PROPAGATION AND DISTRIBUTION OF COSMIC RAYS IN THE GALAXY

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INTRODUCTION :

Although cosmic rays were discovered more than 50 years ago a definite answer to the problem of the origin of the bulk of them has yet to be found. Strong opinions are expressed on the virtues of galactic and universal models of origin (Ginzburg 1975, Burbridge 1975). As far as the dynamics of the Galaxy are concerned the total pressure exerted by the cosmic ray flux is comparable to that of the interstellar gas and the galactic magnetic field and therefore plays an important role. With regard to total energy requirements a galactic origin in supernovae and their associated pulsars and young remnants is attractive. Concerning the electron component, which has an intensity about 1% of the total there is direct evidence for its acceleration in such sources and the existence of 2.7K background radiation in any case precludes an extragalactic origin

In this paper a brief review is given of the properties of the nuclear cosmic ray flux observed at the earth and the question is discussed of whether these properties can be reconciled with the hypothesis of a galactic origin through physically reasonable models of galactic propagation . Some recent interpretations of the evidence on the distribution of the nuclear and electron components throughout the Galaxy are then described.

It must be stressed that, although the energy spectrum of cosmic rays is known to extend to 10^{20}eV, about 99% of the total energy is carried by particles with energies between 10^8eV and 10^{12}eV. It is with these 'low' energy particles that this article is mainly concerned.

OBSERVED PROPERTIES OF THE COSMIC RAY FLUX AT THE EARTH :

A brief summary is given here of the observed properties of the cosmic ray flux that bear on propagation in the Galaxy.

(a) Anisotropy :—

An anisotropy of the primary cosmic ray flux with respect to the Galaxy is observed on earth as a sidereal variation of the secondary particle intensity. The Peak Musala experiment (Gombosi et al. 1975) gives an anisotropy of 1.3 x 10^{-3} significant at a confidence level of 0.7% for air showers corresponding to a mean primary energy of 6 x 10^{18}eV. The upper limit to the anisotropy increases slowly with energy from this point reaching 10^{-2} at 10^{17}eV (Lapikens et al. 1971). It is not clear whether this increase is due solely to the poorer statistics at successively higher energies. At lower energies the diluting effects of the interplanetary field become important and below 10^{11} eV the galactic anisotropy cannot be measured. The oft quoted anistropy of 2 x 10^{-4} at an energy of 1.5 x 10^{11}eV (Elliot et al. 1970) has now been revised to 1.7 x 10^{-3} (Marsden et al. 1976) following the acquisition of further data and a reanalysis of the effects of the interplanetary field. One concludes that in the range 10^{11} to 10^{14} eV the anisotropy is in the region of 10^{-3} corresponding to a streaming velocity of cosmic rays of about 100 km s^{-1}.

(b) Age of Cosmic Rays :—

The total amount of matter traversed by the cosmic rays between their source and the earth can be deduced from the proportion of secondary Li, Be and B and nuclei with $17 < z < 25$ in the flux. The composition observed at about 10^9eV/nucleon indicates an approximately exponential distribution of this 'grammage' with a mean of 6 g cm^{-2}. Recent experiments (Ramaty et al. 1973) show that the grammage is decreasing with energy: at 4×10^{10}eV/nucleon the grammage is 2.5 ± 1.5 g cm^{-2}. This indicates a travel time of 1.5 x 10^6 yr if all the grammage is traversed in an interstellar medium of effective mean density 1 nucleon cm^{-3} as found in the galactic disk. If the cosmic rays are confined to a quasi-spherical halo however the travel time to accumulate such a grammage would be up to 10^8 yr. A direct determination of the age of cosmic rays can, in principle, be made from the relative abundance of radioactive ^{10}Be (mean life 2.2 x 10^6 yr) in the flux. Weber et al. (1973) have obtained an estimate of 3 x 10^6 to 10^7 yr at about 10^9eV /nucleon favouring a disk confinement model. Other observations are consistent, however, with a greater age. Garcia Munoz et al. (1975) obtain a most probable age of 2 x 10^7 yr.

(c) Constancy of the Cosmic Ray Flux :—

Measured abundances of radioactive isotopes in meteorites show that the present day value of the flux of 10^9 to 10^{10} eV cosmic rays is within a factor of two of the flux averaged over the last 10^5 to 10^7 yr (Geiss 1963).

