THE GALACTIC MAGNETIC FIELD AND COSMIC RAYS

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Abstract

The structure of the magnetic field of the Galaxy and other spiral systems and the inseparable problem of the origin of cosmic rays are examined: (1) A variety of evidence is used to show that the galactic field extends far beyond the disk and connects the disk field with a general field fixed in the local system of galaxies. (2) The coronal field extends beyond 10 kpc as an oblique helix which is constantly expanding, and has partially force-free characteristics. (3) As in the case of the disk field, the axi-asymmetric coronal field exercises major control over gas clumping and star formation in the disk. Such a model of spiral arm formation has advantages over gravitational theories. (4) The supernova explosion and neutron star theories of cosmic rays are examined and shown to meet major difficulties. A new model of supernova shell radio sources is proposed. (5) A massive magnetic rotator at the centre may be a major source of cosmic rays in our Galaxy and a proportion of other spirals. (6) A second mechanism of cosmic ray acceleration is by magnetic pumping by hydromagnetic compression waves. These originate in the central rotator (period $\lesssim$ 300 yr) and accelerate particles *in situ* throughout the corona and disk.

I. Introduction

The problem of the structure and dynamics of the galactic magnetic field is inseparable from those of the cosmic rays and interstellar gas. Most measurements of the field are limited to within a kiloparsec or so of the Sun, beyond which data are scarce. While there is evidence of a magnetic halo or corona extending $\gtrsim$ 10 kpc above the disk, this is disputed and the quantitatively most fully developed model (Parker 1968, 1969) is limited to a field more or less uniform over the disk, and substantially confined by and in gravitational equilibrium with the thin gas layer. There is notable disagreement also on the dynamical significance of the field both in determining large-scale spiral structure in the galactic plane and in controlling gas and cosmic ray motions in the corona. These questions are crucial to the determination of the origins of both the field and the cosmic rays.

Evidence relating to the origin and motions of the cosmic ray gas has been reviewed by Ginzburg and Syrovatskii (1964, 1967), Meyer (1969), and others. It is generally accepted that most cosmic rays observed within the solar system originate within the Galaxy, probably in supernovae or their remnants. A suggestion that they originate in radio galaxies (Burbidge and Hoyle 1964) appears unlikely in view of the discussions of Ginzburg (1965), Schmidt (1966), the above reviewers, and others.

In the present paper we examine the observational and theoretical evidence available in an attempt to determine the characteristics of the field and the origin of the cosmic rays.

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II. Synchrotron Emissions of the Galaxy and Other Spirals

Although the electron component accounts for only about 2% of the cosmic radiation measured at the Earth, it is the only component which may be directly observed beyond the solar system. This is by its synchrotron emissions at radio and shorter wavelengths and more recently by inverse Compton X-ray emission. When it was shown that the electron component is not a secondary of the nuclear component, the connection between the two became uncertain. However, since the former provides the only information available, it is assumed that the synchrotron emissions give a measure of the distribution of total cosmic ray flux, as they certainly do of magnetic field strength.

Using the radio data, we first consider, in Subsection (*a*), the likely distribution of magnetic fields and cosmic rays within our Galaxy. It does not seem that adequate significance has been attached to the radio synchrotron emissions from other spiral systems similar to the Galaxy. These are measures of fields and cosmic rays and, since observations are made from outside the galaxies, interpretation is simpler.

An object of particular interest as a possible major source of cosmic rays is our galactic central system; observations are discussed in some detail in Subsection (*c*).

(*a*) *The Galaxy*

The main feature of the radio synchrotron emission of the Galaxy is a general decrease in all directions away from that of the nucleus, reaching minima not at the poles but near the galactic plane at the anticentre (Mills 1964). This distribution led to the suggestion of a more or less spherical system of field and cosmic rays, or *radio halo* (Shklovskii 1952). Later surveys with narrower beams revealed more detail in the form of "loops" and "spurs", and if these features are subtracted from the total the evidence for a halo is reduced. Further evidence of asymmetries in the high-latitude emissions, and the lack of haloes in most external galaxies, caused a further retreat from the halo concept and its replacement by a model in which the magnetic field is mainly confined within the gaseous disk.

However, there is no apparent reason why a halo should be spherically symmetric or even axisymmetric. Nor is there any reason why the loops and spurs should not be parts of a complex halo, as suggested by Mills. There is a good deal of evidence for systems of magnetic fields and cosmic rays around *some* external galaxies. Finally, the radio data appear irreconcilable with the disk model, and some sort of galactic halo seems to be required.

It has long been recognized that the galactic radio emission greatly exceeds the value computed with an electron cosmic ray flux everywhere the same as that near the solar system and a uniform disk field $\sim 3\times10^{-6}$ G, as observed by other methods (Woltjer 1965). The difficulty has been presented in quantitative form by Baldwin (1967) who showed that the distribution of radio emission comprises a disk component and a halo component. The radio disk has a thickness of 750 ± 100 pc with more or less uniform emissivity but some evidence of stronger emission towards the centre of the Galaxy. The disk radius is $\sim 8\cdot7$ kpc, thus lying wholly inside the solar orbit of 10 kpc. The remainder, or halo component, thus provides all of the emission observed over the greater part of the celestial sphere, from latitudes above $\sim 16°$ and longitudes $\gtrsim 60°$ from the galactic centre.

The disk component is interpreted as a magnetic field and cosmic ray system of higher values than those near the solar system, extending far outside the gaseous disk (thickness $\sim$ 100 pc) but lying *inside* the solar orbit.

The halo component, which includes all radiation from within 1·3 kpc of the Sun, is provided by a model of radius 15 kpc, field $2\text{–}3\cdot5\times10^{-6}$ G and cosmic ray flux equal to that near the solar system (Felten 1966; Ginzburg and Syrovatskii 1967). A modification has been proposed by Hamilton and Francey (1969) in the form of a weaker field ($\sim 10^{-6}$ G) and correspondingly larger cosmic ray flux. The change is required to explain different diffuse X-ray spectra observed in the north and south hemispheres which, like the different radio spectra, are attributed to different electron cosmic ray spectra in the two hemispheres. These spectral differences seem explicable only if a substantial part of the X-ray emission is received from the halo, as a result of inverse Compton scattering of the 3°K black-body photons. The large electron flux of the model provides such emission.

The galactic halo is far from homogeneous, the most notable features being the spurs, loops, and arcs (see Baldwin 1967). These start near the galactic equator and extend to moderate or high latitudes. They are not small-scale features such as supernova remnants (Bingham 1967) but are part of a very irregular halo. In general the halo brightness distribution is irregular on a scale which suggests a structure of size $\sim$ 1 kpc (Seeger *et al.* 1965). However, in places the radiation is polarized over regions of extent $\sim 60°$ (Baldwin 1967), which implies that the field is organized over distances of a few kiloparsecs. Models of the field within 1 kpc or so of the Sun (Bingham and Shakeshaft 1967; Gardner, Morris, and Whiteoak 1970) differ considerably in detail but agree in the conclusion that the field is regular on a scale $\sim$ 1 kpc and is not an irregular field stretched out by differential rotation.

