above analysis it is found that unless some additional conditions are imposed one cannot eliminate all the undesired interactions (in particular, those indicated in footnotes 17 and 18). To be more definite, the conclusion is as follows:

The only two possible assignments are

$$(\alpha) \quad P, N\epsilon A, \quad \mu, e, \nu\epsilon C \tag{23}$$

where ϵ reads "belong to type." Notice that this assignment is identical, for example, with the assignment

$$P, N\epsilon B, \quad \mu, e, \nu\epsilon C. \tag{24}$$

(Compare Section II.) Or

$$(\beta) \quad P\epsilon A, \quad N\epsilon B, \quad \nu\epsilon C \quad \text{and} \quad \mu, e\epsilon D. \tag{25}$$

But the additional restrictions will have to be imposed that (a) all terms in which a field and its charge conjugate field appear,[17] and (b) all terms in which four identical fields appear[18] are to be excluded from the Hamiltonian.

If experimental results should show the existence of another neutral spin $\frac{1}{2}$ particle μ_0 such as in[8]

$$P+\mu^-\rightarrow N+\mu_0, \tag{26}$$

and[8, 9]

$$\mu\rightarrow e+\mu_0+\nu, \tag{27}$$

it would be straightforward to include μ_0 in the present scheme of considerations.

The authors wish to thank Professor J. R. Oppenheimer, Professor E. P. Wigner, and Dr. A. Wightman for helpful discussions.

[17] This is to forbid such processes as $P+\mu\rightarrow P+e$ which contradicts the experimental result that no electrons are emitted in the capture of the μ^--meson by heavy nuclei.

[18] This is to forbid such processes as $N+N\rightarrow \bar{N}+\bar{N}$ which would lead to the instability of complex nuclei.

PHYSICAL REVIEW VOLUME 79, NUMBER 3 AUGUST 1, 1950

The Origin of Cosmic Rays

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(Received January 31, 1950)

The original idea of Menzel and Salisbury concerning the origin of cosmic rays has been extended and some of its possible consequences worked out in more detail. It is concluded that low frequency electromagnetic waves (a few cycles per second) may exist in limited regions near the outer edge of the solar corona, and could accelerate ions to cosmic-ray energies. An attempt is made to explain both the "ordinary" cosmic rays and the intensity increases following solar flares in terms of the action of these waves.

I. INTRODUCTION

IN a very interesting paper Menzel and Salisbury[1] have proposed a mechanism for the origin of cosmic rays, in which the active agent is assumed to be low frequency electromagnetic radiation from the sun. These waves, with frequencies of a few cycles per second, would probably be difficult to detect at the earth's surface because of their nearly total reflection by the ionosphere; there is also some difficulty concerning their propagation through interplanetary space. This comes from the fact that the refractive index of a medium containing N free particles of charge e and mass m per cubic centimeter, traversed by a wave of angular frequency ω, is equal to $(1-4\pi Ne^2/m\omega^2)^{\frac{1}{2}}$. If the usual assumption is made that interplanetary space contains at least one free electron per cubic centimeter, one finds that the refractive index becomes imaginary, leading to total reflection of the waves, for frequencies less than 9 kilocycles per second.

This situation is not improved by relativistic effects; the results of Section II of this paper show that electrons starting from rest move so that the relation between their displacement and the phase of the wave is identical with that given by classical laws, so that the refractive index formula requires no relativistic correction, except for that imposed by the initial velocities of the electrons which will not change the order of magnitude of the low frequency transmission limit.

In spite of these difficulties, it seems worth while to examine the possibilities of this type of mechanism in more detail. The initial problem is to find the relativistic motion of ions under the influence of such waves, which is done in the following section.

[1] D. H. Menzel and W. W. Salisbury, Nucleonics 2, No. 4, 67 (1948).

