THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 55, NO. 5 | MARCH 1, 1939 | SECOND SERIES

On the Motion of Cosmic Rays in Interstellar Space

HANNES ALFVÉN
Forskningsinstitutet för Fysik, Stockholm, Sweden
(Received October 29, 1938)

The limitation of a current consisting of charged high energy particles (cosmic rays) passing through interstellar space is discussed. As interstellar matter is ionized, interstellar space is considered as a good conductor so that the electric field always equals zero. The motion of the particles is then governed by the magnetic fields produced by themselves. This sets a rather low upper limit to the currents through space so that a difference in intensity of cosmic rays in different points is smoothed out very slowly. This means that the intensity may vary considerably even within the galactic system. An explanation of the excess of positive particles in cosmic radiation is tentatively suggested. Arguments are given for the view that most of the rays we receive on the earth are generated within less than 1000 light years from us.

I

As the main part of the cosmic radiation very likely consists of positively charged particles an anisotropy of the radiation is equivalent to an electric current through space. As has been shown elsewhere[1] the magnetic field caused by such a current is strong enough to prevent the existence of a measurable anisotropy. Consequently, if in two adjacent volumes in space the intensity of the radiation has different values, the difference cannot be smoothed out very rapidly because a direct current from the high intensity volume to the low intensity one is limited by the magnetic field. The intensity of the cosmic radiation can therefore very well vary considerably in interstellar space. For example the intensity outside our galaxy may be very small although the intensity in our part of the galaxy is considerable.

In order to calculate the motion of cosmic rays in space we have to solve the following problem: *Suppose that cosmic rays of different energies are generated in certain parts of interstellar space* (e.g., at the double stars); *how will these rays move and what is the intensity of the radiation at a certain point?*

The general solution of the problem offers very great mathematical difficulties and no way of attack has as yet been found. We must therefore confine ourselves to a simple special case in which it is possible to estimate the factors limiting the free exchange of cosmic rays between different parts of space. It is clearly understood that there may be some danger in drawing too far-reaching general conclusions from such a special case. But on the other hand, as there no doubt always is an upper limit to a charged particle current through space, the treatment of a special case is very likely to give the right order of magnitude of this limit, and also to give a survey of the types of phenomena which must be taken into consideration.

II

The density of cosmic-ray particles in interstellar space in our neighborhood is of the order

[1] H. Alfvén, Phys. Rev. **54**, 97 (1938).

of magnitude of 10^{-10} or 10^{-11} cm^{-3}. The density of interstellar matter is of the order of magnitude of 10^{-25} g cm^{-3} and at least a considerable part of it consists of slow ions and electrons. Consequently, the number of slow ions in interstellar space can be supposed to be of the order of magnitude of 10^{-2} of 10^{-3} cm^{-3}, i.e., there are about 10^8 slow ions or electrons to every cosmic-ray particle. Any space charge set up by the cosmic rays will therefore be neutralized very

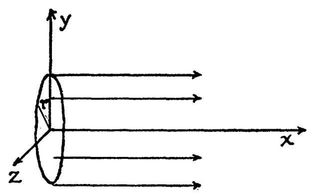

FIG. 1.

easily through a small displacement of the slow particles. In other words, as interstellar space can be assumed to be a good conductor no considerable electric field can be established. In the following we assume that *the electric field is zero* in a system where the interstellar matter is at rest, and that only magnetic forces act upon the cosmic rays. As the magnetic fields from celestial bodies are confined to their close neighborhood the motion of cosmic rays is governed by the magnetic fields produced by their own motion.

III

As an example we will treat the following special case. Suppose that we have an infinite conducting plane (y–z plane (Fig. 1)) in interstellar space. From a circular surface with the radius r_0 charged particles (for example positives) are emitted in the direction of the positive x axis, all of them having the same mass m and the same energy eV, the latter being of the same order of magnitude as that of the cosmic rays. We consider the state when the emission has been going on at a constant rate for a considerable time so that all transient phenomena have disappeared. The space charge of the emitted particles is then neutralized by slow ions so that the emitted particles travel under the influence of the magnetic field of the ray itself. (In order to close the current we can assume that the emitted charge is brought back to the surface through slow ions at a large distance from the x axis. Or we can assume that a corresponding number of negative rays is emitted from the surface in the direction of the negative x axis.)

