On the Origin of Cosmic Rays during the early Part of the Evolution of our Galaxy

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Die Hypothese wird diskutiert, daß das Volumen, in welchem die kosmische Strahlung gespeichert wird, vergleichbar ist demjenigen des Halos unseres Milchstraßensystems, und daß daher (wenn die gesamte Menge des Gases im Halo höchstens vergleichbar ist mit derjenigen in der Scheibe) die mittlere Lebensdauer eines Teilchens der kosmischen Strahlung vergleichbar ist mit dem Alter unserer Milchstraße. Es wird ferner die Vorstellung begründet, daß die Menge des interstellaren Gases, die Anzahl der Sterne frühen Spektraltyps und die Produktion von kosmischer Strahlung in den frühen Phasen der Entwicklung unseres Systems viel größer waren als heute. Es wird gezeigt, daß unter diesen Voraussetzungen die beobachteten Daten über die Isotropie der kosmischen Strahlung (einschließlich der ihrer energiereichsten Teilchen), sowie die Daten über die Häufigkeit der Li-, Be-, B-Kerne interpretiert werden können, und daß die Bedingungen für die Wirksamkeit des statistischen Beschleunigungsmechanismus in den frühen Phasen viel günstiger waren als sie es heute sind.

The hypothesis is considered that the volume in which the cosmic rays are stored is comparable to that of the halo of our system and hence (if the total amount of gas in the halo is at most comparable with that in the disk) the average cosmic ray life time is comparable with the age of the galaxy. Reasons are given which indicate that the amount of interstellar gas, the number of early type stars, and the rate of production of cosmic rays were much greater in the early part of the evolution of our galaxy than they are now. It is shown that under these conditions the observed data on the cosmic ray isotropy, including that of the very high energy component, and the data on the abundance of the Li, Be, B nuclei may be understood, and that in addition the conditions for the statistical (Fermi type) mechanisms of acceleration to be operative were much more favorable in the early stages than they are now.

The galactic theory of the origin of Cosmic Radiation, in its original form, assumed the particles to be confined in a volume essentially equal to the disk region of our galaxy. In this picture the average life time of a cosmic ray proton is at most of the order of some 10^7 years, that is to say a time so short compared to the age of our system that essentially stationary conditions would seem likely to be present.

In recent years evidence from several sides has become known tending to show that both the volume in which the cosmic ray particles are stored and their lifetime in this volume may have been grossly underestimated. The former may be equal to that of the so-called halo of our system [1], and the latter may be comparable to its age. This leads to the theoretical possibility, that the bulk of all cosmic ray particles have been accelerated in the early stages of the evolution of our galaxy, say in the first half billion years. It is the purpose of this paper to examine this possibility in detail.

A. Observations and their direct implications

Let us first review briefly the observed properties of cosmic rays that are important for our argument. Fortunately, precise details are not of vital importance and it should not matter if in the future the best values of the various numbers change by reasonable amounts.

A.1. Isotropy. Anisotropy in the cosmic ray flux would be expected to arise in at least two ways. If cosmic rays are of recent origin and hence are accelerated within our spiral arm (either in the atmospheres of stars or in the interstellar gas), then the leakage flux out of the region in which they are stored should produce some anisotropy everywhere except near points of symmetry. In addition, with either recent or early origin, if the region around the sun is occupied by a hydromagnetic wave in which the magnetic field strength varies, there will be changes in the pitches of the helical trajectories and hence anisotropy will be produced. Such aniso-

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[1] W. L. GINSBURG, Fortschr. Phys. **1**, 659 [1954]; Prog. in Elem. Particle and Cosmic Ray Phys. **4**, 338 [1958]. — J. E. BALDWIN, Mon. Not. Roy. Astr. Soc. **115**, 684 and 691 [1955]. — G. R. BURBIDGE, Phys. Rev. **107**, 269 [1957]; Astrophys. J. **123**, 178 [1956].

tropies will be observed as variations of intensity with the period of a siderial day and the two types may, in principle, be distinguished by a study of their first and second harmonics [2]. Variations of intensity with the period of a solar day are produced by atmospheric effects or possibly by magnetized gas clouds within the solar system. Such clouds could also mask a real anisotropy in low energy cosmic rays, but above about 10^{13} eV, where the radius of curvature in a 10^{-5} gauss field is 200 A.U., any anisotropy should be observable.