PROPAGATION OF COSMIC RAYS :

It is apparent that the galactic magnetic field must regulate the propagation of the particles and their escape from the Galaxy if the above observations are to be reconciled with a galactic origin. Ones direct knowledge of the detailed structure of this magnetic field is poor, however, and the best approach is to evaluate the constraints imposed by the properties of the cosmic rays and to see whether they are consistent with theoretical expectations for the field.

(a) Three-Dimensional Diffusion :—

It can be argued that cosmic ray propagation approximates to 3-dimensional diffusion (ssee for example Ginzburg and Syrovatskii, 1964). The general equation for the concentration of cosmic rays, $N(r, t, E)$ as a function of space, time and enrgy is then

$$\frac{\partial N}{\partial t} - \nabla \cdot (D \nabla N) + \frac{\partial}{\partial E}\left(\frac{\partial E}{\partial t} N\right) + \frac{N}{T} = Q(r, t, E) \quad (1)$$

For 3 -dimensional isotropic diffusion the diffusion coefficient $D = \lambda c/3$ where the diffusion mean free path λ may vary with energy. The third term takes into account energy loss during propagation which may be neglected for nuclei. For elctrons $\frac{\partial E}{\partial t} = bE^2$ due to synchrotron losses and inverse compton interactions with the stellar and 2.7K radiation fields. In the fourth term $1/T = 1/T_c + 1/T_e$. For nuclei T_c is the collision loss time to be usedin the calculation of the production of secondary nuclei by spallation. For electrons it is the mean time for their removal by bremsstrahlung interactions which can be regarded as catastrophic. T_e is a characteristic escape time of cosmic rays from the Galaxy. This has sometimes been used instead of taking a spatial boundary to the Galaxy at which particles emerge. The approximation is valid, within the accuracy of experimental data, when calculating the distribution of spallation products or the relation between the source spectrum and observed spectrum of elctrons. It connot be used, for instance, to obtain a value for the anisotropy of cosmic rays. $Q(r, t, E)$ is the source function which may be a δ-function in space and time corresponding to the production of cosmic rays in discrete events such as supernova explosions. The observed electron spectrum should steepen around a critical energy $E_{crit} = 1 / bTe$ beyond which energy losses dominate escape. Most, but not all, measurements indicate that the spectrum does not steepen between 5 and 300 GeV so that T_e is either greater tnan about 10^8 yr or less than 10^6 yr In the early 1960's it was generally accepted that radio observations indicated the existence of a spherical galctic halo of radius $R \sim 15$ kpc filled with relativistic electrons. The proton component would occupy the same volume. For cosmic ray production in the disk and free escape from the halo boundaries the escape time would be $\tau = R^2/2\lambda c$. For $\lambda = 10$ pc, an observed scale of magnetic field inhomogeneities, this gives $\tau = 3 \times 10^7$ yr consistent with the measured grammage. The sun is sufficiently close to the plane of symmetry of this system to account also for the low anisotropy. More detailed radio observations have, however, led to a reinterpretation in that a large proportion of high latitude synchrotron emission comes from relatively nearby, much expanded supernova remnants, with possibly a radio disk of half thickness 500 pc.

For a disk confinement region extending a distance h on either side of the galactic plane and with free escape from the boundaries the escape time would be $\tau = h^2 / \lambda c$. With $\lambda = 10$pc as before and $h \approx 100$pc, corresponding to the thickness of the gaseous disk the escape time is only $\sim$300 yr. To obtain the observed grammage $\lambda < 0.1$ pc is required. Also with $\lambda < 0.1$ pc, unless the earth was very symmetrically placed with respect to the source distribution the anisotropy would be too large. With $h = 500$ pc corresponding to the suggested 'radio disk' the required mean free path is still much shorter than 10 pc.

(b) **One-dimensional Diffusion :—**

Cosmic rays reaching the earth will, to some extent be bound to the galactic magnetic field lines passing within one gyroradius of the earth and the effect on the flow of cosmic rays must be considered. The concept of 3-dimensional diffusion may indeed have to be abandoned in favour of 1-dimensional diffusion along field lines unless the rate of separation of adjacent field lines is high.