Let i_0 be the current density of the emitted rays. If the total current $I=\pi r^2 i_0$ is very small ($\ll cV$, where c is the velocity of light), the beam is a circular cylinder and causes a magnetic field:

$$H=2Ir/cr_0^2; \quad r<r_0. \tag{1a}$$

$$H=2I/cr; \quad r>r_0. \tag{1b}$$

If I increases so that the magnetic field is considerable, the particles in the beam are deviated towards the axis. The radius of curvature of their path is

$$\rho=(V^2+2mc^2V/e)^{1/2}/H \tag{2}$$

or if $eV\gg mc^2$

$$\rho=V/H. \tag{2a}$$

As a first approximation we assume that (1) still holds. The equation of the motion is then

$$\rho=-\frac{[1+(dr/dx)^2]^{3/2}}{d^2r/dx^2}=\frac{cVr_0^2}{2Ir} \quad \text{if } r<r_0, \tag{3a}$$

$$=cVr/2I \quad \text{if } r>r_0. \tag{3b}$$

The Eq. (3a) can be integrated by means of elliptic functions. Fig. 2 shows the path of particles starting in the direction of the x axis at different distances from it and obeying (3a). It is evident that the particles on the paths $aa'a''$, $bb'b''$, $cc'c''$, and $dd'd''$ on the whole move in the positive direction so that they constitute a part of the beam. But the particles on the paths $ee'e''$ and $ff'f''$ go in the opposite direction. Consequently, only the particles up to a certain limit $r=r'$ situated between d and e will take part in the beam. If we put $r_0=r'$ and apply (3b) to the portion $r>r_0$, the paths $ee'e''$ and $ff'f''$ still go in the negative direction. The limit r_0' is reached when

$$I_0=1.65cV. \tag{4}$$

If we now try to calculate the motion of the particles not in the magnetic field given by (1) but in the real field produced by the particles themselves it is evident that the limit is changed, but it must still have the same order of magnitude. Consequently, *the maximum current in a* *direct beam through interstellar space is of the order of magnitude of*

$$I_0 \sim cV \tag{5}$$

(or expressed in practical units

$$I_0 \sim V/30, \tag{5a}$$

where I_0 is the maximum current in amperes and V is the energy of the particles in electron volts).[2]

It is interesting that the limit does not depend upon the current density or cross section of the beam, but only on the energy. If $V = 10^{10}$ ev and $i_0 = 0.5 \times 10^{-19}$ amp./cm^2 the radius of the beam is $r' \sim 0.5 \times 10^{14}$ cm $= 0.5 \times 10^{-4}$ light year.

IV

We have found that in a beam consisting of positive *or* negative particles the number of particles per second cannot surpass the order of magnitude of $I_0/e \sim cV/e$. But if we have a beam consisting of positive *and* negative particles to the same amount and equally distributed the magnetic field of the beam is zero and there seems to be no upper limit to the number of particles.

But as we have supposed interstellar space to be a good conductor, such a beam represents an *unstable* condition, and even a very small disturbance causes it to break up. Suppose that the beam passes through a very weak magnetic field in the direction of the z axis (Fig. 1). Then the positive particles are bent downwards and the negative particles upwards. The separation of the particles gives rise to a current in the direction of the positive x axis in the part of the beam below the x–z plane and a current in the opposite direction above the x–z plane. The magnetic fields of these currents increase the separation which causes a further increase of the magnetic field, so that the beam breaks up into a positive particle beam and a negative particle beam, traveling in opposite directions (parallel to the y axis).[3]

Consequently, even in this case the number of particles in a beam underlies the same limitation.

[2] If eV is not much larger than mc^2, the limit is $I_0 \sim c(V^2 + 2mc^2 V/e)^{\frac{1}{2}}$.

[3] Also, the isotropic emission of the same amount of positive and negative particles from the surface of a sphere is unstable, if the medium around the sphere is conducting.

