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Cosmic Radiation and Cosmic Magnetic Fields.
I. Origin and Propagation of Cosmic Rays in our Galaxy

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The radiofrequency radiation of the galaxy is shown to be analogous not to the "quiet" but to the "disturbed" radiation of the sun (produced by plasma oscillations). Many arguments point toward its origin on stars with an "activity" qualitatively similar to that of the sun but several billion times stronger. It is assumed that in these stars the relation between radiofrequency radiation and the emission of cosmic rays is similar to that observed for the sun by Forbush and Ehmert. In the magnetic field of the galaxy this primary cosmic radiation is "stored" by a factor 10^3 to 10^4, each particle describing a complicated path until it is killed by a nuclear collision, and directional isotropy established. The cutoff of the energy spectrum at small energies, hitherto mostly ascribed to a solar magnetic dipole, is attributed to the stopping power of interstellar matter. Some other theories concerning the origin of cosmic rays are reviewed critically.

I. INTRODUCTION

The old problem of the origin of cosmic rays has acquired a new aspect through the discovery of quite a different radiation coming from the universe, the radiofrequency radiation discovered by Jansky in 1932. Recently, it has been proved that the sun emits "bursts" of both types of radiation in connection with violent solar "flares" (bright H_α eruptions). Even if we do not yet understand in every detail how the production of solar radiofrequency and cosmic-ray bursts on the sun is accomplished, it is very tempting to assume that the corresponding cosmic radiations are generated in a similar way on stars of our galaxy.

This hypothesis has hitherto met with many objections and in fact has mostly not even received serious consideration. We intend, however, to demonstrate that all these objections are unfounded and that, on the contrary, our idea has very interesting astrophysical consequences which are corroborated by extensive observational material.

II. SOLAR AND GALACTIC RADIOFREQUENCY RADIATION[1]

A

It is well known that the sun emits two kinds of radiofrequency radiations:

(a) The *"quiet" solar radiation*, which can be explained by free-free transitions of electrons in the solar corona ($T\approx 10^6$ °K) and the chromosphere ($T\approx 6000$°K). For quantitative details we may refer to earlier publications.

(b) The *"disturbed" solar radiation* whose intensity may, at times of violent "solar activity," especially during solar flares, surpass by many powers of ten that of the "quiet" radiation always present. Recent theoretical studies by various authors point towards an explanation in terms of plasma oscillations excited by turbulent streams of ionized gases penetrating into each other with high velocities.

Denoting the order of magnitude of these velocities by v_s, it is evident that coherent oscillations with frequency ν producing radiation with a wavelength $\lambda=c/\nu$ can be excited only over domains whose size D is

$$D<\lambda v_s/2\pi c. \tag{1}$$

On the other hand, "plasma" oscillations are only possible if an electron, whose velocity is v_e, cannot leave the domain during unit phase change. That is,

$$D>v_e/2\pi\nu. \tag{2}$$

The conditions (1) and (2) are only compatible, if $v_s \gtrsim v_e$. In a magnetic field, however, the path of an electron is coiled up, and condition (2) may lose considerably in importance, so that excitation of plasma oscillations becomes possible also for $v_s<v_e$.

Putting*

$$v_s\approx v_e=\left(\frac{8}{\pi}\cdot\frac{kT}{m}\right)^{\frac{1}{2}}, \tag{3}$$

where T is the temperature, k and m have the usual meaning, and, following Langmuir,

$$(2\pi\nu)^2=4\pi e^2N/m, \tag{4}$$

where N is the number of electrons per cm^3; it is easily seen that, apart from the unimportant factor $(8/\pi)^{\frac{1}{2}}=1.6$, D is the "Debye length" well known from the theory of electrolytes.

For $\lambda=3$ m, $T=10^6$ °K, and $v_e\approx 6000$ km/sec, an "oscillating domain" has a diameter $D\approx 1$ cm and contains $\sim 10^8$ electrons performing synchronous oscillations. It is easily verified that such domains can well account even for the strongest observed radio emissions (On the other hand, for wavelengths <0.1 cm, the

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[1] For detailed references see the following recent reports: M. E. Stahr, Radio Astronomy Report No. 2, 4, and 10 (Cornell University, Ithaca, New York, 1948, 1950); J. S. Hey, Monthly Notices Roy. Astron. Soc. **109**, 179 (1949); G. Reber and J. L. Greenstein, Observatory **67**, 15 (1947); A. Unsöld, Naturwiss. **34**, 194 (1947) and Z. Astrophys. **26**, 176 (1949).