The configuration of the field line intersecting the earth is not known but a probability distribution for its length between points sufficiently far from the galactic plane that cosmic rays can cause a bubble instability and escape can be calculated from the observed turbulent motion of the gas. Dickinson and Osborne (1974) have taken instantaneous sources randomly distributed in space and studied how, at a fixed point on a line of given length, the properties of the cosmic ray flux (concentration, mean age, and anisotropy) vary with time. An example is given in Figure 1. For given values of the 1-dimensional diffusion mean free path one may then calculate for what fraction of time the anisotropy is not greater than that observed and judge how reasonable is the value of mean free path. A value has to be adopted for the average time interval between sources on a given field line. If the sources are supernovae which release cosmic rays into galactic field lines when their radii reach 15pc then (time interval) x (field line length) $= 4 \times 10^6$ yr kpc. To find the overall probability of observing a given anisotropy the field line length distribution has to be folded in. For example the fraction of the time when the anisotropy is $\angle 10^{-3}$ would be 0.04, 0.16 and 0.43 for mean free paths of 10pc, 3pc and 1pc respectively.

(c) **Compound Diffusion :—**

Thus for either 3-dimensional or 1-dimensional diffusion in a disk confinement region a mean free path < 1pc is required to account for the low streaming velocity. Lingenfelter et al. (1971) introduced the concept of compound diffusion in order to obtain these low velocities with values of λ consistent with the observed field irregularities. The cosmic rays are taken to remain on their field line where they propagate by 1-dimensional diffusion, with mean free path λ_p, due to scattering from minor irregularities while the field lines experience 3-dimensional random walk with a step size λ_m. The result is that the net displacement of particles is proportional to $t^{\frac{1}{4}}$ rather than $t^{\frac{1}{2}}$ as in simple diffusion and anisotropies $\delta \approx 10^{-4}$ can be obtained with $\lambda_p \approx \lambda_m \approx 30$pc. There are strong objections to this concept, however. The anisotropy is low in spite of the long mean free path because it is effectively the 'macro-anisotropy' resulting from the averaging of 'micro-anisotropies' over many field lines. If 1-dimensional diffusion is to hold, adjacent field lines must have the geometry of flux tubes at least one gyroradius wide. Although the sun is moving with respect to the interstellar medium its velocity is such that, even in several years, it will not move accross the magnetic field a distance corresponding to the gyroradius of 10^{11} eV particles. Thus the anisotropy observed at the earth would be the larger micro-anisortropy on the field line passing through the earth as discussed in the previous section.

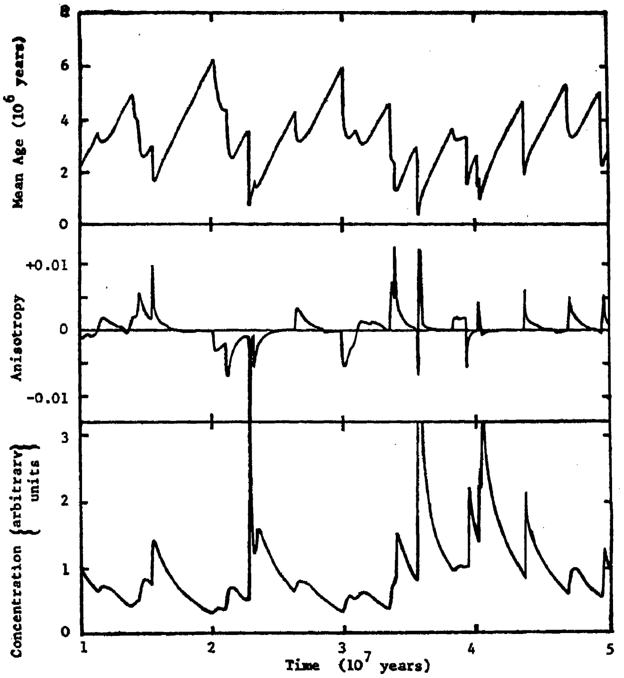

Fig.1 An example of the calculated time variation of the mean age, anisotropy and concentration of cosmic rays at the mid-point of a field line having a length 3 kpc in the disk.

(d) Separation of Field Lines : —

The necessary short mean free path appears to show that the cosmic rays are scattered not only by large scale irregularities in the field but also by hydromagnetic waves in the interstellar medium. The reversal of the particle's direction due to these will be the net result of many small pitch angle scatterings, and in reversing its direction the particle will move, on average, one gyroradius across the field (Skilling 1970). If, after tne sideways step the new field line remains parallel to the old one then effectively one has 1-dimensional diffusion. If field lines, initially one gyroradius apart, separate repidly one must abandon this concept.

