio source model, in which the components do not consist of lumps of matter moving away from the galaxy but are instead the instantaneous positions of interaction of a beam from the centre of the galaxy with the intergalactic medium, is at present the most popular model. There are variants on it in which a beam of relativistic particles rather than a strong electromagnetic wave carries the energy to the components. In this model, as well as in the previous plasma blob model, there still remains a major problem which is the structure of the injector in the centre of the galaxy. There is at present no accepted model for this, and it is generally agreed that understanding the central object will be even more difficult than understanding the components.

27.3 PULSARS

The discovery of pulsars by Hewish *et al.* (1968) has given a great stimulus to the study of astrophysical plasmas and, indeed, pulsar observations give information about a wide variety of plasmas. Let me first describe how pulsars were discovered. Hewish was interested in the scintillation of radio sources; this is similar to the twinkling of stars. Scintillation of radio sources arises because radio waves are scattered by irregularities in electron density in interstellar and interplanetary space and this gives short period variations in the intensity and position of sources; this is itself a plasma problem of interest, the propagation of electromagnetic waves through a turbulent medium. Having constructed a radio telescope capable of time resolution of a fraction of a second, Hewish *et al.* discovered four radio sources which radiated only in sharp pulses with a pulse repetition time of order one second, These were the first pulsars. Several hundred more have been discovered in the past ten years with the shortest period of 30 m sec being that of the pulsar in the Crab nebula.

Before I discuss the origin and structure of pulsars, let me explain how they have given information about the interstellar medium. When radiation of several different frequencies from pulsars was studied, it was found that the radiation was always pulsed but that the time of arrival of the pulses varied with frequency. This occurs because the group velocity of electromagnetic waves in a plasma is frequency-dependent. Thus the dispersion relation

$$\omega^2 = \omega_p^2 + k^2 c^2 \tag{7}$$

leads to a group velocity

$$v_g \approx c\left[1 - \frac{\omega_p^2}{2\omega^2}\right], \tag{8}$$

if $\omega \gg \omega_p$, as is true for radio waves passing through the interstellar medium. Although the change of the group velocity from c is minute, the path length from pulsar to observer is so large that the time of arrival of pulses at different radio frequencies is measurably different. The observations do have the predicted dependence on frequency and they lead to a value of the integrated electron density in the line of sight to the pulsar,

$$N_e = \int n_e \, ds\,. \tag{9}$$

A second plasma effect on propagation of electromagnetic waves is that in the presence of an electromagnetic field there is a further correction to (7) which depends on the sense of polarisation of the wave. Thus

$$\omega^2 \approx \omega_p^2 + k^2 c^2 \pm \frac{\omega_p^2 \omega_{ce}}{\omega} \cos\phi\,, \tag{10}$$

where ω_{ce} is the electron gyration frequency, ϕ is the angle between the magnetic field and the direction of propagation of the wave and $\pm$ refers to the two senses of polarization. This effect leads to Faraday rotation of the plane of polarization of the wave. Observation of the Faraday rotation gives a value for

$$\int B n_e \cos\phi \, ds\,. \tag{11}$$

Combining (9) and (11) gives an approximate value of the mean longitudinal component of magnetic induction between the source and observer. Finally a detailed study of the structure of pulses has enabled some information to be obtained about the length scale of irregularities in the interstellar medium. Pulsars have proved to be excellent diagnostic equipment and have given information about the interstellar plasma which could hardly have been obtained in any other way.

Now let us turn to the pulsars themselves. First we must ask why they are very interesting objects. It was rapidly realised that they must be very small. A pulsed signal lasting t sec could only be emitted by a region of linear extent less than t light sec. In addition an explanation is required of the period. If this is due to either pulsation or rotation, it is relatively easy to show that the period, P, satisfies

$$P \gtrsim 1/\sqrt{G\rho}\,, \tag{12}$$

where ρ is the density of the object concerned; if this is not so the motions exceed the escape velocity and the object must disrupt. To obtain a period as short as that in the Crab nebula, the density is so high that it seems inescapable that the object is a neutron star. It is now generally accepted that pulsars are rotating neutron stars, as proposed by Gold (1968).