From GREISEN's [3] recent survey of variations in cosmic ray intensity, we see that the variation with siderial time is about $10^{-3,5}$ for energies up to 10^{13} eV, is about $10^{-2,5}$ up to 10^{15} eV, and is $\leqq 10^{-1}$ up to 10^{17} eV. In all cases the statistical errors are great enough so that the true anisotropy could be zero. These observations exclude many theories of the origin of cosmic rays. It seems reasonable to assume that the anisotropy is really very small, essentially zero, and hence that the cosmic rays we see are stored in a stationary state with no significant net fluxes due to diffusion, acceleration, or escape from the storage region. Since 10^{17} eV cosmic rays have radii of curvature of the order of 100 lt. yrs, this seems to rule out the older version of the galactic theory in which the cosmic rays were stored in a disk whose thickness was of the order of 1000 lt. yrs.

One can also conclude that any possible hydromagnetic waves in our neighborhood are of such a character that they do not produce anisotropies in the cosmic ray flux. Also, since what data are available on the intensity of cosmic radiation over periods of many years shows no evidence of secular changes for at least 10^4 years, one can conclude that during this time the solar system has not been within a "cosmic ray trap" which would change the intensity. All this makes it probable that the galactic magnetic field in our vicinity does not now have a state of motion that is efficient for the acceleration of cosmic rays.

A.2. The Li, Be, B abundance. The importance of the amounts of these nuclei in the primary cosmic radiation for any theory of its origin has been pointed out often. Theoretically, there are two extreme possibilities: first, that the abundance relative to the heavier nuclei corresponds to fragmentation equilibrium (i. e. comparable abundance of both groups), and second, that the relative abundance corresponds to the cosmical abundances (i. e. about 10^{-4} that of the heavier nuclei). In the first case one would conclude that the cosmic radiation is effectively stored in such a way that losses by diffusion out of the region in which it is stored are rare compared with the losses by nuclear collisions with diffuse matter in that region, and also that the time scale is long enough for the fragmentation equilibrium to become established. In the second extreme case one could conclude either that diffusion out of the region in which the c. r. is stored operates much faster than elimination by collisions (which necessarily means less effective storage) or that the time scale of fragmentation, owing to the low density of diffuse matter, is long compared with the age of the universe or with that of the storage region.

From the collective evidence presented at the recent (1957) IUPAP-Cosmic Ray conference at Varenna [4] we conclude that the most probable value of the ratio of Li, Be, B to C, N, O in the primary cosmic radiation is about 1/3. Thus the fragmentation equilibrium has not yet been reached since in this case the ratio would be about unity, a value almost certainly inconsistent with observation. The ratio 1/3 indicates an average age of the cosmic ray particles of $5 \cdot 10^6/n$ years, n being the average particle density of the diffuse matter in the region in question (assuming protons); the precise value which corresponds to 8 gm/cm^2 of diffuse material, is that proposed by M. SCHEIN. This interpretation of the observations is compatible with a theory in which a stationary state is assumed, with the majority (especially of the protons) of the cosmic ray particles leaking out of the region in which they are stored, instead of being eliminated by collisions; or alternatively with a theory in which the time during which the cosmic ray particles have been stored represents only a moderate fraction of the time needed for establishing fragmentation equilibrium. The picture to be discussed in the present paper is of the second type.

It is of interest to note that the probability that a proton makes a nuclear encounter in traversing 8 gm/cm^2 ist 1/8 and hence the mean life of protons is nearly ten times that allowed for the heavier nuclei.