The rate of separation of field lines, caused by the background spectrum of interstellar turbulence, has been considered by Skilling et al (1974) for a Kolmogorov spectrum of wave intensity. They find that if the initial separation is equal to the gyroradius of a 10^{12}eV proton a distance of 31 pc along a line leads to a separation of ~ 30 pc ; if the inital speparation is the gyrorodius of a 10^{9} eV proton only an additonal 3 pc distance required.

These results imply that at the earth we may, after all, be observing particles reaching us along a number of essentially independent field lines. However, the concept of 1-dimensional diffusion along these lines also breaks down and compound diffusion still does not apply.

(e) Selfconfinement of Cosmic Rays :—

The low streaming velocity of cosmic rays implies the existence of hydromagentic waves in the interstellar medium. Resonant scattering will occur on waves having wavelengths a few times the gyroradius. The mean free path for reversal of the direction of the particle will be approximately equal to the gyroradius multiplied by the ratio of the energy density in the ambient galactic magnetic field to the energy density in the waves causing the scattering. Wentzel (1968) and Kulsrud and Pearce (1969) have shown how the required waves may originate. When cosmic ray particles stream down their density gradient with a streaming velocity V_S greater then the Alfven velocity V_A an instability exists which generates waves. Thus the cosmic rays themselves produce the waves which scatter them. The growth rate of the waves that resonate with particles of energy E is

$$\Gamma_G = \frac{eB}{2\pi^{\frac{1}{2}} M_H c} \; \frac{N(>E)}{n_i} \left[\frac{V_s}{V_A} - \frac{\gamma + 2}{3} \right] \qquad (2)$$

where the differential energy spectrum of cosmic rays is taken as a power law of index-γ, B is the ambient magnetic field, N (>E) is the number density of cosmic rays of energy >E and n_i is the number density of ions in the interstellar medium. The Alfven velocity $V_A = B/(4\pi \rho_i)^{\frac{1}{2}}$ where ρ_i is the ionised gas density. In the galactic plane $V_A \approx 70$ km s^{-1} . The authors considered damping of ths waves due only to collisions between charged particlee moving with the waves and neutral atoms. The damping rate is then

$$\Gamma_D = G n_H \qquad (3)$$

where n_H is the density of the neutral gas and the constant G depends on its temperature. The equilibrium streaming velocity is obtained by equating (2) and (3). For the bulk of the cosmic rays, i.e. those with energy of a few GeV, their number density is such that they would stream little faster than 1.5 x V_A .

For the particles of several hundred GeV, of which the low streaming velocity is actually observed, there are problems with this self-confinement mechanism. Because of the sharply falling energy spectrum, these high energy cosmic rays do not have a number density sufficient to produce a strong instability and they can therefore stream very much faster than the Alfven velocity contrary to observation. This is certainly true in the galactic plane but Skilling (1971) and Holmes (1974a) have pointed out that, because n_i and n_H decrease with height above the plane, the growth rate of the waves increases while their damping rate decreases. Cosmic rays of energy greater than a few GeV need only travel a certain distance away from the galactic plane before they reach a region of strong scattering. Skilling has labelled the region close to the galactic plane where there is essentially no scattering the 'free zone' and the region of strong scattering the 'wave zone'. At the boundary only a fraction $\backsim V_A$ / c of the incident particles can be transmitted. Thus it is proposed that there exists reflecting boundaries on either side of the galactic plane at a height which increases with energy. Holmes has shown how this not only saves the self-confinement mechanism but naturally leads to a grammage that decreases with energy.

A complication of the picture of self-confinement involves the additional non-linear damping of the waves due to wave-wave interactions. The damping does not depend on the gas density and its effect, to a first approximation is not to alter the boundary height but to increase the streaming velocity in the wave zone. This in turn increases the transmission probability and reduces es the grammage. Holmes (1974b) shows that agreement with the observed grammage can still be obtained. There is some doubt, however, whether the streaming velocity from the galaxy can be kept sufficiently low beyond 100 GeV.

It is appropriate at this point to comment on the an isotropy reported by Marsden et al (1976). The streaming is from the direction of galactic longitude $l = 270°$. The authors suggest that this is evidence for a net inflow of particles along the local spiral arm indicating that cosmic rays of these energies are of extragalactic orgin. Osborne et al (1976) have shown that an alternative explanation lies in production of particles in the Vela supernova explosion. The sun and the Vela supernova would both lie in a 'free zone' region near the galactic plane and a diffusion mean free path of 7 pc due to the field line wandering would account for both the observed anisotropy and an excess of galactic gamma-ray emission from a region around the remnant.