* The velocity of sound waves propagated mainly by the electrons is also $\sim v_e$; that of the particles exciting auroras and magnetic storms is only about one-fourth the size.

number of electrons in an oscillating domain becomes so small, according to Eqs. (1) and (4), that only a weak "disturbed" radiation can be emitted.) Self-absorption plays no appreciable role, because the plasma does not contain "preformed" *D*-domains. Since, without magnetic field, every electron stays during only about one oscillation within a domain, its emission should exhibit a bandwidth $\Delta\nu$ of the order of the frequency ν itself. The damping constant of the emission, as various authors have noted,[2,3] should be determined by the number of collisions per sec (e.g. $\sim 1\ \text{sec}^{-1}$ in the solar corona).

Apart from consideration of theoretical details we emphasize that the "quiet" solar radiation is emitted thermally, i.e., in accordance with Kirchhoff's law, while the "disturbed" radiation is typically nonthermal.

B

The *galactic radiofrequency radiation* has, following Henyey and Keenan,[4] been interpreted mostly (in analogy with the "quiet" solar radiation) as free-free radiation of the interstellar gas. At first this hypothesis seemed quite consistent with the observations, even quantitatively. Recently, however, better observations in connection with a more detailed theoretical analysis have shown that the interstellar hypothesis can explain only a small fraction of the galactic radiation, the major part being produced in analogy with the "disturbed" solar radiation.[2,5]

Let us consider the main arguments for this thesis:

(a) *Intensity of galactic radiation in the 10 to 15 m range.* Since the intensity of thermal radiation must always be inferior to that of a blackbody having the temperature of the emitting gas, we can use absolute intensity measurements for deriving a lower limit for the electron temperature of the interstellar gas, assuming that the latter emits the radiation. Following this idea Townes and Unsöld independently arrived at temperatures higher than 100,000°K. Such excessive temperatures, however, are incompatible with our astrophysical knowledge of the interstellar gas. Even in planetary nebulae whose central stars do have temperatures of more than 100,000°, the electron temperature reaches only 6000 to 10,000°, since the fast photoelectrons lose their energy by collisions with oxygen ions.

(b) *Intensity of interstellar H_α radiation.* If the galactic radiofrequency radiation were mostly due to free-free transitions in the interstellar hydrogen gas (other elements being considerably less abundant), it should be accompanied by H_α recombination-radiation whose relative intensity can easily be computed and proves to be almost independent of the assumed temperature. The result of such calculations which were made by Unsöld and later, but independently, by Lambrecht[6] is that the observed radiofrequency radiation of the galaxy is too strong in comparison with the intensity of the H_α radiation measured by Struve and Elvey.

(c) *Spectral intensity distribution of the galactic radiation.* For the quasithermal emission of the interstellar gas by free-free transitions, theory leads us to expect a spectral intensity distribution $I_\nu \approx \text{const.}$ for optically thin layers, while optically thick layers should give blackbody radiation with $I_\nu \sim \nu^2$.

Observations (see reference 2) over the frequency range from 25 to 200 Mc/sec indicate that on the average $I_\nu \sim \nu^{-0.4}$, in definite disagreement with the above predictions but in good agreement with measurements of the disturbed solar radiation, whose I_ν also decreases mostly toward higher frequencies. Solar observations by Ryle and Vonberg for 80 and 175 Mc/sec give on the average $I_\nu \sim \nu^{-0.05}$ and for violent disturbances exponents up to -1.5 (the "quiet" solar radiation in the same frequency range corresponding to $I_\nu \sim \nu^{+0.92}$).

(d) *Cosmic centers of radiofrequency radiation.* We need hardly emphasize that the high intensity of the radiating centers discovered by Hey and others certainly cannot be explained on a quasithermal basis.[7] It must be due to some sort of plasma oscillations. Recent observations by Bolton, Stanley, and Slee[8] seem to identify some discrete sources of radiofrequency radiation with known nebulae (one being the Crab nebula produced by a supernova which exploded A.D. 1054). However, even if other discrete sources should be identified with similar astronomical objects, it does not seem possible to ascribe the general galactic radiofrequency radiation to plasma oscillations of the interstellar medium:

1. The Langmuir frequency of the interstellar gas, 9 kc/sec for 1 electron/cm^3, is far below the "astronomical" frequency range.
2. The concentration of galactic radiofrequency radiation in galactic longitude towards the galactic center $l=325°$ is considerably stronger, and that in galactic latitude much less, than might be expected if it originated from the interstellar medium, which is known to exhibit little concentration in longitude but a strong concentration towards the galactic plane.

(e) *Stellar origin of the galactic radiofrequency radiation.* All the evidence discussed so far points toward the idea that the galactic radiofrequency radiation originates like the disturbed solar radiation in "active" stellar atmospheres, where plasma oscillations are

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[2] A. Unsöld, Z. Astrophys. **26**, 176 (1949) (concerning literature see this paper).

[3] J. C. Jaeger and K. C. Westfold, Austr. J. Research (A) **2**, 322 (1950).