In Section III(*d*) these results are compared with a dynamic model of the galactic field.

(*b*) *Other Galaxies*

Many other spiral galaxies have been studied by Heeschen and Wade (1964), De Jong (1965, 1966), Terzian (1967), Cameron and Glanfield (1968), Whiteoak (1970), and others. Most of the nearer galaxies provide observable synchrotron emission indicating magnetic fields and an accelerating mechanism. In some galaxies the emission originates throughout the optical disk but in others it is concentrated towards the centre, sometimes to a high degree. This suggests the possibility of a central source of cosmic rays, and further evidence is that the radio source dimensions seem to decrease with increasing radio frequency (De Jong 1967). There is also evidence of a transition in the radio spectra which become flatter at lower frequencies (see Lang and Terzian 1969). Finally, when all types of "normal" galaxies are included, there is a notable correlation between the ratio of radio to optical flux and the degree of central concentration of light (Cameron and Glanfield 1968). These results collectively indicate a model comprising a nuclear source from which the cosmic rays spread, losing energy and developing a flatter spectrum as they move outwards.

On the other hand it is difficult to reconcile the results with an origin in supernovae or other stellar objects. Supernovae show little or no concentration towards the centres of spirals (Johnson and MacLeod 1963). An interesting exception to this disagreement is found in our neighbour M 31, where synchrotron emission is strongest from two spiral arms far from the centre (Pooley 1969). However, the overall disk emission from M 31 is much weaker than that of the Galaxy, so perhaps stellar-type sources of cosmic rays become significant in the absence of a strong central source.

Most normal galaxies lack a radio halo, thus providing evidence against an extensive magnetic field around our Galaxy. However, M 31 again proves an exception, having an extensive halo, as shown in early surveys and mapped in more detail by Dickel (1968). This case and the radio and other active galaxies show that radio haloes are quite possible. Here we are concerned mainly with the possibility of an extensive magnetic field and whether or not it contains relativistic electrons and so is visible as a (radio) halo. There is considerable evidence for such fields in the structure of some galaxies (Piddington 1964) and in the satellite radio sources located within ~ 40 kpc of some spiral galaxies (De Jong 1967).

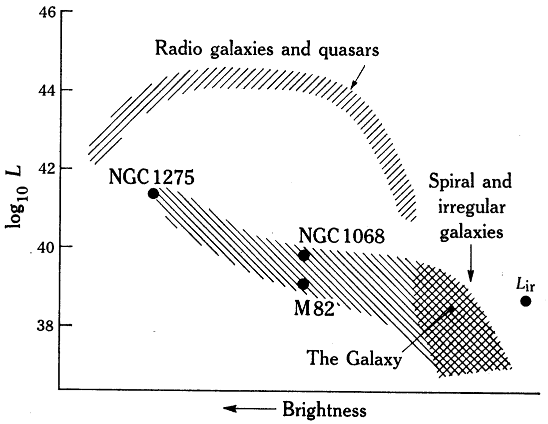

Fig. 1.—Schematic plot (after Heeschen 1966) of radio luminosity L (in erg sec^{-1}) against brightness of two sequences of radio sources, the upper comprising radio galaxies and quasars and the lower spiral and irregular galaxies, including our own. The infrared luminosity (but not its brightness) of our central 1 pc source is shown as L_{ir}.

Further significant evidence concerning the particles and fields of spiral galaxies may be provided by some of the more active spirals. On the basis of radio luminosity L, galaxies may be divided into the classes of radio galaxies (and quasars) with $L > 10^{40}$ erg sec^{-1} (bandwidth $\sim 2 \times 10^{10}$ Hz) and normal galaxies with $L < 10^{40}$ erg sec^{-1}. The cosmic ray electrons responsible for the radio emission of the former originate in the galactic nuclei, which indicates that nuclei of radio galaxies are the most notable sources of cosmic rays in the universe and suggests that nuclei in general may be important sources.

Heeschen's (1966) well-known plot of L against radio brightness is shown schematically in Figure 1. The radio galaxies form a main sequence which is separated from that of spirals and irregulars (cross hatched). A few of the latter (shown as dots) have unusually high brightness, but may *not* be classed as radio galaxies of low luminosity because they have quite different optical characteristics. We consider them spirals and irregulars passing through a phase of remarkable central activity, and so they are shown in Figure 3 as a probable extension of this sequence. They are called Seyfert galaxies, a type of spiral galaxy identified also by violent central activity and emissions of infrared and millimetre waves amounting to $> 10^{44}$ erg sec^{-1}

(Pacholczyk and Weymann 1968). About 2% of all galaxies are so designated, and since the enormous power output could hardly be maintained for more than a small fraction of the life of a galaxy it is likely that *most spiral systems* are Seyferts for roughly 2% of their lifetimes or 2×10^8 yr. Furthermore, it does not seem likely that an explosion could provide emission over such a long period, so that some rather steady process of cosmic ray acceleration must operate for $\sim 2\times10^8$ yr.

If spiral nuclei emit $> 10^{44}$ erg sec^{-1} for this period, then it is likely that they produce cosmic rays at a rate of 10^{41} erg sec^{-1} for a much longer period. Perhaps this was the case in our spiral Galaxy, and a model is proposed in Section V.

(c) *The Galactic Central System*

As we have seen, spiral galaxies have central systems showing highly variable degrees of activity and cosmic ray production. The centre of our Galaxy is not outstanding at present, but does show moderate activity and cosmic ray production as revealed by radio and infrared emissions, by unexpected gas motions, and by anomalously high mass density and low angular momentum per unit mass. As seen in Section V, it is likely that the activity was greater in the past while the gravitational energy of the present large central mass was being released.

The radio source is called Sgr A, a name which may be reserved for a central source extending $\sim 3'\times2'$ or 9×6 pc (Maxwell and Taylor 1968) with a luminosity $\sim 10^{35}$ erg sec^{-1}, or it may include a more extensive source of higher luminosity (Lequeux 1967). The spectra of these two components differ substantially, the core having an index of $-0\cdot25$ and the surroundings $-0\cdot65$ (Maxwell and Taylor). The index for the whole Galaxy may be $-0\cdot7$ (Mills 1964) although there is some uncertainty. These data are consistent with an origin of all cosmic ray electrons within the core and loss of the more energetic particles prior to emerging and spreading through the Galaxy.