It has also to be mentioned, however, that RAO, BISWAS, DANIEL, NEELAKANTAN and PETERS [5] conclude

[2] L. DAVIS, Phys. Rev. **96**, 743 [1954].
[3] K. GREISEN, Prog. Cosmic Ray Phys. 3, 1 [1956] (p. 124).
[4] Nuovo Cim., Suppl. Vol. VIII, Ser. X, 1958.

from their observations and those of others that the average amount of diffuse matter traversed by a cosmic ray since its first acceleration should not exceed 1 gm/cm^2. If this is the correct interpretation, the radius of the storage volume will have to be doubled to about 50 kpc if one is to store cosmic rays for $5 \cdot 10^9$ yrs. (see A.3 below).

A.3. Volume of the galactic halo and average density of diffuse matter in our galaxy

The radioastronomical observations have established that stellar systems, in addition to the structure visible in photographic light, ordinarily possess a larger, much less flattened outer region, in which gaseous matter is so dilute that only the presence of electrons, moving most probably with relativistic speeds in magnetic fields, can be inferred observationally. The radius of this halo of our own galaxy is likely to be at least 15 kpc, and its value may well be as large as 25 kpc, the resulting volume being $10^{4.2}$ $(kpc)^3$ in the former and $10^{4.8}$ $(kpc)^3$ in the latter case, or $10^{68.7}$ and $10^{69.3}$ cm^3, respectively.

The integrated mass of gaseous matter in the disk of our galaxy is now estimated [6] to be $1.5 \cdot 10^9\ M_\odot$ or $1.8 \cdot 10^{66}\ m_H$. If (what is not certain) the mass of the gaseous matter contained in the halo can be neglected for the present purpose, this means average particle (proton) densities, including the halo, of $\approx 4 \cdot 10^{-3}$ and $\approx 1 \cdot 10^{-3}$ cm^{-3}, respectively, depending on the radius of the halo. These figures lead to an equivalent mass traversed in $5 \cdot 10^9$ years of $\approx$ 30 and 8 gm/cm^2, respectively. The latter value is equal to that derived by SCHEIN from the Li, Be, B abundance (see A.2.). It is of course possible that a somewhat larger volume is effective in storing cosmic rays. This would be possible if the magnetic fields in the larger volume were somewhat weaker than in the halo; such fields could store cosmic rays but would not lead to observable radio emissions. If the gas density in the halo proper is less than the average values given above, this increase in storage volume corresponds to a reduction in the average density. We do not consider here the important problems of the statics and dynamics of the halo where one must take account of the cosmic ray pressure, magnetic forces, gravitational forces, gas pressure, centrifugal force (conditions may be such that some of the forces are small), and the magnetic coupling between the disk and the halo.

A.4. Energy considerations

We shall need to make estimates of the power supply to cosmic rays and the power available for their acceleration on various hypotheses. It is convenient to express these in terms of $L_\odot = 3.9 \cdot 10^{33}$ erg/sec, the luminosity of the sun, and $L_g = 2.5 \cdot 10^{10}$ $L_\odot = 10^{44}$ erg/sec, the probable value oft he present integrated luminosity of the stars of our system. Now the cosmic ray energy density in our neighborhood is very nearly 10^{-12} erg/cm^3. Assuming the same density throughout storage volumes with radii of 15 and 25 kps gives total cosmic ray energies of $1/2$ and $2 \cdot 10^{57}$ ergs or about $1.5 \cdot 10^5\ L_g$ yrs and $6 \cdot 10^5\ L_g$ yrs, respectively. Thus to build up this energy density in $5 \cdot 10^9$ yrs from a power supply having the present value requires an efficiency of about 10^{-4}. Essentially the same result is obtained for the older theories in which cosmic rays were stored in the galactic disk or a spiral arm. The light escapes in a time of the order of 10^3 yrs (the thickness of the disk in light years) while the cosmic rays are stored for $5 \cdot 10^6$ yrs if the density is 1 proton/cm^3.