II. MOTION OF IONS IN A PLANE WAVE

It is desired to find the motion of a charged particle in a plane polarized electromagnetic wave. (The more general case of arbitrary polarization with different time variations of the components leads to a very similar solution; since it does not alter any of the conclusions, this extra complication has been omitted.) Let the wave be moving in the positive x-direction with the electric vector in the y-direction, and let the electric field at a fixed point vary with time like $(1/e)F(t)$, where e is the charge on the particle. The field components (in Gaussian units) are then given by:

$$E_y = H_z = F(\theta)/e, \quad \theta = t - (x/c). \tag{1}$$

The dynamical equations are (neglecting radiation reaction):

$$dW/dt = ev_yE_y = v_yF(\theta), \tag{2}$$

$$dp_x/dt = ev_yH_z/c = v_yF(\theta)/c, \tag{3}$$

$$dp_y/dt = eE_y - ev_xH_z/c = [1-(v_x/c)]F(\theta), \tag{4}$$

$$dp_z/dt = 0. \tag{5}$$

In the above, W represents the particle energy, which we shall understand to mean the total relativistic energy, p represents the momentum, and v the velocity.

In order to solve these, we must eliminate the time. Dividing (2) by (3) gives $dW = cdp_x$, so that $W - cp_x$ is a constant of the motion. We also have the relativistic relation $cp_x/W = v_x/c$, and the kinematic relation $d\theta/dt = 1 - v_x/c$. Therefore, letting M be an arbitrary constant determined by the initial conditions,

$$W - cp_x = W[1-(v_x/c)] = W(d\theta/dt) = \text{const.} \equiv Mc^2. \tag{6}$$

With the help of this we find that the components of momentum can be written:

$$\begin{aligned} p_x &= (W/c^2)v_x = (W/c^2)(dx/d\theta)(d\theta/dt) = M(dx/d\theta), \\ p_y &= M(dy/d\theta), \quad p_z = M(dz/d\theta). \end{aligned} \tag{7}$$

Now since $d/dt = [1-(v_x/c)]d/d\theta$, Eqs. (4) and (5) become:

$$M(d^2y/d\theta^2) = F(\theta), \quad d^2z/d\theta^2 = 0, \tag{8}$$

which are identical (except for θ replacing t) with the classical equations of motion of a particle of mass M moving under the y-force $F(t)$. Then (2) and (3) can be written:

$$\begin{aligned} dW/d\theta &= F(\theta)(dy/d\theta) = M(d^2y/d\theta^2)(dy/d\theta) \\ &= (M/2)(d/d\theta)(dy/d\theta)^2, \end{aligned} \tag{9}$$

$$\begin{aligned} d^2x/d\theta^2 &= (1/Mc)F(\theta)(dy/d\theta) \\ &= (1/2c)(d/d\theta)(dy/d\theta)^2. \end{aligned} \tag{10}$$

Thus the energy change is related to $dy/d\theta$ as it is classically to dy/dt, again letting M play the part of an equivalent mass. The procedure in making a solution is now obvious; y, z, and W are found from Eqs. (8) and (9) which are like the classical ones, and x from the integral of (10); then θ can be eliminated to find the path. If the time relations are desired, the relation between t and θ is found from the integral of $dt = d\theta + dx/c$.

As an illustration, consider the case of a particle starting from rest, for which M is the rest mass m_0, and:

$$\left.\begin{aligned} dy/d\theta &= 1/m_0 \int_0^\theta F(\theta)d\theta \\ W - m_0c^2 &= \tfrac{1}{2}m_0(dy/d\theta)^2 \\ dx/d\theta &= (1/2c)(dy/d\theta)^2 \\ dt/d\theta &= 1 + (1/2c^2)(dy/d\theta)^2 \end{aligned}\right\}. \tag{11}$$

An interesting corollary of these relations is that $dy/dx = [2m_0c^2/(W - m_0c^2)]^{\frac{1}{2}}$, so that a particle accelerated from rest to a kinetic energy large compared with its rest energy moves nearly parallel to the direction of propagation of the wave, rather than at right angles to that direction; the sense of this motion is always positive.