Although the central region only contributes $\sim 1\%$ of galactic radio emission and is obscured in the visible spectrum, it is a notable source of infrared, X-rays, and γ-rays. The infrared emission (Becklin and Neugebauer 1968, 1969; Low *et al.* 1969; Hoffmann and Frederick 1969) is from a point-like source (3×10^{38} erg sec^{-1}), a core of extent ~ 1 pc (3×10^{39} erg sec^{-1}), and an extended source (3×10^{42} erg sec^{-1}). Difficulties have been met in explaining all these emissions as thermal. The infrared luminosity of even the point source exceeds that of the Crab Nebula by $> 10^3$, and much of this radiation is likely to be synchrotron. If this is the case, then the input of energy in the form of cosmic ray electrons is likely to exceed 10^{40} erg sec^{-1} and that of all cosmic rays may be higher.

Other phenomena observed in the galactic central region are discussed in Section V, where an attempt is made to explain these and the anomalously high mass density in terms of magnetic braking during past epochs.

III. The Galactic Plasma and Magnetic Field

The galactic cosmic ray gas is frozen into the magnetic field and the two tend to expand and dissipate. Their presence may only be explained in terms of some force or forces which prevent their rapid dissipation. If the problem is considered in terms of the virial theorem, then there must be sufficient mass with enough negative gravitational energy to compensate for the magnetic, cosmic ray, and gas kinetic energies.

Parker (1968, 1969) has shown that it is most unlikely that the anchoring mass is in the galactic central region. He concludes that the field is anchored, more or less in hydrostatic equilibrium, in the gaseous disk. The theory depends basically on the quantity and distribution of the gas and for this reason the observational data are discussed briefly in Subsection (*a*) below. Some difficulties met by Parker's theory are then discussed in (*b*).

As we have seen above, the galactic magnetic field must extend far above the gas disk with the greater part of its flux and energy outside this disk. There is disagreement about the existence of an extensive *radio halo* which requires both correspondingly extensive field and also cosmic ray electron distributions. However, there can be little doubt of the existence of an extensive field system which might be termed a *galactic corona* of magnetic field and very tenuous gas. Ginzburg called this a *physical halo* and stressed the role of gas; we prefer the term *corona* and suggest a model in Subsection (*c*) below.

(*a*) *The Galactic Gas*

Radio line studies of galactic neutral atomic hydrogen have been discussed by Schmidt (1959), Kerr and Westerhout (1965), and many others. Early measurements indicated an average density in the galactic plane $n_{\mathrm{H}} \sim 0 \cdot 55$ atom cm^{-3}. Later evidence of self absorption suggested a higher value, and in the region within ~ 1 kpc of the Sun (the "local arm") an average density, including the helium equivalent, of $1 \cdot 5$–2 atoms cm^{-3} was widely accepted. Considerably higher values have been suggested on the slim evidence of the "missing mass", required to explain the observed acceleration of some stars.

On the other hand, there is substantial evidence in favour of a lower value. First, a reduction by a factor of $1 \cdot 2$ is required to allow for the revised galactic distance scale. Second, measurements of the absorption of Lyman α of starlight and of the radio line emission of Cas A seem to require a downward revision (for a discussion see Spitzer 1968). Finally, optical observations (Carruthers 1967) reveal a very low density of hydrogen in the molecular form. It seems likely that the missing mass is provided by dim stars or invisible singularities.

We conclude that the best estimate of average n_{H} in the local arm and including the molecular form is in the range $0 \cdot 7$–$0 \cdot 9$ atom cm^{-3}. To this must be added a 34% allowance for helium mass equivalent and a few per cent for ionized hydrogen, for a total mass equivalent of 1–$1 \cdot 2$ atoms cm^{-3}.

It must be stressed that this is only the "local" value. In the disk the gas is concentrated into so-called "arms", which might really be better described as pieces of rings. The scale of these arms is ~ 1 kpc radially by a few kpc in azimuth (Kerr and Westerhout 1965, Plate II and Fig. 9) and the above discussion applies to the Carina–Cygnus arm, in which the Sun is situated. Between the arms the gas density is smaller by factors as large as 20 or more. Within the arms themselves the gas is further distributed into clouds of density ~ 10 atoms cm^{-3} and extent ~ 10 pc, with much lower intercloud densities. A notable galactic problem, discussed in Subsection (*e*) below, is the origin of these various inhomogeneities.

All of the above values refer to the galactic plane, outside which the density falls rapidly. Narrow-beam measurements indicate a thickness in the local arm of ~ 160 pc to half density. Well inside the solar orbit the value falls to ~ 100 pc, while within the central system it is only 80 pc.

Outside this thin and very flat disk the density decreases to $\sim 10^{-2}$ atom cm^{-3} at $1 \cdot 5$ kpc above the plane (Oort 1969) and a likely value of $\sim 10^{-3}$ atom cm^{-3} far out in the corona (Roberts 1967). However, many separate *clouds* of gas are observed far above the disk. From measurements of starlight absorption Münch and Zirin (1961) inferred a population of clouds extending to 1 kpc. Numerous clouds observed in radio line emission have inward velocities ~ 100 km sec^{-1} and large turbulent velocities (for reviews see Hulsbosch 1968; Oort 1969). These clouds have integrated line-of-sight densities $\sim 2\text{–}20 \times 10^{19}$ atoms cm^{-3}, which may be compared with that of half the disk $\sim 1 \times 10^{20}$ atoms cm^{-3}. Thus they may be dynamically very important in any model corona.

(b) *Parker's Model Field*

Parker's (1968, 1969) model of the galactic magnetic field is mainly confined to the gaseous disk where it is substantially uniform and parallel with the galactic plane. A scarcely significant halo is a secondary phenomenon comprising "bubbles" of cosmic ray gas and frozen-in field which erupt periodically from the gas disk. This non-equilibrium does not appear to be so violent as to violate the gross hydrostatic considerations whereby the field and cosmic ray gas are held down by the cooler interstellar gas.

The model meets the following difficulties.

(i) The radio observations require a disk of thickness 750 pc and radius ~ 9 kpc in which the emission is an order of magnitude greater than that of the model. This radio disk must have a field strength and/or cosmic ray flux substantially higher than that of the model and a thickness five times as great. It is not possible for the model to account for this radio disk except by assuming a mechanism of radio emission other than synchrotron.

(ii) The radio data also require some sort of radio halo with field $\gtrsim 10^{-6}$ G extending $\gtrsim 15$ kpc. Such a halo has a magnetic flux ψ (per unit distance measured perpendicular to the field and to the disk) $\gtrsim 10^{-6}\,\text{G} \times 15\,\text{kpc} \times 1$ cm or $\gtrsim 5 \times 10^{16}$ G cm^2. The corresponding flux in Parker's model is smaller by a factor $\gtrsim 40$, and so could hardly be capable of creating the halo field while itself remaining substantially confined within the gas disk.