A.5. The energy spectrum

At energies above 10^{10} eV/nucleon the flux of cosmic rays as a function of energy is described by the well known power law, which states that the flux in c.g.s. units of particles with total energy per nucleon greater than w is

$$N(>w) = N_0\, w^{-\gamma} \tag{1}$$

where N_0 is a constant and γ is nearly constant. Surveying the literature, we find that in the range from $1.4 \cdot 10^{10}\,\mathrm{eV} < w < 1.4 \cdot 10^{15}\,\mathrm{eV}$, $\gamma = 1.64 \pm 0.04$ and for $10^{14}\,\mathrm{eV} < w < 10^{17}\,\mathrm{eV}$, $\gamma = (1.74 \pm 0.09) + (0.09 \pm 0.02) \log_{10}(w/10^{15}\,\mathrm{eV})$. At the low energy end, the spectrum is complicated by the facts that the rest mass is not negligible compared to w and that $N\ (>w)$ varies with time, probably due to variations in the interplanetary magnetic fields. The older view that the power law spectrum is only apparent and is to be explained as an accident produced by the superposition of a variety of sources of different kinds now appears very improbable because all new data seems to fit the law and extend it to higher

[5] APPÀ RAO, S. BISWAS, R. R. DANIEL, K. A. NEELAKANTAN and B. PETERS, Phys. Rev. **110**, 751 [1958].

[6] H. C. VAN DE HULST, Report to the Solvay Conference 1958 (further references there).

energies. It now seems better to assume that it is of fundamental importance and to look for a theory of the origin of cosmic rays that will give a power law spectrum.

This leaves only FERMI's statistical theory, or some modification of it. Basically theories of this type may be described as follows. Low energy cosmic rays (or perhaps particles in the energy range 10^7-10^9 eV/nucleon, which might not be defined as cosmic rays) are injected into a region from which the probability of "escape" in the time $\mathrm{d}t$ is $\mathrm{d}t/\tau$. Escape can come either by diffusion out the region or by making a nuclear reaction. While in the region, the particle interacts with the variable magnetic fields imbedded in moving, conducting gas, the mean interval between interactions being t_1. If $c\,\beta_{\mathrm{p}}$ is the speed of the particle and $c\,\beta_{\mathrm{g}}$ the r.m.s. speed of the gas, then at each interaction the energy change of the particle is of the order of $\mathrm{d}w=\pm\beta_{\mathrm{p}}\,\beta_{\mathrm{g}}\,w$, where w is the total energy, including rest energy. For the kind of interactions considered by FERMI in his first treatment of the subject, interactions with a + sign are more likely than those with a − sign in the ratio $\beta_{\mathrm{g}}/\beta_{\mathrm{p}}$ and hence the mean rate of change of energy is

$$\mathrm{d}w/\mathrm{d}t=+(\beta_{\mathrm{g}}^2/t_1)\,w\,. \tag{2}$$

If particles are injected at a constant rate, are accelerated according to (2), and are stored with the time constant τ, all parameters being independent of w, then the power law spectrum results with

$$\gamma=t_1/\beta_{\mathrm{g}}^2\,\tau\,. \tag{3}$$

This fact and the plausibility of a statistical process constitute the main attractiveness of the FERMI mechanism. Its main drawback is the well-known[7] fact that it is difficult to find a region in the galaxy in its present state where astronomically reasonable values of the parameters make $\gamma\approx1.6$ and where sufficient power is available in the gas motion. The consideration of a variety of modifications of the FERMI mechanism by a number of authors has improved the situation in some measure but does not seem to have lead to any widely accepted resolution of the difficulties (cf. the discussions at Varenna, 1957[4]).