[4] L. G. Henyey and P. C. Keenan, Astrophys. J. **91**, 625 (1940).

[5] A. Unsöld, Nature **163**, 489 (1949).

[6] H. Lambrecht, Astr. Nachr. **277**, 223 (1949).

[7] The "variability" of these centers has recently been proved by Smith, Little, and Lovell [Nature **165**, 422 (1950)] to be mainly by ionospheric origin. The sizes and velocities of the required "ionospheric striae" agree quite well with those of the "luminous night clouds" observed by Jesse, Störmer, Publ. Oslo Univ. Observ. **1**, No. 6 (1933); Astrophys. Norv. **1**, 87 (1934); and others.

[8] Bolton, Stanley, and Slee, Nature **164**, 101 (1949).

excited by turbulence, sometimes perhaps in conjunction with magnetic fields.

This hypothesis, however, has usually met with one weighty objection: the ratio of the average radiofrequency radiation at 64 Mc/sec to the visual radiation is $\sim 2\times 10^9$ times higher for the galaxy than it is for the sun.

We propose[2,5] to interpret this ratio as indicating that our sun is only a very poor radiofrequency transmitter and that other stars show an "activity" qualitatively like our sun, but quantitatively several billion times stronger.

Even so, the total energy radiated by the stars in the range of radiofrequencies is still a minute fraction of their total light and heat radiation.

An increase of the ratio of radio to visual radiation by a factor $\sim 10^9$ to 10^{11} compared with the average sun can be understood without difficulty, considering the tremendous increase of the solar radiofrequency radiation observed during solar flares. On July 25, 1946, Lovell and Banwell observed at 72 Mc/sec the solar radiation (compared with the quiet one) increasing by a factor $\sim 5\times 10^6$ during a flare whose total area was only 1/800 of the visible hemisphere while the actually radiating part probably was still smaller. Moreover, it should be remembered that for cool stars the visual radiation per unit surface is much smaller than for the sun; for M stars by a factor ~ 90. Combining these factors, 10^{10} is reached quite easily.

In this connection it is very remarkable that astrophysicists have found numerous spectroscopic indications of "stellar activity" vastly superior but qualitatively similar to that of our sun.

1. On the sun, "active" areas are indicated by bright reversals of the Ca II H and K lines and of hydrogen H_α. These emissions, however, are barely visible in the integrated solar spectrum.

Recently, Joy and Wilson[9] have collected all the evidence, beginning from Eberhard and Schwarzschild's discovery in 1913, concerning bright H and K lines in stellar spectra, mostly of types later than the sun. These spectra indicate that the surface of such stars quite frequently exhibits an average activity superior to that within spot groups on the sun which occupy only a minute fraction of the solar surface.

2. In the variable M-type giant Mira Ceti, Joy[10] discovered bright hydrogen lines with superposed metallic absorption lines of the reversing layer. Quite a similar structure was observed by Ellermann[11] in the so-called "solar bombs," indicating a very high degree of local activity. Again, the average stellar spectrum corresponds to the most active areas on the sun.

3. Recently, Luyten, Kron, Joy, and Humason[12] have detected in several late-type dwarf stars most violent variations of light and spectrum, which can be interpreted almost only as "flares" similar to those familiar on the sun. Kron,[13] moreover, detected regular light variations of 0^m06 with a period of 115 days for Ross 248, which point towards an explanation in terms of a rotating star with a patchy or spotted surface.

Other objects like Babcock's "magnetic" variables, Struve's close binaries emitting prominence-like gaseous streams, and the Wolf-Rayet stars with their enormous doppler effects should perhaps be mentioned also in this connection. Statistical evidence, which however cannot yet be considered as definitive, seems to indicate that late-type stars produce the largest part of galactic radiofrequency radiation.

III. ORIGIN OF COSMIC RAYS IN THE ATMOSPHERES OF HIGHLY ACTIVE STARS

The ratio of the average solar radiation to the radiation flux coming from the universe or the galaxy is,[2] for visual light, 4×10^8; for cosmic rays (according to Ehmert), 0.7×10^{-3}; and for radiofrequency radiation at 64 Mc/sec $\sim 10^{-1}$. It seemed, therefore, quite hopeless to try to ascribe the general cosmic radiation to stars as long as it was compared with visual light. The work of Forbush[14] and Ehmert,[15] as well as that of Clay, Jongen, and Dijker[16] and others, however, has shown that solar cosmic-ray bursts occur always in connection with large solar flares which also give strong radiofrequency bursts. Accepting our hypothesis that the galactic radiofrequency radiation and cosmic rays both originate in stars, whose "activity" surpasses that of the sun by a factor of $\sim 10^{10}$, in qualitatively the same way and the same ratio as they do in the sun, we are able to explain the great intensity of cosmic rays up to a factor 10^{-1}: $0.7\times 10^{-3} \approx 140$. In the following section we show that a factor of this order of magnitude or probably somewhat larger can, together with other important features of cosmic radiation, be accounted for by a galactic magnetic field. For the present we note that we do not presume that cosmic rays and radiofrequency radiation originate exactly together, but that they are connected statistically within the general frame of solar and stellar activity.