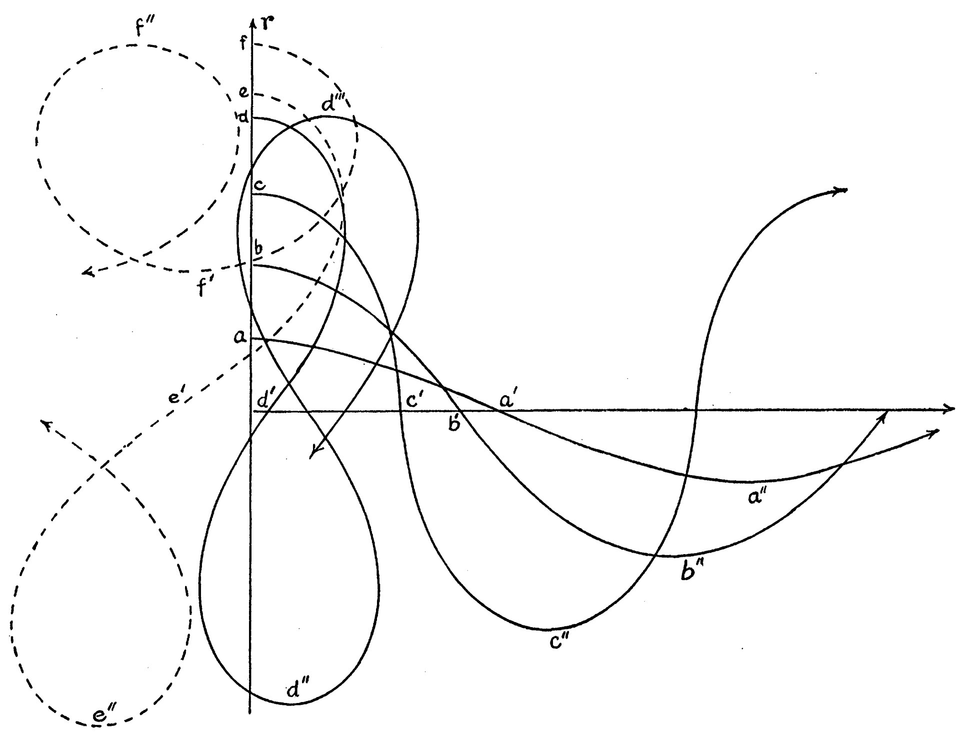

FIG. 2. Paths satisfying Eq. (3a) for particles starting in the direction of the x axis at different distances from it.

V

The upper limit to the current in a beam as found in Section III does not, however, represent the upper limit of the total current through a plane perpendicular to the x axis. Outside the beam the magnetic field decreases as r^{-1}. If a positive particle starts at g in Fig. 3 in the direction of the positive x axis, it follows the path $gg'g''g'''$. It is evident that upon the whole it moves in the direction of the positive x axis. It is

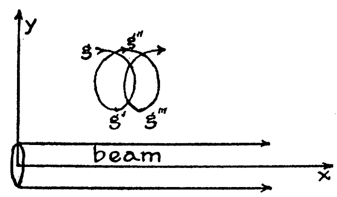

FIG. 3.

easy to show that all positive particles drift in this way if they move in regions where $dH/dr<0$. If $dH/dr>0$ they drift in the opposite directions and if $dH/dr=0$ they have no drift at all in the x direction.

If a lot of particles symmetrically distributed around the axis and at the distance r from it drift in this way, the drift current causes an increase of the magnetic field outside the drift current. This tends to increase dH/dr. As a negative value of dH/dr is necessary in order to give a positive drift, the current limits itself. If $I(r)$ is the current within a cylinder with the radius r we have

$$H=2I(r)/cr.$$

The condition

$$\frac{dH}{dr}=\frac{2}{cr}\left[\frac{dI}{dr}-\frac{I}{r}\right]<0 \tag{6}$$

gives

$$I(r)<kr \tag{7}$$

where k is a constant. This means that the current density decreases at least as r^{-1}.

An upper limit for k can be obtained through the condition that H may never surpass the boundary value of the direct beam, which according to (1) is $H=2I_0/cr_0=2(\pi i_0 I_0)^{\frac{1}{2}}/c$. This gives *the maximum current through a circular surface with the radius r*

$$I<(\pi i_0 I_0 r^2)^{\frac{1}{2}}, \tag{8}$$

where i_0 is the current density in the direct beam and I_0 is given by (5).

It must be pointed out that except in the direct beam and its close neighborhood the anisotropy of the radiation is very small.

VI

It is interesting to observe that if a positive-particle current of the type described in Section V is established, a negative particle must drift in the opposite direction. Thus even in the drift-current region we have the same phenomenon as described in Section IV. Positive and negative particles have a tendency to travel in opposite directions. In the absence of electrostatic forces the magnetic forces between currents in wires tend to make the currents parallel. This is a phenomenon of the same type.

Thus it seems likely that if positive and negative cosmic-ray particles are generated in a certain volume, they will leave it in opposite directions. Consequently, an observer situated on one side of the generators finds an excess of positive particles, an observer on the other side receives more negatives. This means that the sign of the prevalent particles varies with the situation of the observer. Thus, the excess of positive cosmic rays observed here on our earth may be fortuitous, and not representative for the cosmic radiation in other parts of space.