(iii) On a smaller scale, say within 3 kpc of the Sun, the model meets further difficulties. The required gas density is equivalent to $1 \cdot 6\text{–}4 \cdot 5$ atoms cm^{-3} of hydrogen. This is larger than the estimate made above of $\lesssim 1\ \text{cm}^{-3}$ for the average density, although uncertainties may bridge the gap. However, in the so-called interarm regions the density falls as low as $0 \cdot 2\ \text{cm}^{-3}$ over regions of extent ~ 1 kpc, and here the model fails to provide stability unless field strength and cosmic ray flux are also much lower.

(iv) On a yet smaller scale the Rayleigh–Taylor instabilities of dimensions $\sim 1\text{–}100$ pc will provide large gradients in the field vector and cosmic ray flux.

These should be evident in several ways, particularly as changes in cosmic ray flux with time scale $\lesssim 10^7$ yr, yet there is no evidence of change within the past 10^9 yr (Meyer 1969).

It is concluded that the galactic field is not substantially controlled and confined by the gas disk, but has most of its flux outside this disk. It does not seem possible that such a field could be confined by the very tenuous halo gas, as suggested by Pikelner and Shklovskii (1957), although this may play a part. Other stabilizing factors, discussed below, are continuous magnetic amplification and expansion, and partial force-free characteristics until the field merges with an intergalactic field from which it was originally formed.

(c) *An Oblique Helical Field Model*

The galactic field model suggested here stems from a unifying theory of galactic fields and their effects (Piddington 1964, 1967, 1969). All fields develop from a weak universal field frozen into the galactic gas, and in the case of spiral galaxies the rotation vector $\boldsymbol{\omega}$ is oblique to the original field. The effect of contraction alone

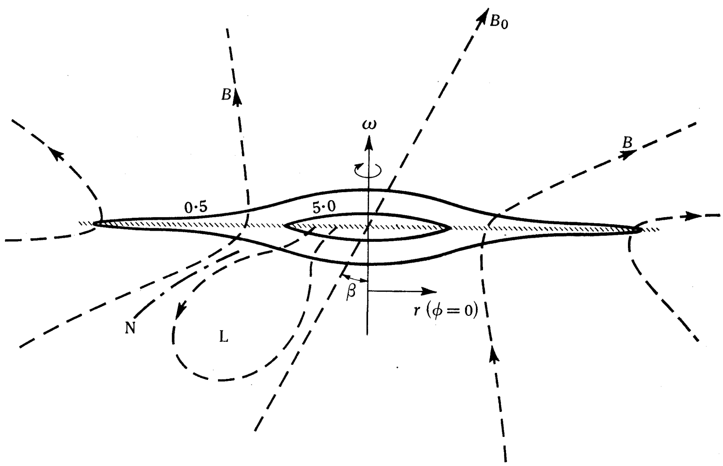

Fig. 2.—Cross section of the Galaxy through the rotational axis $\boldsymbol{\omega}$ and parallel with the intergalactic magnetic field. Lines of equal total (star plus gas) mass density correspond to 0·5 and 5 times that in the region of the Sun (after Oort 1969). The gas disk is shown hatched, with uniform thickness ~ 200 pc. The original field, parallel to $\boldsymbol{B}_0$, is shown pinched by galactic contraction but free from the striking effects of galactic rotation. A magnetic loop L has erupted from the wound-up disk field and has formed a magnetic neutral sheet N.

(as if no rotation had occurred) is shown in Figure 2, the direction of the original field being given by $\boldsymbol{B}_0$. The pinched field, shown by the lines B, remains frozen into the thin gas layer shown hatched. Most of the galactic material is in the form of stars whose equal-density contours are seen to be much thicker than the gas layer and more concentrated towards the centre.

It is evident that rotation of the gas disk must twist the external field into an oblique helical form and provide the basis of an evolving magnetic corona. Inside the gas disk the field lines are frozen into the gas and where they cross the shear planes they will be stretched and the field amplified. More detailed features of the model are as follows.

(i) The model provides a plausible explanation of the origin and form of the galactic field: more or less azimuthal within the gas disk, yet extending into a large asymmetric corona. Extended to other galaxies the theory (references above) explains the differences in forms and activities, even including radio galaxies, simply in terms of different angles between $\boldsymbol{\omega}$ and $\boldsymbol{B}_0$.

(ii) The model resolves the dilemma of Subsection (*b*) above that the disk field and cosmic ray gas are too powerful to be contained by the ambient gas yet are frozen to this gas. The external model field is twisted by galactic rotation into a roughly helical form of strength comparable with the disk field (Subsection (*d*) below). The pressure of the external field compensates for the lack of adequate weight of retaining gas. The system is self regulatory because excessive internal pressure will cause field lines and gas to erupt in the manner described by Parker, thus relieving the disk pressure and contributing more flux to the corona.

(iii) Inside the disk, motions parallel to the galactic plane are dominated by the gas so that the radial component B_r and the vertical component B_z remain unchanged, but the azimuthal component B_ϕ increases with time t as

$$B_\phi = -B_r tr\,\partial\omega/\partial r\,, \tag{1}$$

where ω is the angular velocity. At the present winding rate near the solar system, $B_\phi \sim 100\, B_r$ within a period of 3×10^9 yr, so that an intergalactic field of say 10^{-9} G compressed to 10^{-7} G would have been wound up to $> 10^{-5}$ G. This is excessive and so would have regulated itself to the present observed form and value of $\sim 3\times10^{-6}$ G.

(iv) Let us define the vector $\boldsymbol{r}$ ($\phi = 0$) as shown in Figure 2; it is seen that within this sector B_r is positive and so from equation (1) B_ϕ is negative. In the opposite sector B_ϕ is positive, and in the sectors $\phi = \frac{1}{2}\pi$ and $\frac{3}{2}\pi$ it is zero because the field $\boldsymbol{B}$ is in the shear planes. Thus the fields in these four quadrants have quite different configurations, and the gas and fields of these quadrants are themselves wound into four tight interleaved spirals. These are much too tightly wound to explain galactic spiral structure; in the Galaxy some 20 differential rotations have occurred between $r = 5$ and 15 kpc. The quadrants will have been wound almost into rings of width $\delta r \sim 200$ pc, and may explain some of the HI ring structure as described below.