As a still further specialization, consider the wave described by $F = eE_0 \sin(2\pi c\theta/\lambda)$, with the particle starting at $\theta = 0$, $x = 0$, $y = 0$. The integrations are elementary and will not be written down. One cycle of the path is a monotonic S-shaped curve, something like half of a curly bracket, with the initial motion in the y-direction. At the end of the cycle $x = \frac{3}{4}k^2\lambda$, $y = k\lambda$, and the elapsed time is $(1+\frac{3}{4}k^2)\lambda/c$, where $k = eE_0\lambda/2\pi m_0c^2$. The time interval is longer than the period of the wave because the particle tends to follow the wave crest. The kinetic energy reaches its maximum value of $2k^2m_0c^2$ at the middle of the cycle, and returns to zero at the end. The next cycle will repeat this motion from the new starting point. Thus the energy is oscillatory, while the displacements are cumulative. A similar treatment with arbitrary starting phase shows that the path is always made of "curly bracket" segments, the energy is always oscillatory and the x-displacement always cumulative, while the y-displacement is cumulative except in the singular cases of starting phase $\pm 90°$. The mean velocity of progression in the x-direction ranges from $\frac{1}{4}k^2c/(1+\frac{1}{4}k^2)$ to $\frac{3}{4}k^2c/(1+\frac{3}{4}k^2)$. This continued displacement is not to be described as an effect of "radiation pressure" in the usual sense; the latter has in fact been left out by the omission of radiation reaction terms from the equations of motion.

III. ORIGIN AND PROPAGATION OF THE WAVES

It is clear that low frequency waves cannot propagate through the solar corona. This is a highly ionized medium in which mass motions of matter, currents, and magnetic fields are linked together by magneto-hydrodynamic laws. It is probable that the motions have a high degree of turbulence, driven by the turbulent motion of the sun's surface. The outer boundary of such a medium would then be expected to radiate at frequencies corresponding to the fluctuation frequencies of the currents; it is therefore postulated that the Menzel-Salisbury waves originate in the extreme outer parts of the solar corona. Their further fate is hard to predict. They may simply be totally reflected by electrons in the immediately adjacent region of space, but there is another possibility. The results of Section II show that charged particles will be rapidly driven along by the waves, and if this rate of removal exceeds the rate of escape from the corona, which is probably limited by the static magnetic fields accompanying the coronal matter, the waves may be able to clear a path for themselves by sweeping out all the ions in their way. This process could conceivably proceed to the extent of clearing the ions out of a large part of interplanetary space. The latter however seems unlikely, and we shall tentatively suppose that the waves gain only an occasional temporary victory over the electrons in local regions of high solar activity. According to this idea, sometimes there will be a sufficient long wave intensity over some part of the coronal surface that electrons and ions will be pushed out of a region many wave-lengths in extent. The front of this region will still be totally reflecting, but since the boundary is not likely to be flat the reflected waves will not be expected to retrace the path of the incident waves, and therefore there can be an appreciable volume occupied by traveling waves. In the following, such regions will be treated as the accelerating agents of cosmic rays; for convenience they will be called "wave bubbles."

Some justification should be made for invoking a mechanism which is at first sight rather strange, and may turn out to be impossible when the physical circumstances at the edge of the corona are better understood. One reason is that it does not seem possible to generate a sufficiently high electric field strength in the presence of the normal concentration of free electrons; another is that standing waves in regions of total reflection are not as effective as traveling waves in accelerating particles to relativistic velocities. The correct treatment of the situation at the coronal edge, involving the transition from a magneto-hydrodynamic region to one of relatively free ion motion, is beyond the author's competence but it may be a rewarding field for investigation. If it should turn out that "wave bubbles" cannot be formed, the idea of cosmic-ray acceleration by electromagnetic waves may have to be abandoned. There would still remain the possibility that the non-radiative fields (chiefly magnetic) associated with the turbulent motion of the corona could accelerate cosmic rays by a mechanism similar to that suggested by Fermi[2] for interstellar fields.