VII

Let us suppose that in a cylinder with the radius r and the length l we have a current of the type discussed here, in the direction of the axes. The maximum of energy which can be transported through the surface of the cylinder is obtained if the current through one of the circular surfaces consists of positive particles and the current through the other one of negative particles. If V is the energy of the particles, the maximum energy per second through the surface amounts to

$$W_r=2VI=2V(\pi r^2 i_0 I_0)^{\frac{1}{2}}=2(\pi c)^{\frac{1}{2}} i_0^{\frac{1}{2}} r V^{\frac{3}{2}}.$$

But if the intensity of the radiation within the cylinder is w erg cm^{-2} sec.$^{-1}$, the total energy of the radiation within the cylinder is

$$W=3w\pi r^2 l/c.$$

The time necessary to empty or to fill the cylinder is (if $w=i_0V$)

$$T=W/W_r=(3\pi^{\frac{1}{2}}rl/2c^{\frac{1}{2}})(i_0/V)^{\frac{1}{2}}.$$

Putting $V=\frac{1}{3}\times10^8$ e.s.u. and $i_0=2\times10^{-10}$ e.s.u. (which corresponds to the intensity at the top of the atmosphere) and $l/2=r=1000$ light years (10^{21} cm), we find $T=10^{11}$ years, which is more than the age of the universe! Further, if we calculate the absorption in interstellar matter within the cylinder, we find that it is many times as large as W_r.

Let us now suppose that our earth is situated within the cylinder. We have found that unless the values of i_0 and V are *many* times larger at the surface of the cylinder than the values measured at the top of the earth's atmosphere (which is improbable), the current through the surface can neither fill the cylinder to the intensity measured here, nor compensate for the absorption losses. Consequently, *cosmic radiation must have been generated within the cylinder.*

This indicates that *most of the cosmic radiation we obtain here on earth has been generated within a distance of less than 1000 light years.*[4] (The thickness of the galactic system is about 10,000, the diameter about 100,000 light years.)

[4] Compare, H. Alfvén, Comptes rendus **204**, 1180 (1937).

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Long Period Variations of Cosmic Rays

PIARA S. GILL
University of Chicago, Chicago, Illinois
(Received November 14, 1938)

With the data from the Carnegie Institution's Model C cosmic-ray meters at four widely separated stations, a study of yearly variations and of a variation of cosmic-ray intensity with a 28-day period, apparently connected with the sun's rotation, has been made. The amplitude of the first annual harmonic with a maximum in colder months varies from 2.15 ±0.06 percent at Cheltenham, 38°.7 N to 0.15±0.03 percent at Huancayo, 12°.05 S. The amplitude of a 27.9-day period is 0.18 percent. Values of the atmospheric temperature coefficient at the different stations are given. The results give some support to Blackett's theory that the annual variation is due to changes in elevation of the barytron producing layer with the thermal expansion of the atmosphere. No other essential relationship between observed annual variation of cosmic-ray intensity and meteorological or astronomical phenomena has shown itself.

IN ADDITION to the well-known daily variation of cosmic-ray intensity, evidence has been given for the existence of seasonal variations and of variations following the rotation of the sun.[1–7] With the data that has come from the Carnegie Institution's Model C cosmic-ray meters[8] at various widely separated stations, a more thorough study of such variations has been possible.* For the periods during which the data are available, it is found that in the northern and southern temperature zones the cosmic-ray intensity has been significantly greater during the winter months. Seasonal variations occur likewise in the tropics, but here a six-month peri-

[1] J. Clay, Proc. Roy. Acad., Amsterdam **23**, 711 (1930).
[2] E. G. Steinke, Zeits. f. Physik **64**, 48 (1930).
[3] J. A. Priebsch and R. Steinmaurer, Gerlands Beitr. z. Geophys. **37**, 296 (1932).
[4] V. F. Hess, Terr. Mag. **41**, 345 (1936).
[5] J. A. Priebsch and W. Baldauf, Ber. Wien Akad. IIa, **145**, 583 (1936).
[6] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937).
[7] B. F. J. Schonland, B. Delatizky and J. Gaskell, Terr. Mag. **42**, 137 (1937).
[8] A. H. Compton, E. D. Wollan and R. D. Bennett, Rev. Sci. Inst. **5**, 415 (1934).

* *Note added in proof:* S. E. Forbush, has just published (Phys. Rev. **54**, 975 (1938)) an independent analysis of the same data, following a different method. He finds seasonal variations closely similar to those here reported, and in addition world-wide changes closely correlated between the various stations. Forbush pays slight attention to the variations following the solar rotation.