IV. PROPAGATION OF COSMIC RAYS IN THE GALAXY

It is well known that the energy of cosmic radiation is about equivalent to the total light plus heat flux from all the stars. This fact in connection with the second law of thermodynamics would preclude a stellar origin of the cosmic radiation, and it is, in this connexion, also not astonishing that our hypothesis of superactive stars by itself explains only a fraction of the observed inten-

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[9] A. H. Joy and R. E. Wilson, Astrophys. J. **109**, 231 (1949); and A. H. Joy, Astrophys. J. **110**, 424 (1949).

[10] A. H. Joy, Astrophys. J. **108**, 288 (1947).

[11] F. Ellermann, Astrophys. J. **46**, 298 (1912).

[12] See numerous notes in Publ. Astron. Soc. Pacific **61** (1949); etc.

[13] Kron, Sky and Telescope **9**, 161 (1950).

[14] S. E. Forbush, Phys. Rev. **70**, 771 (1946).

[15] A. Ehmert, Z. Naturforsch. **3a**, 264 (1948).

[16] Clay, Jongen, and Dijker, Proc. Acad. Sci. Amsterdam **52**, 899, 906, and 923 (1949).

sity. As various authors, especially Alfvén and Fermi,[17] have pointed out, this difficulty, together with the observed isotropy of cosmic rays, can be accounted for by the assumption of a turbulent interstellar magnetic field.

It is evident that such a field will at once establish directional isotropy of cosmic rays.

By "coiling" the paths of the primary cosmic-ray particles the magnetic field will "store" the cosmic radiation in the galaxy. An upper limit of this effect can at once be derived, essentially following Fermi's ideas: A fast particle can at most wander through the galaxy until it hits an atom of interstellar matter so closely that a meson shower is produced whose secondaries "degenerate" rapidly. Taking the density of interstellar matter $\sim 2.5\times 10^{-24}$ g/cm^3, the mean free path Λ, determining the "life" of a cosmic-ray particle corresponding to ~ 100 g/cm^2,† becomes 4×10^{25} cm $=1.3\times 10^7$ parsec. If the particles were not deflected by a magnetic field (as, for instance, the accompanying radiofrequency waves) they would come from an average distance of only $r_1 \approx 1000$ pc (half the thickness of the galaxy being $z_0 \approx 150$ pc, and our distance from its center $R\approx 10{,}000$ pc). Thus, the "storage-factor" can at most amount to $\sim 10^4$. Evidently the factor ~ 140 (or more likely $\sim 10^3$) missing in our previous considerations can, together with the directional isotropy, be well explained by an interstellar magnetic field.

Let us now consider the propagation of cosmic rays in our galaxy in somewhat greater details.

(A) Scattering by Magnetic Turbulence Elements

Following Fermi,[17] we might assume that a cosmic-ray particle can be scattered (isotropically) by magnetic turbulence elements in interstellar space with a mean free path $l \ll \Lambda$. A total path r_2 corresponds then to $n=r_2/l$ free paths. According to a well-known theorem, the distance towards a fixed direction reached after n random steps of length l is $l(n/3)^{\frac{1}{2}}$. On the other hand, a particle should leave the galaxy after having permeated about half its thickness $z_0\approx 150$ pc. Therefore, the total path of a particle within the galaxy will be

$$r_2 = 3z_0^2/l = 7\times 10^4/l. \tag{5}$$

(B) Reflection at the Boundary of the Galaxy

Having arrived at the boundary of the galaxy, a particle may either be "reflected" or escape into intergalactic space. Ascribing formally to the galactic boundary a reflexion coefficient $\rho = 1-\zeta$, a particle will still be present after 1, $2\cdots$ reflections with a probability ρ, $\rho^2\cdots$. The distance $\approx 4z_0$, which it must on the average permeate until it reaches the boundary of the galaxy, is therefore effectively extended by a factor

$$1+\rho+\rho^2+\cdots = 1/(1-\rho) = 1/\zeta. \tag{6}$$

i.e., we obtain a total average path r_3,

$$r_3 \approx 4z_0/\zeta = 600/\zeta. \tag{7}$$

Let us now *summarize* our results:[17a]

A particle will migrate within the galaxy over a distance

$r_1 \approx 1000$ pc in the case of straight motion.

$r_2 \approx 7\times 10^4/l$ pc in the case of scattering by turbulence elements with an average size $\sim l$.