The following points connected with the power law are important to our argument. If we let τ go to infinity and hence store all cosmic rays forever, then we do not have a steady state nor do we get a power law. To get the power law when cosmic rays are stored in the halo, we need to accelerate them in a limited subregion of the galaxy out of which they diffuse in a time independent of energy. Once a particle has left the subregion, its chances of returning (or entering another accelerating subregion) must be very small. If the acceleration of cosmic rays is an important factor in damping the gas motions, then γ will probably adjust itself to about the observed value in spite of variations in the power supply. If injection is not at a constant rate, one will not get a power law inside the subregion; but since the energy with which each particle emerges from the subregion is independent of the number of other particles present, one should get a power law spectrum for the particles that escape. The subregion must continue to be active for at least 20 times the characteristic time, τ, in order that a few cosmic rays may be accelerated to 10^{18} eV. In order that the number of particles in the highest energy ranges not drop far below the power law value, this activity must continue for 30 or 40 times τ. It may not be easy to find a suitable magnetic field configuration for the subregion that will result in storage for a time roughly independent of energy. A possibility is that the scales of the irregularities in the magnetic field are either larger than the gyro-radii of the most energetic particles or smaller than the gyro-radii of 10^{10} eV particles (the least energetic for which the power law should hold). Then the rate at which a particle progresses along a line of force with occasional scatterings in its helical motion can be independent of energy.

B. Stellar evolution and the origin of cosmic rays

B.1. Stellar evolution, especially in the early stages of our galaxy

In a discussion of the possibility of an early origin of the cosmic rays it is of primary importance to decide whether the integral energy output in our system, in particular the rate of stellar evolution (which depends largely on the number of massive early type stars) has been essentially constant in time or whether it has decayed considerably since the early stages. If, as is now commonly believed, the typical course of stellar evolution is represented by condensation from interstellar material and sub-

[7] A. UNSÖLD, Phys. Rev. **82**, 857 [1951]. — L. BIERMANN, Kosmische Strahlung (W. HEISENBERG ed.) 1953; Ann. Rev. Nucl. Sci. **2**, 335 [1953].

sequent contraction to a star, by burning in the stars' interior of the hydrogen to helium and possibly to still heavier elements (provided the time scale which depends mainly on the mass of the star allows this), one might expect a secular decay of the rate of star formation and thereby of the overall rate of stellar evolution with the decrease of the content of interstellar material to its present low value of $1^1/_2$ or 2%. We are thus led to consider whether there are observational facts from which the rate of star formation and evolution in the early stages of our system may be inferred.

The most direct indication bearing on this question is probably the number of white dwarfs. In our neighbourhood (within 5 pc distance) 5 white dwarfs, that is 0.01 per $(\mathrm{pc})^3$, are directly observed. Even in case they were produced at a uniform rate over the last $5 \cdot 10^9$ years most of them would be older than the present structural features of our galaxy; hence it appears legitimate to use this figure to extrapolate their total number in our system. GLIESE's[8] results indicate, that (assuming a mass of $\approx 0.8\,M_\odot$ for a typical white dwarf) in our neighbourhood roughly 15 (± 3)% of the mass of the known stars ($\gtrsim 0.05\,M_\odot\,\mathrm{pc}^{-3}$) are present in the form of *known* white dwarfs. The actual percentage can only be higher, since the observational data for these stars are almost certainly incomplete beyond 3 parsecs. Whether the average figure for our system is more likely to be higher than in our neighbourhood, or to be lower, is difficult to say; the sun may be located in a region with above average population I material (newer stars), and the white dwarfs, in general, owing to their greater age should occupy a volume extending on the average to larger distances from the disk than other stars. If a density of 0.01 white dwarfs per $(\mathrm{pc})^3$ is representative for the region inhabited by old stars, of a volume of say $\pi \cdot 500$ $(\mathrm{kpc})^3$, their total number is found to be $1.6 \cdot 10^{10}$.