Neutron stars are believed to be formed during the explosions of at least some supernovae. The presence of a pulsar in the Crab nebula is good evidence for this idea as it is known that the nebula was produced by a supernova explosion in 1054. In the explosion part of the star is ejected into space but a remnant may be imploded to high density and form either a neutron star (if its mass is low enough) or a black hole. One current problem with this association between pulsars and supernovae is that the recent discovery of hundreds of pulsars has made it appear that they are more common than they should be in comparison with the estimated frequency of supernova explosions (Davies *et al.*, 1977).

Given that a pulsar is a rotating neutron star, we must explain why it emits electromagnetic radiation and why this radiation is pulsed. Initially it seemed very difficult to understand how this radiation could be produced. A neutron star has a very thin dense atmosphere. A naive calculation suggests that there are very few particles above the layer from which radio waves are able to propagate and that even radiating coherently they could not possibly radiate energy at the required high rate. This argument is false for several reasons. As mentioned earlier, if an electromagnetic wave is strong enough, it may sweep up the particles through which it is not supposed to be able to propagate. In addition it now seems clear that pulsars have very strong magnetic fields which completely alter their atmospheric structure.

One important observation of pulsars is a gradual increase in their periods; there are also occasional sharp decreases with which we shall not be concerned. If the pulsar is a rotating neutron star, this implies that it is slowing down. It was pointed out (see for example, Ostriker and Gunn, 1969) that it would automatically slow down, it it had a magnetic dipole moment whose axis was not aligned precisely with the axis of rotation. In this case we have a variable magnetic dipole which radiates low frequency waves which carry away angular momentum. Gunn and Ostriker showed that the rate of variation of period could by understood provided that pulsars possessed magnetic fields with strengths of order 10^8T. At first sight this sounds like a very large field but it is, in fact, a perfectly reasonable field for a neutron star. Thus a neutron star has a radius which is down by a factor of 10^5 on that of an ordinary star. If an ordinary star is imploded to neutron star densities and magnetic flux is conserved, as seems likely because the electrical conductivity of stellar material is so high, a magnetic field of only 10^{-2} T can be amplified to 10^8 T.

This discovery of a method by which a supernova remnant could lose energy was very useful as far as studies of the Crab nebula were concerned. For some time it had been apparent that the properties of the nebula could only be understood if it was being continuously supplied with energy at a high rate of order 10^{31} W. This is more than 10^4 times the rate at which the Sun radiates energy and it was difficult to understand how energy was being fed into a supernova remnant at this rate so long after the explosion of the supernova. Now this rate of energy injection fits in well with the idea of radiation from a rotating dipole. In addition using the intense low frequency waves it may be possible to accelerate continuously electrons to relativistic energies in the nebula so as to provide electrons to radiate at radio frequencies in the nebula as a whole. This model is clearly similar to the radio source model discussed in the previous section. It has been thought for a long time that cosmic rays might be produced in explosions of supernovae; it is still probable that this is correct but an alternative possibility is that at least some cosmic rays are produced by pulsars long after the supernova explosion.

When it was realised that pulsars possessed intense magnetic fields, it was pointed out by Goldreich and Julian (1969) that it was not reasonable to suppose that the neutron stars could be surrounded by a vacuum through which low frequency electromagnetic waves would propagate freely. On the surface of a rotating magnetised neutron star there will be electric fields given by

$$E = -(v \times B) \tag{13}$$

and these electric fields will exert such strong forces on the particles near the surface of the neutron star that it must possess an extensive magnetosphere. Near the surface of the neutron star the magnetosphere will co-rotate with the star but this property cannot extend beyond the light cylinder, where the co-rotation speed would equal the speed of light.

The pulsar magnetosphere is a very complicated and interesting plasma. Despite many attempts to obtain an understanding of its properties (Ruderman, 1972; Mestel *et al.*, 1979; Mestel and Wang, 1979) it is still not obvious how the energy radiated by the star propagates through the magnetosphere and across the light cylinder. In addition the origin of the pulsed radiation is not yet clear. There has been dispute as to whether it originates in localised regions on or near the surface of the neutron star or whether it is produced near the light cylinder. The latter is the more favoured explanation and the pulses are thought to arise by coherent emission from the plasma being beamed in particular directions.