(*d*) *The Coronal Field and its Effects*

In addition to a disk field consistent with observations, the model provides a coronal field attached to the disk field and extending without limit. The effect of galactic rotation on the field of Figure 2 is to twist it into a roughly helical form, and when a steady state is attained two hydromagnetic waves propagate away to infinity from the sides of the disk with the Alfvén velocity V_{A}. If V_{R} is the rotational velocity, then the pitch angle of the twisted field is $\tan^{-1}(V_{\mathrm{R}}/V_{\mathrm{A}})$. At 1 kpc above the disk, n_{H} is $\sim 0\cdot03$ cm^{-3}; if the field strength is 2×10^{-6} G then $V_{\mathrm{A}} \sim 23$ km sec^{-1}. For a rotational velocity of 200 km sec^{-1}, the pitch angle is $\sim 83°$, so that the original untwisted field is amplified by a factor of ~ 9. The original field is $\sim 2\times10^{-7}$ G and the intergalactic field perhaps $\sim 10^{-9}$ G. All of these seem reasonable values and lead to an adequate coronal field $\sim 2\times10^{-6}$ G at 1 kpc.

If we assume that the coronal field is of helical form with B_ϕ the major component, then for a steady state the magnetic flux crossing any plane $z = z_1$ in unit time must be independent of z. This flux per unit distance measured in the direction r, is given by $V_A B_\phi$. Hence, since $V_A \propto B_\phi n_H^{-\frac{1}{2}}$, we have $B_\phi \propto n_H^{\frac{1}{2}}$. A common estimate for n_H in the distant corona is 10^{-3} atom cm^{-3}, in which case $B_\phi \sim 9\times10^{-7}$ G. It seems that the field may extend to a very great distance before its strength falls much below $\sim 10^{-6}$ G.

The structure of the coronal field will be complicated by magnetic loops, such as L of Figure 2, which will be ejected from the disk as a result of the Rayleigh–Taylor instability. These loops will be wound into the original field and in places must form magnetic neutral sheets such as that shown by the line N. Field annihilation and reconnection in these sheets (galactic "flares") might be important in providing particle acceleration and in controlling bulk motions of cosmic rays. The radio spurs, loops, and arcs referred to in Section II(a) may be coronal condensations of cosmic rays and field formed from earlier eruptions.

The corona seems capable of explaining the distant gas clouds mentioned in Section III(a). Gas carried away from the galactic plane by magnetic and cosmic ray pressure will tend to form "prominences" as in the solar corona. Later this gas may fall back into a different part of the disk, being guided by the field lines. This would account for the relatively low velocity of the incoming gas and would remove the difficulty that accreted gas causes excessive loss of angular momentum (Oort 1969). Some observational evidence which is consistent with these various possibilities is the close association between some of the gas clouds and a radio loop (Meaburn 1965).

The coronal field model is capable of explaining the radio and X-ray haloes discussed in Section II(a), including their lack of north–south symmetry. The very large extent of the model allows the X-ray emission to be explained without invoking such a large cosmic ray flux as that of Hamilton and Francey (1969), thus providing greater stability.

The existence of an extensive and evolving corona may also resolve the difficulty that cosmic rays have a lifetime of only $\sim 10^6$ yr in the gaseous disk and yet show no observable anisotropy or change of flux over the past 10^9 yr (Meyer 1969). Storage in the corona also reduces the power requirement and raises the possibility that the cosmic rays observed near the Sun may have originated in a distant part of the disk such as the nucleus.

(e) *Galactic Spiral Arms or Pieces of Rings*

As seen above, HI in the galactic disk shows order of magnitude variations in surface density from place to place over the disk. Whether these are isolated blobs and elongated patches or parts of two tightly wound spiral arms, their origin is of interest and has provoked two main theories both of which describe the effects as wave phenomena.

The gravitational theory invokes a gravitational potential which rotates in the galactic plane in a spiral wave. It seems that if we are to explain density variations by factors > 10, then there must be corresponding velocity variations and corresponding enormous variations in gravitational potential. The *large and irregular potential field* must be provided by the stars and must operate equally on the stars, although its concentrating effect may be less drastic if the stars have larger random motions than the gas. Furthermore, the field must extend equally into the corona to affect the stars far above the gas sheet (see Fig. 2) and also to be provided by these same stars. It seems impossible that such a field, while causing drastic and irregular variations in gas surface density, could fail to wrinkle the thin flat sheet or to cause observable concentrations of the older stars.

The magnetic theory of twin spiral arms rejects the assumption made in the above theory: that magnetic forces and their effects are small compared with gravitational forces on a galactic scale. When we include motions perpendicular to the disk the reverse may be true. As seen in Figure 2 the value of B outside the disk is higher in the top right and bottom left sectors, and lower in the others. As the Galaxy rotates the changing field controls gas clumping and star formation by the magneto-gravitational mechanism of Parker (1968, 1969). The result is a distribution of new stars in two sectors which are then wound into two spirals (Piddington 1967, 1969).

While this model may explain the twin spiral pattern observed in some other galaxies, an extension may be necessary to explain the pieces of gas rings observed in the Galaxy. As seen in Section III(c) the disk may be divided into a series of rings in which B_ϕ is successively positive, zero, negative, and zero. In those rings where B_ϕ is zero the field cannot support the gas which must long ago have collapsed to a very thin layer and turned into stars.

IV. The Supernova Theory of Cosmic Rays

The most widely favoured theory of the origin of galactic cosmic rays is that involving supernovae or their remnants. This theory, together with several others, originated from simple energy considerations (see e.g. ter Haar 1950). It has received strong support from radio observations of supernova shells and remnant stars, attributed to synchrotron emission from fast electrons. If one accepts the disk model of the galactic magnetic field then the model provides a simple explanation of the apparent spread of cosmic rays throughout the Galaxy.

The radio evidence is examined in Subsection (a) below, and it appears that the sum total of emissions from all sources, including those postulated by the theory but too weak to be observed individually, falls far short of that observed as "galactic emission". Thus, as far at least as the electron component is concerned, the radio evidence is *opposed* to the supernova theory.

It is possible that cosmic rays escaped from the supernova ahead of the expanding shell and now provide the galactic radio emission and cosmic ray content. This possibility is examined in Subsection (b) below.

Finally, in Subsection (c) the possible advantages of the neutron star version of the theory are considered. These are, first that emission of cosmic rays is spread over a long period, and second that the electron component may lose more energy than the proton component before leaving the nebula, thus explaining the negative radio evidence of Subsection (*a*).

(*a*) *Radio Sources in Supernova Remnants*

Radio sources associated with supernova remnants have been studied by Kesteven (1968), Holden and Caswell (1969), Milne and Hill (1969), and others. Identification is on the basis of spectra, angular structure and size, and galactic latitude, and typically shows concentrations of fast electrons and/or magnetic field usually associated with shells but sometimes with central stars.