From SCHMIDT's[9] analysis it appears that the total mass of our system is $\approx 0.7 \cdot 10^{11}\,M_\odot$, or perhaps even $1 \cdot 10^{11}\,M_\odot$ (depending on which of his models one prefers); if the total mass of white dwarfs in our system is assumed to be only 10%, their total number would again be $\gtrsim 1 \cdot 10^{10}$.

It is concluded that the value last mentioned should represent a conservative estimate of the present number of white dwarfs in our galaxy.

[8] W. GLIESE, Z. Astrophys. **39**, 1 [1956].
[9] M. SCHMIDT, Bull. Astron. Netherlands **13**, 15 [1957].

We estimate now the total energy output during their life time, and compare the resulting figure with the integral energy radiated by the stars of our galaxy over $5 \cdot 10^9$ years, assuming first their present luminosity to mass ratio.

The energy gained in the conversion $\mathrm{H} \rightarrow \mathrm{He}$ is $6{,}1 \cdot 10^{18}$ erg/gm, the additional gain by the conversion of He into heavier elements is of the order of $1 \cdot 10^{18}$ erg/gm. The original mass of the present white dwarfs must have been on the average somewhat above $1.3\,M_\odot$, probably between 1.5 and $2\,M_\odot$, but roughly half of this mass must have been lost to the star before becoming a normal white dwarf.

We shall hence make the assumption that an amount of $0.7\,M_\odot$ has been burned to heavier elements in a typical white dwarfs. This allows for the possibility that a fraction of the order of 10% of the mass was helium when the star was formed – a higher proportion seems unlikely in view of the present abundance of helium in stars and in interstellar space – and that the larger part of the ejected material did not participate in the nuclear transmutation (otherwise more He would be found in the interstellar material). With our assumption, each present white dwarf has contributed in the past $1.0 \cdot 10^{52}$ ergs ($90\,L_\odot \cdot 10^9$ years) to the integral energy production of our system.

The average contribution over $5 \cdot 10^9$ years of those stars which became white dwarfs, i. e. those with an absolute magnitude in the main sequence stage above $+3$ or $+2$, would than appear to have been $\gtrsim 18 \cdot 10^{10}\,L_\odot$, that is to say larger than the present integral luminosity of our galaxy (see A.4.) by a factor of the order 10.

Similarly, the integral amount of stellar matter added to the interstellar material over the last $5 \cdot 10^9$ years, comes out to be five times its present amount (or more), if we adopt VAN DE HULST's figure of $1.5 \cdot 10^9\,M_\odot$.

These considerations appear to lend considerable weight to the hypothesis that the rate of star formation from interstellar material and of stellar evolution into the white dwarf state was much more rapid in the earlier stages of our galaxy. Since the decay should have been gradual, (say of an exponential type), the integral luminosity, which in this picture must have been essentially given by the contribution of fairly luminous stars, in the first 500 or $1000 \cdot 10^6$ years must have been again larger, say by a factor 2 (or 3), than the average over the last 5 or $6 \cdot 10^9$ years.

Hence about 20 (or more) times as many early type stars would appear to have been present in these early stages of our system. At present only $1^1/_2$ (or 2)% of the total mass is in the form of interstellar gas, but also the volume occupied by it is probably considerably smaller than it was in the early stages. The average density of the interstellar gas was therefore not necessarily greater by a large factor than its present value. On the other hand, the activity in a general sense, and specifically the energy fed into the interstellar gas by the early type stars, should have been larger roughly by the factor (of 20 or more) mentioned above. There should have been correspondingly more H II regions and somewhat more violent turbulence, and the energy flowing into the gas and dissipated ultimately into heat should have been likewise larger than today.

Since these considerations were first made, several additional arguments, e. g. from more detailed investigations on stellar evolution and stellar dynamics (S. v. HOERNER, S. TEMESVÁRY [10]) and from the theory of the synthesis of helium (G. R. BURBIDGE [11]) and heavy elements in stars (E. M. BURBIDGE et al. [12]) became known to the authors, leading essentially to the same conclusion regarding the rate of stellar evolution in the early stages of our galaxy. It is not planned to present here a complete discussion of all these arguments, but we shall adopt the position that valid astrophysical evidence from several sides appears to justify our hypothesis of a much faster rate of evolution during the early phase of our stellar system [12a].