IV. DIRECT ACCELERATION OF COSMIC RAYS

The recent observations of large temporary increases in cosmic-ray intensity following solar flares suggest that in these cases at least one is dealing with a direct production of cosmic rays by the sun. The following connection is proposed. The flare initiates a large magnetic disturbance at the sun's surface; this is propagated through the corona, and when it reaches the surface of the latter a "wave bubble" is formed. Then ions are accelerated by the mechanism of Section II. Assuming, for example, a sinusoidal wave of frequency 10 cycles per second and peak electric field of 10 volts per cm acting on protons, and applying the formulas of the last paragraph of Section II, it is found that an energy of 5×10^{10} ev can be imparted to the protons. They would move forward 9.4 wave-lengths during their acceleration, which would take place in a half-cycle of wave phase as seen by the particle. Electrons in the same wave field would tend to acquire still higher energies, but would move forward so far that the finite size of the bubble would be a limiting factor. Thus if the wave field is terminated at 10 wave-lengths, electrons starting at the most favorable phase (maximum field) would pick up only about 6×10^{9} ev. On the other hand, multiply charged heavy ions would acquire great energy; a completely stripped iron nucleus would be accelerated to a maximum of 6×10^{11} ev by the same field.

The above figures show that no extreme assumptions regarding field strength or frequency are necessary to account for acceleration to energies sufficient to penetrate the earth's magnetic field. The question of escape from the sun's general magnetic field must be left open since so little is known about its magnitude at present. No "prediction" of particle energies can be made since the intensities and frequencies of the waves, as well as the dimensions of the bubbles, are not known. However it is suggested that the energy spectrum and composition of the "solar flare" cosmic rays may be rather different from that of the "ordinary" cosmic rays; in particular, the very highest energies (Auger showers) may be lacking, and some primary electrons may be present.

V. SOURCE OF THE "ORDINARY" COSMIC RAYS

The steady flux of cosmic rays can hardly be accounted for by the direct action of the process discussed, the most compelling argument against this being the contrast between the constancy of cosmic radiation and the variability of solar activity. Various mechanisms involving cumulative acceleration have been proposed, such as the theories of Fermi,[2] Richtmyer and Teller,[3] and Alfvén.[4] In the first of these, the acceleration is assumed to occur in interstellar space; in the other two, the ions are assumed to be confined to the solar system by a weak but very extended magnetic field. In this paper the second assumption will be made. (It should be pointed out that the process of Section IV could serve as an injector for the Fermi acceleration mechanism, but this does not remove all the difficulties of that mechanism in accelerating the heaviest ions.) The source of the trapping magnetic field is rather obscure, but an extremely small unbalanced rotation of the interplanetary positive ions and electrons would be capable of producing a field having suitable magnitude and configuration, and the general rotation of the solar system may be capable of exciting such a motion.

It is clear that in the presence of a trapping field, ions will continue to circulate in the solar system until removed by collisions or perhaps by escape from some orbits that extend very far out. If this situation exists, a very small average rate of "injection" from the sun would be sufficient to account for the observed cosmic-ray flux, and therefore it is suggested that the process of Section IV, even though it may occur infrequently, is the

[2] E. Fermi, Phys. Rev. **75**, 1169 (1949).
[3] H. D. Richtmyer and E. Teller, Phys. Rev. **75**, 1729 (1949).
[4] H. Alfvén, Phys. Rev. **75**, 1732 (1949); **77**, 375 (1950).

primary source of all cosmic radiation. The particles of the cosmic rays would then represent a sample of ions taken from the edge of the solar corona, and since even relatively heavy elements exist there in a highly ionized state these heavy particles would be accelerated as effectively as protons.