The absolute radio luminosities L of the major sources have been listed by Ginzburg and Syrovatskii (1964). First there are the young luminous sources Cas A ($L \sim 2\times10^{35}$ erg sec^{-1}, age 250 yr) and the Crab Nebula (corrected $L \sim 2\times10^{34}$ erg sec^{-1}, age 916 yr). Then there are 11 sources of intermediate age and brightness (average $L \sim 5\times10^{32}$ erg sec^{-1}). Since these lie within 1 kpc or so of the Sun there should be a total of ~ 100 of this type throughout the disk. Finally, since the supernova theory predicts a new source every 50 yr and a life of $\sim 10^6$ yr, there should be a class of $\sim 2\times10^4$ old sources that are too faint and too numerous to be observed individually.

It is easily seen that none of these classes provide total luminosity anything like the galactic total of $\sim 4\times10^{38}$ erg sec^{-1}. The old sources would require luminosities $\sim 2\times10^{34}$ erg sec^{-1}, whereas in fact they are at least 100 times weaker. The younger source classes fail by larger factors so that the radio sources provide evidence which, if anything, is contrary to the supernova theory.

It is usual to take the Crab Nebula as the prototype of cosmic ray sources, and in fact 2×10^4 such sources would provide the galactic emission. However, if the cosmic ray electrons were moved from the Crab field (3×10^{-4} G) to the galactic field (3×10^{-6} G) they would emit at a rate 10^{-4} times smaller. In addition there is the question of whether the electrons or other cosmic ray particles *can* escape from the magnetic field of the nebula before they suffer disastrous adiabatic losses. This problem is more acute in the neutron star version of the supernova theory, and so is discussed in Subsection (*c*) below.

(*b*) *Expanding Cosmic Ray Clouds*

The radio source data provide evidence against the supernova theory of cosmic rays unless it is possible that most of the cosmic rays escaped *ahead* of the expanding supernova shell at an early stage of its expansion and are now completely dissociated from the optical remnants.

A cloud of cosmic rays formed within a small volume and short period does not dissipate into the galactic magnetic field, as would a few particles. The cloud particles are diamagnetic and so capable of clearing a volume of all magnetic field. If W_{p} is the total particle energy, then the magnetic moment of the particles is W_{p}/B_0, where B_0 is the field strength. The demagnetized volume has characteristic radius R_{d}, where $R_{\mathrm{d}}^3 B_0 \sim W_{\mathrm{p}}/B_0$, so that a cloud of energy say 10^{47} erg can demagnetize a region $R_{\mathrm{d}} \sim 0\cdot1$ pc, $B_0 = 3\times10^{-6}$ G.

In the Galaxy the expansion of the cosmic ray cloud is controlled by the interstellar gas which is frozen into the field. The cloud expands as a more or less spherical bubble as shown in Figure 3, with a shock front advancing ahead of the bubble surface (piston). The particles inside the bubble tend to escape along the magnetic field lines but cannot move far because they generate hydromagnetic waves which scatter the particles (Wentzel 1969, where earlier references are given).

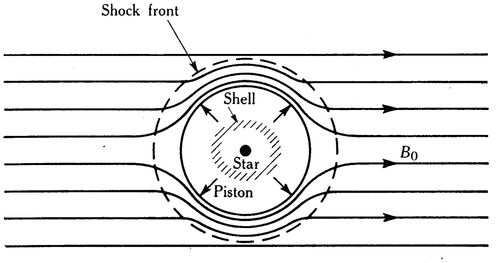

Fig. 3.—A cloud of relativistic particles released from the vicinity of an exploding star or magnetic neutron star acts as a piston, pushing back the interstellar gas and field and creating a shock wave. Behind this piston the supernova shell moves, first more slowly but eventually to overtake the piston and so create a radio shell source.

The expansion of a cosmic ray bubble has been considered by Khan and Woltjer (1967), whose concern was the amount of energy transferred to the external gas. During the early stages of expansion the cosmic rays move out more or less radially, accelerating the gas to velocity $\sim c$. When each relativistic particle has transferred momentum to the swept-up shell comparable with its initial momentum, then the cosmic rays are effectively scattered and adiabatic expansion commences. Hence the mass of the shell of radius R_0 must be about E_0/c^2, where E_0 is the initial energy of the bubble. At this stage the bubble has lost half its original energy and the radius is

$$R_0^3 \sim 3E_0(4\pi\rho_0 c^2)^{-1}, \tag{2}$$

where ρ_0 is the original mass density of the external gas. Putting $E_0 = 10^{51}$ erg and $\rho_0 = 2\times10^{-24}\,\mathrm{g\,cm^{-3}}$, we find $R_0 \sim 0\cdot1$ pc. Beyond this point the cosmic rays behave as a relativistic gas whose total energy decays inversely as the radius. Allowing for some loss up to the R_0 stage, the energy remaining when the radius has increased to say $10R_0 \sim 1$ pc is only a few per cent of the initial energy, and is decreasing. It seems likely that $\lesssim 10^{-2}$ of the original energy will escape from the bubble.

Instead the energy is transferred to the swept-up gas which becomes an *outer supernova shell* whose expansion rate decreases rapidly when the radius is of order 1 pc. Meanwhile the massive supernova shell, released behind the cosmic rays, expands unimpeded at a velocity of $\sim 6000\,\mathrm{km\,sec^{-1}}$ (type II supernova) and overtakes the outer, nearly stationary shell after a period of order 100 yr. A violent collision must follow between the two shells, their magnetic fields, and the remaining cosmic ray gas.

Although this swept-up shell plus ejected shell model does not appear to help explain the galactic cosmic rays, it may possibly explain the unexpectedly high radio luminosity and other curious features of type II supernovae. Many of these provide optical evidence of two shells, and the radio source Cas A seems to have a fast-moving shell of mass $\sim 2\,M_\odot$, a stationary shell of mass $\sim 1\,M_\odot$, and a jet extending beyond (Minkowski 1968). These features are usually attributed to two separately ejected massive shells, but the simultaneous emission of a bubble and shell appears more plausible in the first place, and their effects more easily explain the observations.

The bubble–shell model may also explain the radio emissions from type II supernova sources. According to Shklovskii's (1960) hypothesis the magnetic field and cosmic rays are all generated by the outburst and expand within the shell. In Van der Laan's (1962) model the particles are generated by the outburst and the field is due to a compression of the galactic field. Both meet difficulties: the former in explaining the origin of the field, and the latter in a failure to fit observational data (Kesteven 1968). The bubble–shell model may avoid these difficulties by utilizing the galactic field as well as any shell field, and also by accounting for some very large sources which have excessively high luminosities.

(c) *The Neutron Star Model*

The difficulty of explaining the escape of cosmic rays is inherent in the "explosion" form of the supernova theory of cosmic rays, and also the fact that such a rapid increase in the cosmic ray population would cause anisotropy and flux changes near the solar system, neither of which have been observed. Fenton (1969) has suggested that a neutron star supernova remnant might continue to accelerate cosmic rays for ~ 5000 yr at an average rate of $\sim 5\times10^{40}$ erg sec^{-1} for a total output of $\sim 10^{52}$ erg. The apparent advantages of this version are now considered.