27.4 MAGNETIC FIELDS IN STARS

I have already mentioned that it seems probable at first sight that the formation of stars from interstellar gas should produce stars with strong magnetic fields. I have also stated that the electrical conductivity of stellar interiors and the length scale of any large scale magnetic field which they contain are such that little decay or diffusion of an internal magnetic field can be expected during a stellar lifetime. Most stars are not observed to have very strong surface magnetic fields. It is possible that the flux loss during star formation has been underestimated but it is of interest to ask whether, if a star is formed with a strong magnetic field, there is any way in which this field can decay at a rate faster than that predicted by (1).

One suggestion is that convective motions can tangle up the field and lead to efficient flux reduction. This proposal was made at a time when work by Hayashi (1961) suggested that all stars during their early evolution passed through a phase in which the major energy transport throughout the whole star was by convection. Might not this convection reduce the length scale of the field so that most of the flux would be destroyed? This has been made less probable by more recent work by Larson (1972). He has suggested that many stars do not have a fully convective phase and that, even if it does exist, it may not last long enough for really effective field decay to occur.

We will therefore suppose that stars can be formed with a strong internal field and ask whether there is any way in which this field can be reduced in a stellar lifetime. Mestel (1971); Markey and Tayler (1973, 1974); Tayler (1973, 1980); and Wright (1973) have suggested that many stellar magnetic fields will suffer hydromagnetic instabilities with a growth time which is very short indeed compared to the stellar lifetime and that these might lead to flux reduction.

The instabilities which occur are closely analogous to the pinch instabilities which are of such importance in thermonuclear experiments and they can be described quite simply. Consider first the case in which a star possesses a poloidal field of the type shown in Fig. 2. If the star is to contain a flux which is greatly in excess of that observed on stellar surfaces, it must certainly possess field lines closed within the star of the type shown in the diagram. In the neighbourhood of the

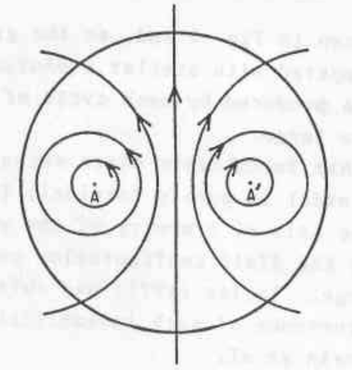

Fig. 2 *Poloidal field lines inside a star whose surface is also shown. The direction of the magnetic field is shown by the arrows.*

magnetic axis *AA'* we now have a magnetic field configuration which is essentially the same as that of a toroidal pinched discharge. It is well known that such a system has instabilities whose growth time is comparable with the time taken for a hydromagnetic wave to cross the system. For a strong field in a star, this time is measured in months or years compared with stellar evolution times of at least millions of years.

There is of course one important difference between the laboratory problem and the stellar situation. The most important force acting in a star is the gravitational force and it is difficult for the magnetic field to drive motions against gravity. However, although gravity affects the hydromagnetic instabilities, it does not remove them. It is for example possible to construct an unstable kink perturbation in which all motions are perpendicular to the gravitational field so that it exerts no stabilizing effect on the instability. This qualitative argument has been confirmed by Markey and Tayler (1973) and Wright (1973), who have used the energy principle of Bernstein *et al.* (1958) to show that instability definitely occurs, without necessarily finding the worst instability. Markey and Tayler (1974) have indicated that all poloidal field configurations with closed field lines will be unstable whatever is the strength of the field. It is well known that short wavelength kink instabilities are particularly unstable and this leads to the suggestion that the ultimate effect of the instability may be field decay. The instability should continue to be excited while the topology of the magnetic field is as shown in Fig. 2 and, as the growth time of the instability is so short compared with stellar evolution timescales, very little field decay need be produced by each cycle of instability for the cumulative effect to be large.

It is easy to demonstrate that instability often arises if the magnetic field instead of being poloidal is purely toroidal; in this case the magnetic field lines circle the axis of symmetry of the star and near enough to the axis of symmetry the field configuration once again looks like that of a pinched discharge. Tayler (1973) has obtained complete algebraic criteria for the occurrence of such instabilities again using the energy principle of Bernstein *et al.*

Although these results are suggestive, they are at present far from conclusive. There are at least three reasons for this. No full discussion has yet been given for the case of mixed poloidal and toroidal fields although some comment on results which have been obtained is made below. Most stars rotate and rotation will certainly change the stability criteria particularly if the rotation speed exceeds the hydromagnetic speed. Finally the large scale development of the instabilities has not yet been studied, so that a conclusive demonstration that flux destruction occurs is lacking.