DISTRIBUTION OF COSMIC RAYS THROUGHOUT THE GALAXY :

In addition to the properties of the cosmic ray flux at the earth there are observations allowing one to draw some conclusions about the distribution of 10^9 to 10^{10} eV cosmic rays throughout the Galaxy which has a bearing on cosmic ray propagation. The distribution of non-thermal radio continuum at around 100 MHz relates to the electron distribution while the distribution of gamma-rays with energies $> 10^8$ eV relates to the distribution of nuclear particles. There are however problems in the interpretation relating to uncertainties in the distribution in the Galaxy of magnetic field and gas respectively.

(a) Distribution of Electrons :—

From observations of the non-thermal continuum one does not obtain values of the electron density and magnetic field at discrete points in the Galaxy, rather one obtains the integral along the line of sight ds at a particular galactic longitude l, $\int \mathrm{Ne}\,(R, l) B_{\perp}^{\,(\Upsilon + 1)/2}\,(R, l)\,ds$ where R is the galactocentric radius, N_e is the electron density and B is the component of the galactic magnetic field perpendicular to the line of sight. The power $\Upsilon \approx 2.6$ is the slope of the electron energy spectrum in the appropriate energy region. Reasonable functional forms for N_e and $B_\perp$ have to be chosen and tests can then be made to see which best fits the data. The conductivity of the interstellar medium is such that the magnetic flux is frozen in to the gas and one expects that on the large scale the galactic magnetic field runs along the direction of galactic rotation and undergoes compression and rarefaction in proportion to that of the gas. A model of galactic spiral structure is therefore required to interpret the synchrotron radiation distribution. Previous workers have used models of spiral structure from the 21 cm hydrogen line observations. Within the solar circle there are difficulties in unambiguously interpreting the 21 cm data and a semi-empirical 2-armed spiral model based on density-wave theory Lin Shu (1967) has been used. The galactic plane profiles of synchrotron emission predicted from these regular 2-armed spirals give overall agreement with observation but do not agree in detail with the positions and magnitudes of the features. In a recent paper Osborne and French (1976) use a new composite model of galactic structure. For $R < 10$ kpc the pattern derived by Georgelin and Georgelin (1976) from optical and radio observations of HII regions is adopted . This has a 4-arm structure with the sun in a local feature rather than a major spiral arm. For $R > 10$ kpc, where there is no distance ambiguity, the map of atomic hydrogen of Verschuur (1973) is used. The region within $R = 4$ kpc is not considered.

An overall gaussian radical dependence of the field strength of the form exp $(-(R/R_0)^2)$ is assumed but R_0 is left as a free parameter since there is no information on this other than the synchrotron profile itself. The field strength is modulated between the arm and interarm regions by a factor of five to one in line with density wave theory. A second free parameter is the ratio of regular to irregular field strength F, the galactic field being taken as the superposition of a regular field running along the direction of galactic rotation and an isotropically random irregular field. Observations of the field within a few kiloparsecs of the sun suggest that F is approximately unity. With these free parameters for the field two different forms of the electron distribution were adopted to see whether they could be distinguished. In the first the density was taken to be constant out to R=15 kpc. This would correspond to weak scattering and easy propagation of cosmic rays in the 1-10 GeV range close to the plane of the Galaxy in both arm and interarm regions. In the second case the electron density was taken to vary as the square of the gas density and hence as the square of the magnetic field. Simple proportionality would be expected if the cosmic rays are strongly scattered and compressed with the gas but as an extreme case some allowance is made for Fermi acceleration and an increased incidence of sources in regions of compression.

Figure 2 shows the comparison of the profiles predicted by the two models and the observed profile. The latter is taken from the map of Landecker and Wielebinski (1970) at 150 MHz when subtractions have been made for a thermal contribution, the extragalactic background and local loops and spurs. The dashed portions near $l = 264°$ and 80° are due to the Vela supernova remnant and the Cygnus X source complex respectively. The former must be included when studying the large-scale structure of the Galaxy but the latter may be partly due to viewing a local spiral feature tangentially. Figure 2b is the profle for the uniform electron distribution with $R^2_0 = 125$ kpc^2 and $F = 1.1$. Figure 2a shows the profile for the elctron density proportional to B^2. Here the optimum values of the free parmeters are $R^2_0 = 310$ kpc and $F = 1.25$.

One can see that there is a marginally better fit for the uniformly distributed electrons in Figure 2(b). The overall radial decrease of field strength has to be faster in this case but there is no independent information to contradict this.