If the magnetic neutron star is braked electromagnetically, then irrespective of the precise mechanism, which may be particle ejection (Goldreich and Julian 1969), dipole radiation (Gunn and Ostriker 1969), or hydromagnetic shocks (Piddington 1969), the rate of energy loss is given by

$$\mathrm{d}K/\mathrm{d}t = A\omega^4\,, \tag{3}$$

where A is a constant, $K = \frac{1}{2}I\omega^2$ is the kinetic energy, I being the moment of inertia, and ω is the angular velocity. Solving we find

$$\omega = \omega_0(1+\alpha t)^{-\frac{1}{2}}\,, \tag{4}$$

where ω_0 is the value of ω at the present time $t = 0$ (for the Crab Nebula $\omega_0 = 190$ sec^{-1}) and α is a constant. The braking rate is given by

$$\dot\omega = -\tfrac{1}{2}\alpha\omega_0(1+\alpha t)^{-3/2}\,, \tag{5}$$

which for the Crab is given roughly by $\alpha \sim (1000\text{ yr})^{-1}$. The available energy and power are given by

$$K = K_0(1+\alpha t)^{-1}\,, \qquad \dot K = -\alpha K_0(1+\alpha t)^{-2}\,, \tag{6}$$

where K_0 is the present energy and is $\sim 10^{49}$ erg for a star of mass $1\,M_\odot$ and radius 10^6 cm.

It is uncertain how far back these equations may be extrapolated before other energy sinks become important. However, if they are applied for times $-0\cdot900$, $-0\cdot990$, and $-0\cdot999$ of the age of the nebula, the corresponding values of K are 10^{50}, 10^{51}, and 10^{52} erg respectively. This means that if we started with 10^{52} erg as suggested, then 90% is dissipated after 10 yr and 99% after 100 yr. The rates of dissipation at the above times are 10^2, 10^4, and 10^6 times the present rate. Thus on a cosmic scale the event approximates an explosion, and the neutron star version seems to offer little advantage in this respect.

The Crab Nebula is usually cited as the prototype of this model because it is one of only two known supernova remnants which are also pulsars, and has been studied in far greater detail. According to the model $K_0 \sim 10^{49}$ erg, and much of this is being converted to cosmic radiation. However, it is doubtful if a significant proportion of this radiation will ever escape to join the galactic cosmic rays. The field is so strong ($\sim 3\times10^{-4}$ G) that electrons of energy $\gtrsim 10^{11}$ eV lose their energy by synchrotron emission within periods $\lesssim 100$ yr. If there is a comparable nucleon component this is firmly trapped within the field and shell. The diffusion time exceeds 10^6 yr for particles of energy 10^{11} eV, even assuming the maximum rate of diffusion provided by inhomogeneities of size just equal to the cyclotron radius. Some cosmic ray gas may escape by the Rayleigh–Taylor instability, but the smooth contours of radio and optical brightness and polarization (Johnson and Hobbs 1969; Piddington 1969) suggest that such eruptions are not significant.

When we consider the period back to $-0\cdot900$ of the lifetime, the model meets greater difficulties. A full analysis would be too lengthy but these difficulties may be indicated. The magnetic field strength then was greater and cosmic rays able to survive synchrotron losses would remain trapped. An upper limit to the energy of this cosmic ray gas is set by the acceleration of the shell (Piddington 1957) observed by Baade and determined more accurately by Trimble (1968). Most of the gas and field energy would be transferred to the shell, and the shell must have mass $> 10\,M_\odot$ in order to absorb 10^{50} erg and limit its velocity to 10^8 cm sec^{-1} as observed. This is much greater than the estimated mass, and if we extrapolate to yet earlier periods the difficulties increase further.

We conclude that only an insignificant part of the Crab cosmic radiation has escaped or is likely to escape from the nebula to contribute to the galactic cosmic radiation.

V. Acceleration in the Galactic Nucleus

The notable concentration of radio synchrotron emission towards the centres of many spiral galaxies including the Galaxy, the remarkable activity in many central systems including our own, and the many difficulties met by the supernova theory all suggest a nuclear source of cosmic rays. A nuclear source provided by a series of explosions (Ginzburg and Syrovatskii 1967) meets some of the difficulties of the supernova theory, and so we consider here the possibility of continuous emission from a massive magnetic rotator. The discussion is brief because many features of the model have been described already (Piddington 1967, 1969, 1970).

(a) *A Galactic Magnetic Rotator*

The synchrotron emissions from the galactic central region reveal the presence of a magnetic field and cosmic ray concentration. The angular rotation rate within 100 pc of the centre exceeds that near the Sun by a factor > 100 and it is likely that at some period the differential rotation rate was correspondingly higher. If this were the case, then according to equation (1) the original field would have been amplified by a factor ~ 3000 in a period of 10^9 yr. At the same time the field components B_r and B_z would have been increased by a large factor due to contraction of the gas cloud.

It has been shown that near the centre, where the product of the radial distance r and the radial field component B_r must increase with r, the gas is magnetically braked and contracts inwards. Further away from the centre, where $\partial(rB_r)/\partial r < 0$, the angular momentum increases with time and the gas moves outwards to separate from the fast spinning central cloud. The latter with its compressed field becomes a magnetic rotator and cosmic ray accelerator. The model rotator is shown in Figure 4 in a section through the rotational axis $\boldsymbol{\omega}$. The components B_r and B_z although smaller than B_ϕ cause some obliquity in the mainly toroidal field B_{t} as shown. The central cloud and expelled ring are connected through a disk field B_{d} which, in the absence of sufficient restraining gas, is likely to expand into a coronal field. The cloud field will also erupt by the Rayleigh–Taylor instability to provide a poloidal field B_{p}.

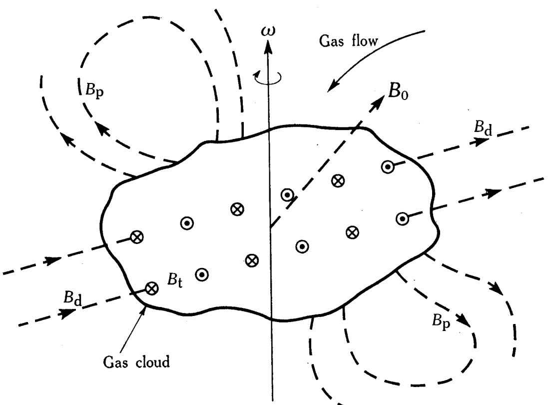

Fig. 4.—Galactic nucleus as a magnetic rotator. Differential rotation within the cloud of gas and stars winds the oblique field $\boldsymbol{B}_0$ into a spiral, nearly toroidal field B_{t}. Rayleigh–Taylor eruptions create loops of an external poloidal field B_{p} leading to cosmic ray acceleration.