Accepting tentatively the assumption that trapping of ions takes place, one can then proceed in two ways. One can suppose that no further acceleration takes place, and that the observed steady flux represents an average of all the "solar flare" particles emitted for the past few million years, with the electrons removed by radiative losses and by the inverse Compton effect. This would imply that some flares cause waves intense enough to accelerate the highest energy particles observed. (If the orbits are distributed uniformly throughout a sphere of radius 50 times the earth-sun distance, the mean life for capture by the planets is about 6 million years. Capture by the sun, if allowed by the solar magnetic field, would reduce this by a factor of 50. Capture by meteoritic matter, because of the large cross section per unit mass of finely divided material, could be even more important but is hard to estimate.)

The second possibility is that the circulating ions receive further acceleration by subsequent passages through "wave bubbles." One bubble with a diameter of 10 wave-lengths of 10-cycle radiation would have a cross section about twice that of the combined planets. The frequency of occurrence of bubbles cannot be inferred from the observed cosmic-ray intensity increases, since they may not all contain waves intense enough to cause such increases, and may not all eject particles in a suitable direction for observation at the earth. Therefore a reasonable estimate of the chance for an ion to undergo repeated traversals through strongly accelerating regions, with an average cumulative gain in energy, cannot be made. Nevertheless a cumulative process for the production of the very highest energies is attractive, and if the regions of strong acceleration are not sufficiently numerous, another source of cumulative acceleration may be found in the action of the non-radiative magnetic fields of the solar corona.

PHYSICAL REVIEW VOLUME 79, NUMBER 3 AUGUST 1, 1950

The Extraordinary Increase of Cosmic-Ray Intensity on November 19, 1949

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(Received April 20, 1950)

Four sudden increases in cosmic-ray intensity associated with solar flares or chromospheric eruptions have so far been observed during more than a decade of continuous registration of cosmic-ray intensity. The last and largest of these increases occurred on November 19, 1949, when such an effect was recorded for the first time at a mountain station at Climax, Colorado. Here the intensity increased to about 200 percent above normal in half an hour. At the sea-level station at Cheltenham, Maryland, the increase was about 43 percent. No increase occurred at the equator. From the increase in the effect with altitude and latitude, it is concluded that the increase was due to the nucleonic component produced by relatively low energy primary charged particles probably accelerated by some solar mechanism.

THE sudden increase in cosmic-ray intensity which began at 10^h45^m GMT, November 19, 1949, was the largest yet recorded during more than a decade of continuous registration of cosmic-ray ionization at several stations (see Table I). Only three other unusual increases had been previously recorded.[1] These occurred on February 28, 1942, March 7, 1942, and July 25, 1946. All were registered with Compton-Bennett ionization chambers completely shielded with 12-cm Pb. Three of the increases began during intense chromospheric eruptions or solar flares.[1] While no solar flare was actually observed during the increase of cosmic-ray intensity on March 7, 1942, a radio fadeout occurred very near the time the increase in cosmic-ray intensity began. The fadeout, which occurred only on the daylight side of the earth, quite definitely indicates the existence of a solar flare.

The terrestrial-magnetic effect of such solar flares is

TABLE I. Location and elevation of Compton-Bennett cosmic-ray meters.[a]

Station	Latitude (degrees)	Longitude (degrees)	Geomagnetic latitude (degrees)	Elevation (meters)	Operation began
Godhavn, Greenland	69.2 N	53.5 W	79.9 N	9	October, 1938
Cheltenham, Maryland	38.7 N	76.8 W	50.1 N	72	March, 1935
Climax, Colorado	39.4 N	106.2 W	48.1 N	3500	
Teoloyucan, Mexico	19.2 N	99.2 W	29.7 N	2285	February, 1937[b]
Huancayo, Peru	12.0 S	75.3 W	0.6 S	3350	June, 1936
Christchurch, New Zealand	43.5 S	172.6 E	48.6 S	8	June, 1936

[a] 12-cm Pb shield around all meters, except that the meter at Climax had, in addition, a slab of Fe 16.5 cm thick directly over the meter.
[b] Not operating after 1945.

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