The amount of energy present in the form of cosmic rays – 10^{57} erg (see A.4.) – has then to be compared with the integral output of the stars during the life time of our galaxy, which was found to be $\gtrapprox 10^{62}$ erg. Hence only 10^{-5} of this amount has been needed for the acceleration of cosmic ray particles if there has been no loss to intergalactic space.

B.2. Consequences for cosmic rays

The enlargement of the storage region from the disk or a spiral arm to include the galactic halo makes it much easier to store the highest energy cosmic rays and to get isotropy; but, as seen in A.4, it does not make the serious energy supply problem any easier. In either case, with the *current* amount of stellar activity, about 10^{-4} of the energy going into starlight must be converted to mechanical motions of magnetized gas clouds and then to the acceleration of cosmic rays. An efficiency of 10^{-4} for these processes is so large that it imposes severe, but perhaps not impossible, restrictions on all acceleration processes. It does mean that one must draw on a substantial fraction of all stellar thermal power; one can not use stars with only a negligible fraction of the total power. But, as seen above, with the probable much greater activity in the early stages of the evolution of the galaxy, the efficiency required is only 10^{-5}. This decrease by a factor of 10 will tend to make more reasonable all galactic theories of the origin of cosmic rays. For in the absence of more detailed information, the only reasonable assumption is that there have been ten times as many supernovae as expected on the basis of the current rate, ten times as many BABCOCK magnetic stars, and more than ten times as much power to run a FERMI mechanism in the interstellar gas.

With the present frequency of supernovae, it would just be possible to account for the energy needed for the acceleration of cosmic rays if one assumes a very high efficiency for the conversion of thermal to cosmic ray energy. Even with a higher frequency in the early stages, the efficiency required still remains so high (several percent) that the present authors find this proposal difficult to accept. It must be mentioned in this connection that, according to a recent result of WOLTJER [13] (cf. also GINSBURG [1]), the supernovae might well maintain the energy and number balance of the relativistic

[10] Private communications (to be published).

[11] G. R. BURBIDGE, Publc. Astron. Soc. Pacific **70**, 83 [1958].

[12] E. M. BURBIDGE, G. R. BURBIDGE, W. A. FOWLER and F. HOYLE, Rev. Mod. Phys. **29**, 547 [1957].

[12a] Notes added in press: In the I.A.U., Moscow Symposion on the Hertzsprung-Russell diagram (Trans. I.A.U. X, to appear), M. SCHMIDT has discussed the time dependence of the rate of star formation and of stellar evolution near the sun more in detail. He concludes that the initial rate was much faster than the present rate and that in our region 10% by mass of all stars are now white dwarfs. A similar analysis for our whole system would in principle allow to take account also of the initially larger fragmentation rate of cosmic rays, due to the higher gas density, which was neglected in the present investigation. M. SCHWARZSCHILD and L. SPITZER, in a letter to the "Observatory" **73**, 77 [1954], reached similar conclusions by comparing the present number of white dwarfs in our galaxy with the rate of star deaths to be expected from the present luminosity function. (I.A.U. = Intern. Astron. Union.) We are indebted to Dr. SCHMIDT and to Dr. SCHWARZSCHILD for discussions of these points.

[13] WOLTJER, kindly communicated to the authors by Dr. VAN DE HULST.

electrons responsible for the radio frequency radiation of the halos. This is independent of the overall energy balance of the nuclei, which constitute $\geqq 99\%$ of the cosmic rays.

In any case, if cosmic rays are stored in the halo for a time of the order of the age of our galaxy and if the rate of cosmic ray production is proportional to the stellar thermal output, at least 90% of all cosmic ray particles should be very old. At present, the cosmic ray density should be in a more or less static state, although it may well be slowly decreasing because of a certain amount of leakage and because of collisions with nuclei.