$r_3 \approx 600/\zeta$ pc in the case of reflexion at the boundary of the galaxy to which a transmission coefficient ζ is ascribed.

$\Lambda \approx 1.3\times 10^7$ pc if its path is very coiled.

Scattering should become important if $r_2 \gg r_1$, i.e. $l<10$ pc, and reach its full effect if $r_2>\Lambda$, i.e., $l<5\times 10^{-3}$ pc. In galactic gaseous nebulae, good photographs show details down to at least 10^{-2} pc, but recent evidence makes us feel doubtful whether these structural elements can be considered as "magnetic turbulence elements." If the observations of Hiltner[18] and Hall[19] on the polarization of starlight by cosmic clouds are interpreted in terms of a magnetic field, this must be rather uniform over dimensions of at least 200 pc. Also, theoretical considerations by Biermann and Schlüter[19a] indicate that only turbulence elements $\geqslant 200$ pc can be magnetized, while small scale motion should be considerably restricted by the magnetic field of the larger turbulence elements.

Cosmic radiation, once generated, should then spread chiefly along the magnetic lines of force. Since the intensity at such points in space, which can be reached at all, is the same according to the generalized Liouville theorem,[20] we expect that, in general, a tube of force will be filled with cosmic radiation rather uniformly. In order to make the storage within extended tubes of force efficient, $r_3=600/\zeta$ must reach the order of magnitude of $\Lambda=1.3\times 10^7$ pc; i.e., the transmission coefficient ζ must be $<1/20000$.

One might ask first whether the magnetic field of the galaxy could produce totally reflecting torus surfaces of the kind familiar from Störmer's theory of the aurora. It is easily seen, however, using the dynamics of a charged particle in a magnetic field in the form developed, for example, by Alfvén,[21] that such surfaces are only encountered moving towards increasing field strength. A cosmic-ray particle intending to leave the galaxy, however, is moving for the most part just the other way.

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[17] E. Fermi, Phys. Rev. **75**, 1169 (1949).

† We are indebted to Dr. Haxel, Göttingen, Germany, for his kind advice on this problem.

[17a] A more detailed mathematical analysis of the discussed items has been made, following closely the methods developed for radiative equilibrium problems in stellar atmospheres, by A. S. Eddington, *The Internal Constitution of the Stars* (University Press, Cambridge, England, 1930), chapter 12. For the present purpose it is hardly worthwhile to present it in detail.

[18] W. A. Hiltner, Astrophys. J. **109**, 471 (1949).

[19] J. S. Hall and A. H. Mikesell, Astron. J. **54**, 187 (1949).

[19a] L. Biermann and A. Schlüter, Phys. Rev. **82**, 863 (1951).

[20] W. Heisenberg, *Kosmische Strahlung* (Berlin, 1943), contribution by J. Meixner, p. 148.

[21] H. Alfvén, Arkiv Mat. Astron. Fysik **27A**, 22 (1941).

Nevertheless, an extremely small ζ is not as unreasonable as it might appear, offhand. A particle can leave the galaxy only under the following conditions: 1. If its Larmor radius R becomes large compared with the geometrical dimensions of the field. For $H=10^{-5.5}$ gauss, however, 10^{10} ev give $R=3.4\times 10^{-6}$ pc only; i.e., such an escape is practically impossible. 2. If the pressure (resp. energy density) of the accumulated cosmic radiation becomes larger than that of the magnetic field $H^2/8\pi$ and of the interstellar matter $\rho v^2/2$. The well-known observational evidence that the three mentioned pressures are of the same order of magnitude indicates that probably cosmic radiation is accumulated in the galaxy until it begins to escape under its own pressure gradient together with magnetized interstellar matter.

Our present estimates of the rate of production of primary cosmic radiation are not yet accurate enough to judge the possible cosmogonical importance of this process. However, we can feel fairly sure that the storage factor of cosmic radiation in our galaxy is near its upper boundary value 10^4.

Apart from a storage factor $\sim 10^4$, our considerations automatically account for the observed high degree of isotropy of cosmic radiation.

Since, according to our present ideas, cosmic radiation is connected with interstellar matter through the magnetic field of the galaxy, and since the solar system almost shares the galactic rotation of the latter, we should even expect no "Compton-Getting effect."

As Professor Bagge kindly pointed out to us, observational evidence concerning this effect seems not yet convincing. While the recent measurements by Hogg,[22] comparing the sidereal period in the northern and southern hemispheres, as well as a previous comparison of north and south absolute intensities by Compton[23] and his collaborators, appear unfavorable for the existence of the effect; the old investigation by Rau,[24] measuring only the hardest component under very good conditions, is more in favor of a positive effect. A clear decision can probably only be gained by repeating Rau's experiment simultaneously on the northern and southern hemispheres over an interval of several years.