(b) Distribution of Cosmic Ray Nuclei :—

The data from the SASII statellite (Fichtel et al. 1975) give line of sight integrals of the gamma-ray emissivity of the Galaxy. Assuming axial symmetry as an approximation the galactic plane profile can be unfolded to give the radial dependence of emissivity (Strong 1975). If the majority of these gamma-rays are from the decay of neutral pions produced in the interaction of cosmic ray nucle with the interstellar gas the emissivity is proportional to the product of gas density and cosmic ray intensity. The gamma-ray emissivity rises to a peak at $R = 5$ kpc that could not be accounted for by a uniform distribution of cosmic rays and the distribution of neutral atomic hydrogen deduced from 21 cm line observations. The implied peaking of the cosmic ray distribution was taken as a strong indication that cosmic rays are of galactic origin (Dodds et al. 1975). A reinterpretation was demanded when it was discovered that there is a very significant proportion of molecular hydrogen in the inner parts of the Galaxy (Scoville and Solomon 1975). The radial distributions of molecular hydrogen and gamma-ray emissivity show a very strong correlation. The molecular hydrogen is not observed directly, however. Its distribution is derived from that of CO molecules with which it is closely associated but there is an uncertainty of a factor of three in the absolute density of the hydrogen. The upper limit to the density would give a gamma-ray distribution close to that observed from the inner parts of the Galaxy assuming a uniform distribution of cosmic rays. Stecker et al. (1975) show, however, that a better detailed fit to the gamma-ray distibution is obtained if the cosmic ray intensity rises to twice the local value at R = 5 kpc and its distribution is similar to that of supernovae. An increase in proportion to total gas density is ruled out. The need for any increase is lessened if, as seems possible, there is a significant contribution to the gamma-ray emissivity from the inner parts of the Galaxy due to unresolved pulsars (Higdon and Lingefelter 1976).

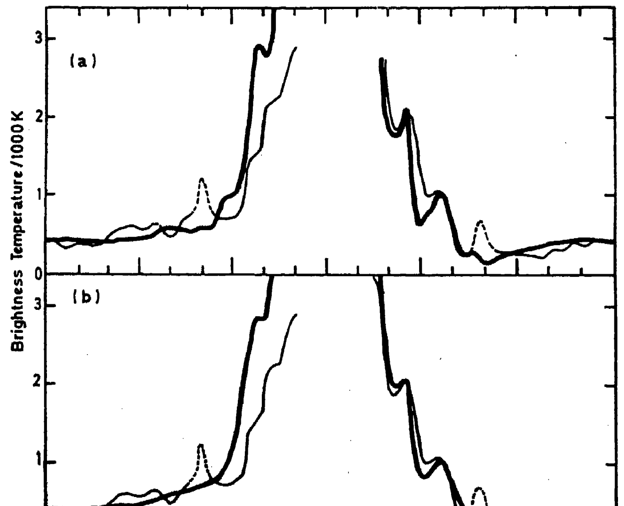

Fig. 2 Profiles of the 150 MHz synchrotron emission along the galactic plane. Thin lines show the observed emission. Thick lines are the predictions for density of relativistic electrons a) proportional to the square of the magnetic field b) uniform throughout the Galaxy.

The distribution of gamma-rays about the galactic anticentre direction has a much less ambiguous interpretation. Dodds et al. (1976) have used the neutral atomic hydrogen distribution observed from 21 cm data to predict the latitude distribution of gamma rays around the anticentre for galactic and extragalactic hypotheses of cosmic ray origin. Their results are shown in figure 3. The 'extragalactic' curves assume that the cosmic ray intensity is everywhere uniform at its local value. The 'galactic' cur-es are the predictions for a cosmic ray intensity falling off as $\exp - \left[\frac{R-10}{2.44} \right]$ from its local value at R = 10kpc. The extragalactic hypothesis gives twice the observed gamma ray intensity. Outside the solar radius any contribution from molecular hydrogen would be small but would strengthen this result.