One point is worth making about the influence of helical (mixed poloidal and toroidal) magnetic fields. It is known that the introduction of an axial magnetic field into a laboratory pinched discharge produces some measure of stability. It is also known that complete stability can only be obtained if the magnetic field configuration is very carefully designed. There is then a temptation to say that stellar magnetic fields, even if helical, are almost bound to be unstable because there is no reason to expect a very special stable configuration to be produced. This argument is, however, erroneous. The most unstable perturbations are helical and in a star a perturbation cannot simultaneously be helical and be perpendicular to the gravitational field everywhere. This means that the gravitational field does exert some stabilizing influence on pinch configurations when both poloidal and toroidal fields are present. The possibility then exists that the toroidal field might stabilize instabilities near the magnetic axis and the poloidal field might stabilize near the axis of symmetry. Preliminary results (Tayler, 1980) suggest that there might be a wide class of stable mixed field configurations but it is not obvious that such stable configurations would arise naturally during stellar evolution.

There is also a possibility that magnetohydrodynamic instabilities of the above type can occur in interstellar gas clouds during the process of star formation. This possibility has not yet been studied in detail although some calculations of contracting gas clouds (Mestel and Strittmatter, 1967) have indicated that field lines closed within the cloud are likely to arise. The instabilities in a gas cloud will have a somewhat different character from those in a star because, in contrast to the stellar situation, the timescale for energy flow is less than the dynamical timescale. Perturbations are therefore more likely to be isothermal than adiabatic.

27.5 THE SOLAR PLASMA

As a final example of an astrophysical plasma, I shall make a few remarks about the plasma in the solar atmosphere and just outside the Sun. The Sun is the only star whose surface can be studied in great detail and we must presumably regard it as typical at least of those stars whose overall properties are similar to the Sun. It is usual in studying stellar structure to regard stars as spherically symmetrical and quiescent and it is a sobering thought to realise how much the solar atmosphere departs from the norm.

A good photograph of the solar atmosphere reveals the existence of granulation, a cellular pattern covering the surface. This granulation is believed to be visible evidence of the convection zone which theory predicts should exist in the outer solar atmosphere and the pattern has some similarity to the hexagonal Bénard convection pattern which can be obtained in laboratory experiments. Further study of motions in the solar atmosphere reveals the existence of the supergranulation, which is a cellular structure on a much larger scale and which presumably penetrates to a much greater depth in the atmosphere. Thus, whereas the granulation has a scale measured in 100's of km, the supergranulation is on a scale of order 10^4 km compared with a solar radius of 7×10^5 km.

Observations of the Zeeman effect in light from the solar surface shows that there are magnetic fields everywhere. Far from the Sun it appears to have a basically dipolar field with a surface field of order 10^{-4} T. However, the actual field at the solar surface is totally different from this. There are regions where the field is very much stronger and particular concentrations of magnetic flux occur at the edges of supergranules. It has been suggested by numerical calculations by Weiss (1966) that in a convective zone magnetic flux will be expelled from eddies and that it will be concentrated in flux ropes at eddy boundaries. If the supergranulation is the main scale of motions in the convection zone, and if the granulation is only a surface phenomenon, it seems reasonable to suppose that the field should be strongest at supergranule boundaries.

Another feature of the surface is the appearance of sunspots. Sunspots recur with a 22 year cycle. A sunspot is a region of strong magnetic field (~ 10^{-1} T or more) and it is darker than its surroundings and therefore cooler. It has been suggested (Biermann, 1941) that sunspots are cooler than their surroundings because the strong magnetic field interferes with convection in the spot region. It is well known (Thompson, 1951; Chandrasekhar, 1952) that magnetic fields can inhibit convection in a liquid and Gough and Tayler (1966) obtained similar results for a compressible gas. It does therefore seem plausible that spots arise because of interference with the efficiency of convection. Presumably the motions in the convection zone occasionally cause strong magnetic fields to break through the solar surface and thus give rise to sunspots. This model is still not universally accepted and there are some problems related to where the energy that does not flow out through the spot does cross the solar surface.