Concerning the energy spectrum of the cosmic radiation we can make the following comments: Since an average cosmic-ray particle before reaching the earth has traversed some 50 g/cm^2 of interstellar matter, most particles with energies below about 5×10^8 ev should have been removed from the primary cosmic radiation simply by ionization.[25] In order to explain the cutoff of the cosmic-ray spectrum for small energies it is, therefore, not necessary to appeal to the action of a general magnetic field of the sun, whose existence has become very doubtful through recent observations by Babcock and Thiessen.[26] In connection with our theory it would be important to observe the low energy limit more accurately by high altitude flights (with less than 50 g/cm^2 air mass) near the geomagnetic poles.[27]

As to the *chemical composition* of the cosmic radiation observed at high altitudes, certain difficulties pointed out by Bradt and Peters[28] concerning the light nuclei cannot yet be explained in a satisfactory way. This point should be investigated in greater detail.

The well-known 2.9 power law governing the energy distribution of cosmic rays is, in our theory, more or less a consequence of similar power laws determining the number of turbulence elements (e.g. sunspots) of various sizes in stellar atmospheres. The sun is known to produce particles up to about $5\cdot 10^9$ ev; a supergiant with a surface area 10^5 times larger and correspondingly larger spots may well produce particles up to 10^{14} ev. The observed energy spectrum of cosmic rays should roughly reflect the frequency distribution of various

$$\oint(\mathbf{E}, d\mathbf{s})=\frac{1}{c}\frac{d}{dt}\int \mathbf{B}_n d\sigma$$

(in the notations usual for Maxwell's theory). Since the small whirls are produced by subdivision of larger ones, they are more abundant, as we observe with sunspots. Smaller spots will have smaller fields and faster changes; these two factors operate against each other. Finally, small stars are more frequent than large ones. It is not yet possible to make detailed statistics concerning all these factors, but we may expect, offhand, that something like an inverse power of the observed order of magnitude will turn out.

V. OTHER THEORIES CONCERNING THE ORIGIN OF COSMIC RAYS

Let us now review critically the theories of cosmic radiation recently advanced by Fermi[17] as well as those of Richtmyer and Teller.[29] On the other hand, we shall not deal with theories attempting to connect cosmic radiation with the beginnings of the universe some 5×10^9 years ago.

(A) Fermi's Theory

Fermi assumes that cosmic-ray particles gain an essential part of their energy on their way through the galaxy by collisions with magnetic turbulence elements. The exponent $n=2.9$ in the law of energy distribution has, according to Fermi, the meaning

$$n=1+(l/\Lambda)(c/v)^2, \qquad (8)$$

where again Λ and l, respectively, are the mean free paths for absorption by nuclear collisions and for

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[22] A. R. Hogg, Nature **162**, 613 (1948).

[23] A. H. Compton, Revs. Modern Phys. **11**, 136 (1939).

[24] W. Rau, Z. Physik **114**, 165 (1939).

[25] See, for example, H. Bethe, *Handbuch der Physik* (Verlag. Julius Springer, Berlin, 1933), **24/2**.

[26] G. Thiessen, Z. Astrophys. **26**, 16 (1949).

[27] Compare also M. A. Pomerantz, Phys. Rev. **77**, 830 (1950).

[28] H. L. Bradt and B. Peters, Phys. Rev. **77**, 54 (1950).

[29] R. D. Richtmyer and E. Teller, Phys. Rev. **75**, 1729 (1949); and several subsequent papers.

scattering by turbulence elements. Here v is the average relative velocity of the scattering turbulence elements, and c is the velocity of light. Numerically, Fermi takes $\Lambda = 2.3 \times 10^7$ pc and $l = 0.4$ pc. For the velocity of the turbulence elements he assumes $v = 30$ km/sec or $v/c = 10^{-4}$, and thus obtains the required $n = 2.9$.

An observational average value of the velocity of interstellar matter can be derived in the first place from its density distribution in the gravitational field of the galaxy.

The acceleration which the galaxy exerts at a distance z [cm] from its central plane in our neighborhood is, according to Oort[30] for $z < 200$ pc

$$K(z) = -0.57 \cdot 10^{-29} z \ [\text{cm sec}^{-2}]. \tag{9}$$

Let the velocity component of matter perpendicular to the galactic plane be Z. Then (as in an isothermal atmosphere of temperature $kT = \mu \overline{Z^2}$) the density distribution $\rho(z)$ is determined by

$$(1/\rho) d\rho(z)/dz = -K(z)/\overline{Z^2} \tag{10}$$

or

$$\rho(z)/\rho(0) = \exp\left\{ -\frac{0.57 \times 10^{-29} z^2}{2\overline{Z^2}} \right\}. \tag{11}$$