The model converts gravitational energy to kinetic and magnetic energy, and then in part to cosmic ray energy. We assume a total requirement of 10^{41} erg sec^{-1} for 3×10^9 yr, or 10^{58} erg, which equals that of some radio galaxies. The gravitational energy Ω released by a cloud of radius R and mass M is

$$\Omega \sim GM^2R^{-1}, \tag{7}$$

where G is the gravitational constant, and some reduction is required if some of the gas has formed stars. The above requirement is met by such combinations as

$$M = 10^6\,M_\odot, \quad R = 3\times10^{13}\,\mathrm{cm}, \quad T = 3\times10^{-3}\,\mathrm{yr}, \quad \rho = 0{\cdot}02\,\mathrm{g\,cm^{-3}},$$

$$M = 10^8\,M_\odot, \quad R = 3\times10^{17}\,\mathrm{cm}, \quad T = 300\,\mathrm{yr}, \quad \rho = 2\times10^{-12}\,\mathrm{g\,cm^{-3}},$$

where T is the rotation period and ρ is the average gas density. In the more massive of these clouds the density is $\sim 10^{10}$ times that near the solar system (including the stellar contribution), indicating a linear contraction by a factor of $\sim 2\times10^3$ and an increase in field strength due to compression by 4×10^6. If we also allow a factor of $\sim 10^2$ for faster winding, fields $\gtrsim 10^3$ G are possible.

A requirement is support of the gas cloud against collapse into a thin sheet. This may be provided by the toroidal field B_t, the strength required being $\sim 10^3$ G in the massive cloud. The magnetic forces in the plane perpendicular to $\boldsymbol{\omega}$ mainly cancel, and support is by rotation as in most of the Galaxy. Such a strong field would brake the cloud within a rotation if it exerted maximum torque. It cannot do so, however, because the gap field must dissipate into the corona and disconnect the cloud from the expelled ring.

Eventually the cloud may contract within the Schwarzschild limit $R_S = 2GMc^{-2}$ and shrink to a singularity. At this stage it seems likely that the gas will disconnect from the field and cease to operate as a magnetic rotator.

(*b*) *Comparison with Observations*

An estimate of the mass of the galactic central region must depend on rotation rates given by HI and OH line measurements. The former (Rougoor 1964) show a central region of width too small to be resolved by the radio beam (radius $\lesssim 50$ pc) with gas velocities ranging beyond 200 km sec^{-1}. If these are mainly rotational, then a central mass of $\sim 5 \times 10^8 M_\odot$ is required. How much of this is concentrated in a rotator of $R < 1$ pc cannot be determined because of the low HI luminosity and very large velocity spread in such an object. However, a mass as large as $\sim 10^8 M_\odot$ seems possible.

In arguing for such a large central mass one notes first that on the basis of disk area the mass density within the 50 pc disk is already some 10^3 times that of the whole Galaxy. This is probably caused by magnetic braking and this is likely to be more effective at smaller radial distances so that a concentrated gas mass is theoretically possible. Similarly, stars forming a compact cloud also tend to develop a nucleus (Spitzer 1969). Second, there is the evidence of the synchrotron sources (Section (II*c*)) of radii $\lesssim 5$ pc indicating the presence of a strong field and probably violent motions. If these are to continue without exploding the nucleus, then a large mass is required. Finally, we have the evidence of the various rotating and expanding gas rings and clouds extending out to 4 kpc. These could hardly have resulted from a central explosion as this would not account for the large angular momentum of the gas. However, they could develop as a result of magnetic torque as discussed above. Their angular momentum is equal to that of a mass a few times $10^8 M_\odot$ at a radial distance of 300 pc, and it is possible that in the past they derived their angular momentum from such a mass. If so, then it must have moved inwards to much lower Keplerian orbits to provide nuclear mass of this order.

The radio source Sgr A and the infrared emission might be explained by a massive magnetic rotator. Alternative theories based on one or more explosions face the difficulties of the supernova theory of such sources.

Two other observed phenomena appear to support the oblique rotator model. The first (for a summary of both see Oort 1968) is HI gas moving away from the galactic centre in opposite directions at a large angle to the galactic plane. It is difficult to envisage an origin in a central explosion or in some gravitational anomaly, but the rotator with a tilted poloidal field might well cause such an effect. The second phenomenon is a "ridge" of radio synchrotron emission similarly tilted and extending ~ 200 pc in the same quadrants. This effect might well be a direct manifestation of the poloidal field B_p of Figure 4.

(c) *Cosmic Ray Acceleration and Bulk Motions*

Cosmic rays will be accelerated by the magnetic rotator of Figure 4 in a number of ways which have been mentioned previously (Piddington 1967, 1969, 1970). First, we have acceleration in magnetic neutral sheets which must develop between oppositely directed spiral fields as these are wound more and more tightly.

Second, we have the various mechanisms of particle acceleration which have been proposed in connection with the pulsars. The simplest quantitative discussion starts with the emission of electromagnetic waves of frequency ω by the rotating poloidal field. These waves interact with the surrounding plasma and field to provide cosmic rays, the maximum available power being

$$P = Q^2\omega^4c^{-2}, \tag{8}$$

where Q is the magnetic moment given by $Q \sim R^3B_{\rm p}$. For an energy requirement of 10^{41} erg sec^{-1}, it is found that the rotators of masses $10^8 M_\odot$ and $10^6 M_\odot$ require surface fields of 120 and $1 \cdot 2 \times 10^4$ G respectively. Both of these values appear quite reasonable.

One of the pulsar mechanisms provides most of its energy in the form of hydromagnetic compression waves which radiate away from the star. These waves alternately compress and expand the magnetic field far from the star and so accelerate existing cosmic rays to higher energies by the method of magnetic pumping (Alfvén and Fälthammar 1963, p. 64). There is little doubt that this occurs in the Crab Nebula where cosmic ray electrons far from the central star emit X-rays. These electrons have lives of only months and could not have moved so far from the star; they must be accelerated and radiate *in situ*. We envisage the same mechanism providing magnetic pumping throughout the galactic corona and so raising the energy of all the particles there at the rate needed to replace lost particles. The mechanism has the great advantage that cosmic rays need not diffuse or move in other ways outwards from the central region.

The effectiveness of large-scale hydromagnetic waves in accelerating cosmic rays has been investigated by Kulsrud and Pearce (1969). They find that, within the disk, waves of length ~ 1 pc have little effect. The situation in the *corona*, particularly for waves of frequency $\gtrsim 100$ times greater as envisaged here, is very different. In fact, the substitution of the new quantities into their equation (82) shows that cosmic ray acceleration by magnetic pumping is likely to be important.

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