There is then the question as to why there is a regular sunspot cycle. This is believed to be bound up with the mechanism by which the magnetic fields in the outer layers of the Sun are produced. Although I have said previously that it is difficult to see how magnetic fields can be produced or destroyed in the entire interior of a star in a stellar lifetime, the same is not true in an outer stellar region where the conductivity is lower and the length scale shorter. It is believed that the field in the outer layers of the Sun is produced by a dynamo mechanism (see for example, Parker, 1970; Weiss, 1971) which should also explain the solar cycle.

Another unusual property of the Sun is that the outer atmosphere (Corona) has a kinetic temperature (~ 10^6 K) which is very much greater than the temperature of the visible surface of the Sun. In addition plasma is continually flowing from the surface of the Sun into interstellar space (the solar wind). Given that the Sun has such a hot upper atmosphere it is not difficult to understand how the solar wind arises but some explanation must be found for the existence of the corona. It has been suggested that turbulence in the convection zone of the Sun generates acoustic waves and magnetohydrodynamic waves which propagate upwards in the solar atmosphere (Lighthill, 1967). As they move into a region of lower density, they steepen into shock waves and eventually dissipate their energy producing the high temperature of the corona and ultimately the solar wind. The belief in this mechanism has been weakened by the recent discovery that coronae are more common than was previously believed and in particular that they can be possessed by stars without outer convection zones. It has been discovered that mass loss from stars is widespread and in the case of the Sun there is particular interest in discovering how the strength of the solar wind depends on parameters such as the solar magnetic field.

The first hint that there was important mass outflow from the Sun came from the study of terrestrial magnetic storms by Chapman and Ferraro (1931). At that time they supposed that there was only a mass outflow at the times of high solar activity. It was Parker (1958) who first made a clear prediction of a solar wind related to the high temperature of the solar corona, and its subsequent discovery was one of the first triumphs of space research. The interaction of the solar wind with the Earth's magnetic field leads to the existence of the magnetosphere and it is a disturbance of the magnetosphere by an enhanced solar wind which produces a magnetic storm. Just outside the magnetosphere boundary is a collisionless shock transition; this was discovered at a time when plasma physicists were still arguing about whether such collisionless shocks could in fact exist.

Magnetic storms are associated with spectacular and erratic events on the solar surface known as solar flares. These involve a sudden eruption in a local region of the solar surface including very intense radiation in visible and ultraviolet and an enhancement of the production of low energy cosmic rays by the Sun. A flare covering a small area of the solar surface can release more than 10^{25} J in a time as short as 10^3 s and this corresponds to an optical energy density in the flare region of order $10^2\,\mathrm{J\,m^{-3}}$. In contrast the thermal energy density in the upper solar atmosphere, in which the flare is situated, is only of order 10^{-3} to $10^{-1}\,\mathrm{J\,m^{-3}}$. Clearly the thermal energy of the solar atmosphere is too low by a large factor to account for the energy released locally in a flare. The only adequate source of energy is the magnetic energy associated with regions of strong magnetic field, as a field strength of 1.5×10^{-2} T corresponds to an energy density of $10^2\,\mathrm{J\,m^{-3}}$. Hence all modern theories of solar flares assume that their immediate cause is a sudden conversion of magnetic energy into heat.

There are several mechanisms which have been proposed. One suggests that they occur near neutral points in the magnetic field (Dungey, 1953; Sweet, 1958) where field dissipation can be particularly fast, reconnection of field lines occurs and strong electric fields can develop, which may accelerate the solar cosmic rays. Observations suggest that neutral points do occur in flare regions. Another suggestion (Sturrock and Coppi, 1966) is that the mechanism for release of magnetic energy is a magnetohydrodynamic resistive instability.

The solar atmosphere is certainly a region in which many interesting complicated nonlinear plasma phenomena are occurring. Our knowledge of the solar atmosphere and its surroundings has recently been increasing very rapidly because use of rockets and satellites enables study to be made in regions of the spectrum which are inaccessible from the ground.

27.6 CONCLUSION

A proper discussion of astrophysical plasmas would require a whole book to itself. In this chapter I have only been able to give a very sketchy discussion of a few problems in which I have been personally interested. One particularly glaring gap is my failure to discuss any of the complicated nonlinear processes involving wave particle interactions which are studied in the book by Kaplan and Tsytovich (1973).

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