On the observational side van Rhijn,[31] summarizing also earlier evidence, describes the density distribution of interstellar "smoke" (grains) by the formula,

$$\rho(z)/\rho(0) = e^{-qz} \text{ with } \tfrac{1}{q} = 120 \text{ pc}. \tag{12}$$

Equating (11) and (12) for $\rho(z)/\rho(0) = 1/e$ we get immediately[31a]

$$[\langle Z^2 \rangle_{\mathrm{Av}}]^{\frac{1}{2}} = 6.3 \text{ km/sec}. \tag{13}$$

This velocity refers to turbulence elements filling approximately the cross section of the galaxy or having a diameter of ~250 pc. Since the velocity distribution of galactic turbulence will probably be not far from isotropy, we compare it with the turbulent velocities derived from Mt. Wilson measurements of interstellar sodium and calcium lines by Jentzsch and Unsöld.[32] They find for a distance of 250 pc that $[\langle Z^2 \rangle_{\mathrm{Av}}]^{\frac{1}{2}} = v_D/\sqrt{2}$ (using the notation of that paper):

$$[\langle Z^2 \rangle_{\mathrm{Av}}]^{\frac{1}{2}} = \begin{cases} 7.1 \text{ km/sec for Ca II } H+K \\ 4.4 \text{ km/sec for Na } D. \end{cases} \tag{14}$$

It is not known how the difference between the Ca^+ and Na velocities should be explained, but, in any case, their average value, 6.6 km/sec, agrees well with Eq. (13). The limits of uncertainty may be estimated to be ±2.5 km/sec.

Passing to smaller turbulence elements, we should be aware that according to v. Weizsäcker[33] and Heisenberg[34] the velocities decrease about as the cube root of their diameters. For the interstellar gas the determination of turbulent velocity as a function of distance between $D = 100$ and 2000 pc by Jentzsch and Unsöld (reference 32, Fig. 8) agrees well with this law. For elements 0.4 pc in diameter we should then expect a $[\langle Z^2 \rangle_{\mathrm{Av}}]^{\frac{1}{2}} = 6.3(0.4/250)^{\frac{1}{3}} = 1.2$ km/sec and relative velocities v (in analogy with well-known formulas of kinetic theory) $4/\sqrt{\pi}$ times greater, i.e.,

$$v = 2.7 \text{ km/sec}. \tag{15}$$

This would give a "theoretical" exponent $n \approx 200$, according to Fermi's Eq. (8), which means that we get practically no additional acceleration in the interstellar gas.

One might try to remedy the matter by reducing in Eq. (8) the diameter l of the turbulence elements, about which our knowledge is still admittedly meager. Then however, v decreases again. It is easily seen that no reasonable choice[34a] of l can remove the difficulty which, indeed, proves fatal for the theory of interstellar acceleration even if one should be inclined to disregard the aforementioned objections concerning the magnetization of the small turbulence elements.

Finally, it appears rather unsatisfactory that according to Fermi's theory the existence of a cosmic radiation is connected with quite definite properties of interstellar turbulence, i.e., that it is almost a matter of chance.

(B) The Richtmyer-Teller Theory

Let us now examine the hypothesis advanced by Richtmyer and Teller,[29] that the cosmic radiation is really solar radiation entrapped by a magnetic field surrounding the sun. Denote by $I_\odot$ the average intensity (per unit surface, time, and solid angle) of the cosmic rays emitted by the sun, by I the average intensity of the general cosmic radiation. Then, the average ratio of the observed fluxes due to the sun and space is $I_\odot \Delta\omega/\pi I$, where $\Delta\omega = 6.8 \times 10^{-5}$ is the solid angle of the solar disk. As the observational value of our ratio, according to Ehmert, is $\sim 7 \times 10^{-4}$, we find $I_\odot/I \approx 32$.

Since the mean free path of a cosmic-ray particle in galactic space is $\Lambda = 1.3 \times 10^7$ pc, it may at most keep going during a time $T = \Lambda/c \approx 4 \times 10^7$ years. During this time interval the sun (radius $R_\odot$) emits altogether

$$\pi I_\odot \cdot 4\pi R_\odot^2 \cdot T. \tag{16}$$

If the space to which cosmic-ray particles are confined is a sphere $4\pi \bar{R}^3/3$, the average density of cosmic radia-

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[30] J. H. Oort, Bull. Astr. Inst. Netherlands No. 238 (1932).

[31] P. J. v. Rhijn, Publ. Kapteyn Astr. Inst. (Groningen) No. 50 (1946); No. 53 (1949).

[31a] If the pressure of the magnetic field and of cosmic radiation should be important in addition to the dynamic pressure, this velocity would become still smaller.

[32] Ch. Jentzsch and A. Unsöld, Z. Physik **125**, 370 (1948).