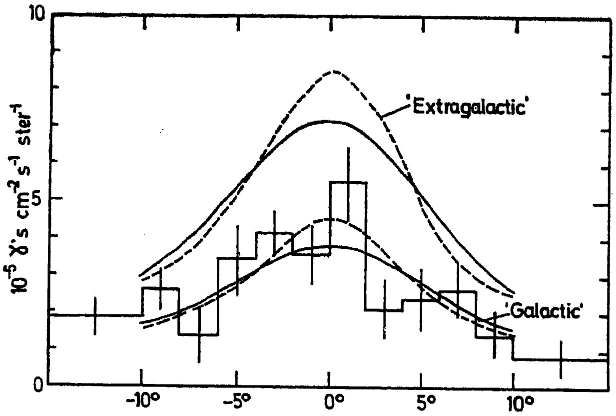

Fig.3 Latitude distributions of gamma-ray intensity around the anticentre direction (Dodds et al. 1976). The SAS -II data are compared with the predictions for 'Galactic' and 'extragalactic' models. Dashed lines are the predictions not allowing for finite angular resolution of the detector; solid lines include this.

CONCLUSIONS :

The gamma-ray observations in the galactic anticentre region rule out a universal origin of cosmic rays in the 1 to 10 GeV energy range. In the inner parts of the Galaxy a moderate increase in the intensity of cosmic ray nuclei is suggested but is not definitely required by the gamma-ray data. The radial distribution of cosmic ray electrons is more uncertain because of the strong dependence of the emissivity on the magnetic field strength, on the radial dependence of which there is no independent information. A constant ratio of electrons to nuclei over the Galaxy for R>4 kpc would be consistent with the data. An important point from the the analysis of French and Osborne (1976) is that the 3μG galactic magnetic field strength observed in the the vicinity of the sun must be typical of an interarm region, rather than an arm region in order to explain the absolute intensity of the synchrotron radiation from the Galaxy.

In a recent paper Paul et al. (1976) claim that there is an observational support for a simple relationship throughout the Galaxy between the cosmic ray nuclear and electron concentrations Np and N_e, the galactic magnetic field strength B and the total (molecular and and atomic) gas density ρ_T such that

$$N_e \propto Np \propto B^2 \propto \rho_T$$

Since this relation, if correct, would have very important implications concerning the production of cosmic rays- and the dynamics of the Galaxy a critical examination of this observational support is appropriate here. Firstly (t is claimed that there is a close similarity between the profiles along the galactic plane of the gamma-ray and synchrotron radiation distributions. This would imply that $Np\ \rho_T \propto N_e\ B^{(\gamma+1)/2}$. Under the reasonable assumption that $N_p \propto N_e$ this gives $\rho_T \propto B^{(\gamma + 1)/2}$ or, approximating γ to 3, $\rho_T \propto B^2$. A comparison of the synchrotron profile of Paul et al. and that given in figure 3 shows marked dissimilarities although they are both derived from the data of Landecker and Wielebinski (1970). The latter was obtained from the contour map by reading off the contours along $b = 0$. Because of the finite beam widths of the surveys the profile is effectively an integral within about 2° of the galactic plane. The profile of Paul et al. is a straight average of the digitised values of emission at $b = -10°, -5°, +5°$, and $+10°$ omitting the contribution from the galactic plane. The gamma-ray profile from the SASII data is summed over $|b| < 10°$. If the radiation is produced by cosmic rays interacting with the thin layer of interstellar gas however, the observed width in galactic latitude is mainly due to detector resolution and most of the radiation in fact comes from $b| < 3°$. When the gamma-ray profile is compared with that of figure 3 there is no strong resemblance to imply $\rho_T \propto B^2$. To complete the relationship (4) Paul et al. invoke the similarity between the radial distribution of synchrotron emission and the square of the atomic hydrogen density, ρ_A^2, in the external galaxy M31. This gives $N_e B^2 \propto P_A{}^2$ which, together with the previous relations implies $N_p \propto P_A$. The final step to get $N_p \propto \rho_T$ is to take $\rho_A \propto \rho_T$ in M31. If this is true however, it must mean that the distribution of molecular hydrogen in M31 is entirely different to that in the Galaxy and this casts doubt on the validity of extrapolating other properties of M31 to the Galaxy. We conclude that relation (4), although attractive in its simplicity, does not have a good observational basis.

On balance the present observational data favour some moderate gradient in the density of 1 to GeV cosmic rays in the Galaxy but are against it rising in proportion to or faster than the total gas density. This may be interpreted on the one hand as evidence against a free zone of weak scattering being continuous over the whole mid-plane of the Galaxy and on the other hand as ruling out scattering sufficiently strong to bind the particles to the gas everwhere. A likely condition is that the particles move freely within the spiral arms but are prevented by their strong scattering in the less dense interarm regions from flowing radially from one arm to the next.