It is very difficult to say just what the conditions in the galactic magnetic field were during the early stages of its evolution and hence it is difficult to make a realistic estimate of the efficiency of cosmic ray acceleration then. Nevertheless, it seems highly plausible that conditions were much more favorable for the FERMI mechanism then than they are now. With a much greater density of bright stars embedded in a moderately dense gas, the gas velocities should be relatively high, the wavelengths relatively short, and the strong shock waves needed to reduce the anisotropy and allow continued acceleration should be plentiful. To satisfy equation (3), one could take $\tau = 10^6$ yrs, $t_1 = 10^{-1}$ yr, $c\,\beta_g = 3 \cdot 10^{-4}\,c = 100$ km/sec. These values might be possible, but they seem a bit extreme. The required conditions are considerably less extreme if one considers some modifications of the FERMI mechanism which allows $t_1/\beta_g^2\,\tau$ to be from 30 to 100 times larger [4, 14]. An alternative possibility is that each hot new star acts as a source of hydromagnetic waves that are damped strongly as they propagate along the magnetic field lines. These waves should be in part compressional and hence will reflect cosmic ray particles, almost all reflections being head-on collisions that increase the energy. For each collision, $\Delta w/w = 2\,\beta_W/\sqrt{3}$ where $c\,\beta_w$ is the velocity of the waves and the factor $1/\sqrt{3}$ allows for the spiraling motion of the cosmic ray particles. If the mean time between collisions is t_1, then the mean rate of change of energy is given by

$$\mathrm{d}w/\mathrm{d}t = (2\,\beta_W/\sqrt{3}\,t_1)\,w \tag{5}$$

in place of (2), and (3) becomes

$$\gamma = \sqrt{3}\,t_1/2\,\beta_W\,\tau\,. \tag{6}$$

To make an order of magnitude estimate of the parameters, we may suppose that at the epoch considered the core of the galaxy contained about 1/5 of the total galactic mass and that 10% of this had condensed into early type stars, most of the rest being gas. Then if the volume of the core was about 100 kpc^3, the gas density was about 10^{-23} gm/cm^3 and the density of early type stars about $(1/20)^3$ per (lt yr)^3. Now the STRÖMGREN sphere around an A0 star under these circumstances is 1 lt yr and that around a B5 star is 4 lt yr. The region from which hydromagnetic waves spread is larger than these spheres; suppose we assume that waves of moderate strength are produced in a bundle of lines of force 7 lt yrs in radius about each star. Then the mean distance, L, between reflections is

$$L \approx 20^3/\pi\,5^2 \approx 100 \text{ lt yrs.}$$

Thus $t_1 \approx \sqrt{3}\,L$, to allow for spiraling and if $\tau = 10^6$ yrs (the maximum allowed by the density) and $\beta_W = 3 \cdot 10^{-4}$ corresponding to a magnetic field of 10^{-4} gauss (not impossible with the high density and gas velocity), (6) gives $\gamma \approx 1.5$ as required. Actually, this over-estimates the efficiency since some particles in steep helices will not be reflected while others in very flat helices will have larger t_1 and smaller $\Delta w/w$.

The particular numerical values used in the previous paragraph are not to be taken too seriously. They are designed only to show that with the expected greater activity during the early stages of the evolution of the galaxy the difficulties previously experienced with the numerical values of the parameters in the various modifications of the FERMI mechanism largely disappear. Also, recent work [15] on the structure of hydromagnetic shocks indicate that they should have a structure in which there are substantial changes in magnetic field strength over distances of the order of the gyro-radius of the thermal particles. Thus cosmic ray particles will be scattered and made isotropic by such shocks, and the FERMI process does not fail because of the objections raised when it was thought that all structures in a hydromagnetic shock had dimensions of the order of the mean free paths of the thermal particles.

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