[33] C. F. v. Weizsäcker, Physik **124**, 614 (1947).

[34] W. Heisenberg, Z. Physik **124**, 628 (1947).

[34a] The free paths of atoms in the interstellar gas are $\sim 0.3 \times 10^{-4}$ pc.

tion inside will be $4\pi I/c$ and its total content

$$(4\pi\bar{R}^3/3)\cdot(4\pi I/c). \tag{17}$$

Equating (16) and (17), we get

$$\bar{R}^3=\tfrac{3}{4}(I_\odot/I)R_\odot{}^2\Lambda \tag{18}$$

or

$$\bar{R}=5.4\times10^{-3}\ \mathrm{pc}=1.1\times10^{3}\ \text{astr. units.} \tag{19}$$

Assuming a larger than average density of interstellar matter in our neighborhood, Λ and $\bar{R}$ would become smaller.

It seems quite impossible that the sun can maintain a systematic magnetic field of the strength required to deflect hard cosmic rays appreciably within dimensions of the order $\bar{R}$. If we return, however, to the previous assumption that the magnetic field originates in the interstellar matter, there will always be "channels" allowing cosmic-ray particles produced by the sun to escape into galactic space. Then, however, the observed intensity of the general cosmic radiation can again only be explained by combining the theory of the "storage factor" with our idea of the existence of superactive stars all over the galaxy.

I am indebted to Professor Biermann and Dr. Schlüter for many interesting and stimulating discussions on problems of plasma physics and cosmic magnetic fields.

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Cosmic Radiation and Cosmic Magnetic Fields. II. Origin of Cosmic Magnetic Fields

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The equations governing the behavior of a wholly or partly ionized gas moving in the presence of a magnetic field are given. It is emphasized that the electric conductivity is independent of the magnetic field strength in many cases of actual interest. The stationary case of a magnetic field arising from the nonrigid rotation of a gaseous body is considered. Such a field is of the toroidal type. Fields of poloidal type may arise by the contraction of magnetized interstellar matter towards a star. The increase of strength of a magnetic field in turbulent conducting matter (stellar or interstellar) is considered. The conclusion is reached that the turbulence of every order of magnitude leads finally to a magnetic field, the energy density of which corresponds roughly to the energy density of the turbulence considered. If the magnetic field was weak in the beginning, this state was reached at first by the turbulence of smallest scale and smallest velocity, and then by the turbulence of higher orders; hence, the magnetic field strength must change secularly, as long as this process goes on. If our galaxy had only weak fields in its earlier stages, the present magnetic field should correspond to the turbulent velocity associated with distances of the order of 10^3 light years (between 10^{-6} and 10^{-5} gauss), and these fields should be more or less homogeneous over distances of this order. If there were already fields in the beginning, the present fields might be somewhat stronger.

INTRODUCTION

THE problem of the origin of stellar magnetic fields has caused considerable interest since Hale[1] communicated his measurements of the sun's general field. Although these results have not been confirmed lately, the discovery by Babcock[2] of highly magnetized stars has renewed this interest. No definite theory of the origin of these fields has as yet been proposed. We will show that one has to expect that differential rotation and other internal motions inside the stars will quite naturally cause magnetic fields, since electrons and ions will not move in exactly the same way just because of the different masses.

The existence of interstellar magnetic fields has been derived[3] from the properties of cosmic rays. If the cosmic rays occupied the whole universe with the energy density observed in our immediate neighborhood, their total energy would exceed that of light, and it would not be easy to escape the conclusion that more energy is continuously being transformed into that of cosmic rays than into that of heat radiation. Barring this possibility, it has to be assumed that the cosmic rays observed by us are continuously being produced within the galactic system or within a part of it. The approximate isotropy of their intensity is then explained by assuming interstellar magnetic fields of sufficient energy density to overcome the pressure of the cosmic-ray particles (10^{-5}–10^{-6} gauss). In this case the required production of cosmic rays would become much smaller than in the case of the first assumption; as discussed in detail by Unsöld[3a] in the preceding paper, it would be sufficient to assume that only a small fraction of the energy output of the stars is converted into cosmic-ray energy.

Here, of course, the question imposes itself of whether there are independent reasons for assuming galactic

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[1] Hale, Seares, v. Maanen, and Ellermann, Astrophys. J. **47**, 206 (1918).

[2] H. W. Babcock, Astrophys. J. **105**, 105 (1947).

[3] H. Alfvén, Arkiv. Mat. Astron. Fysik **25B**, No. 29 (1937); Z. Physik **107**, 579 (1937); E. Fermi, Phys. Rev. **75**, 1169 (1949). See also H. Alfvén, *Cosmical Electrodynamics* (Oxford, 1950).

[3a] A. Unsöld, Phys. Rev. **82**, 857 (1951).