Self-generated waves may not be able to confine cosmic rays beyond ~ 100 GeV. It is probable that a spectrum of waves will be generated by the large-scale turbulent motion of the gas. Waves with wavelengths equal to the gyroradius of particles from a few times 10^{13} eV upwards will almost certainly be present with sufficient amplitude but the spectrum of turbulence will cut off at shorter wavelengths due to viscous damping in the interstellar medium. It appears then that the diffusive confinement mechanism changes from self-confinement to that due to externally generated waves in the region of 10^{11} to 10^{12} eV. This is the region below which we have information on grammage only and above which only the drift velocity is known. It may well be wrong to extrapolate the energy dependence of these quantitites respectively to higher and lower values and it is of great interest to close the energy gap experimentally.

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References :

Burbidge, G.R. 1975, *Phil. Trans. Roy. Soc.*, **277**,481.
Dickinson, G.J. and Osborne, J.L. 1974, *J. Phys.* A. **7**,728.
Dodds, D., Strong, A.W., Wolfendale, A.W. and Wdowczyk, J. 1975, *J. Phys.* A. **8**,624.
Dodds, D., Wolfendale, A.W., and Wdowczyk, J. 1976, *M.N.R.A.S.*, **176**,345.
Elliot, H., Thambyahpillai, T. and Peacock, D.S. 1970, *Acta Phys. Acad. Sci. Hung.* **29** *Suppl.* 3, 491.
Fichtel, C.E. et al 1975, *Ap.J.*, **198**,163.
French, D.K. and Osborne, J.L. 1976, *M.N.R.A.S.* (in the press).
Ginzbrug, V.L. 1975, *Phil. Trans. Roy. Soc.*, **277**,463.
Ginzburg, V.L. and Syrovatakii, S.I. 1964, "*Origin of Cosmic Rays*" (Oxford : Pergamon).
Gombosi, T. et al. 1975, *Nature*, **255**,687.
Geiss, J., 1963, *Proc. 7th Int. Cosmic Ray Conf.*, Jaipur, Vol. 3, p434.
Georgelin, Y.M. and Georgelin, Y.P. 1976, *Astron. Astrophys.*, **49**,57.
Higdon, J.C. and Lingenefelter, R.E. 1976, *Ap.J.* **208**, L107.
Holmes, J.A. 1974a, *M.N.R.A.S.*, **166**, 155.
Holmes, J.A. 1974, Ph.D. Thesis, University of Oxford.
Kulsrud, R. and Pearce, W.P. 1969, *Ap.J.*, **156**,**445**.
Landecker, J.L. and Wielebinski, R. 1970, *Aust. J. Phys. Astrophys. Suppl.*, **16**,1.
Lapikens et al. 1971, *Proc.* 12th *Int. Cosmic Ray Conf.*, Hobart, Vol. **1**, p316.
Lin, C.C. and Shu, F.H. 1967, *IAU Symposium, No.* 31 (Noordwijk), p313.
Lingenfelter, R.E. Ramaty, R. and Fisk L.A. 1971, *Astrophys. Lett.*, **8**,93.
Marsden, R.G., Elliot, H., Hynds, R.J. and Thambyahpillai, T. 1976, *Nature*, **260**,491.
Osborne, J.L., Wdowczyk and Wolfendale, A.W. 1976, *J. Phys.*, **9**,1399.
Paul, J., Cassé, M. and Cesarsky, C.J. 1976, *Ap.J.*, **207**,62.
Ramaty, R. Balasubrahmanyam, V.K., and Ormes, J.F. 1973, *Science*, **180**,731.
Scoville, N.Z. and Solomon, P.M. 1975, *Ap.J.*, **199**, L105.
Skilling, J. 1970, *M.N.R.A.S.*, **147**,1.
Skilling, J. 1971, *Ap. J.*, **170**,265.
Skilling, J., McIvor, J. and Holmes, J.A. 1974, *M.N.R.A.S.*, **167**,87.
Stecker, F.W., Solomon, P.M., Scoville, N.Z. and Ryter, C.E. 1975, *Ap. J.*, **201**,90.
Strong, A.W. 1975, *J. Phys. A*, **8**,617.
Verschuur, G.L. 1973, *Astron. Astrophys.*, **27**,73.
Webber, W.R., Lezniak, J.A. and Kish, J. 1973, *Astrophys. Space Sci.*, **24**,17.
Wentzel, D. 1968, *Ap.J.*, **152**,987.