fluctuations in the background had a disproportionately large effect on the net counts. The most reasonable conclusion to draw from the data is that the yield curve is substantially flat above 1.8 or 1.9 Mev. Perhaps this indicates that stripping, rather than compound nucleus formation, is the dominant feature of the reaction at high energies.

ACKNOWLEDGMENTS

It is a pleasure to thank Mr. Philip R. Malmberg for his help with some of the apparatus and the energy calibration of the Van de Graaff accelerator. This work has benefited greatly from stimulating discussions with Professor James A. Jacobs and Professor Edward B. Nelson.

PHYSICAL REVIEW VOLUME 95, NUMBER 4 AUGUST 15, 1954

Production of Cosmic Radiation at the Sun*

J. W. Firor† and J. A. Simpson, *Institute for Nuclear Studies, University of Chicago, Chicago, Illinois*

and

S. B. Treiman, *Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*

(Received March 31, 1954)

A calculation is made of the average production rate of 4-Bv cosmic-ray particles at the sun. The calculation is based upon the recent experimental evidence that the frequently occurring small solar flares produce temporary increases of neutron intensity in suitably located neutron pile detectors. This production rate, averaged over the 11-year solar cycle, is somewhat in excess of the absorption rate of 4-Bv particles by bodies in the solar system. If the production at the sun is to account for most of the observed cosmic radiation intensity, a trapping magnetic field is required. Limits on the size of such a trapping volume are estimated by considering the limits of cosmic-ray lifetime; the requirement of a high degree of radiation isotropy at the earth is satisfied. The existence of high-energy particles in the cosmic radiation imposes the principal difficulty for any solar origin hypothesis.

I. INTRODUCTION

THE four large increases in cosmic-ray intensity which have been observed in association with large solar flares[1] indicate that the sun occasionally produces cosmic-ray particles. More recently it has been found that the smaller, but more frequent solar flares are also associated with increases in cosmic-ray intensity at the earth.[2] That these increases represent true cosmic-ray production on or near the sun is suggested by analogy with the large flare events, where the size of the increases clearly excludes the possibility of a modulation effect on pre-existent cosmic radiation.

The results on the small flare effect may be summarized as follows:[2] A neutron detector[3] at Climax, Colorado, recorded increases of ~ 1 percent for flares of importance 1+ or greater during the period studied (May, 1951, to August, 1953), provided that the local solar time at Climax was 4 A.M.$\pm$2 hours. No observable effect, however, was found to accompany flares which occurred outside of this "impact zone" of local solar time. This local time dependence of the flare effect indicates that the particles which give rise to the intensity increase approach the vicinity of the earth from the direction of the sun. For both the large and small flare events increases were observed for flares near the limb of the sun as well as for those which occurred at the center of the visible solar disk. The distribution on the visible disk is shown in Fig. 1 for a group of flares which entered into the studies reported in reference 2. The indication is clear that the particles are emitted in a wide angle cone. An analysis of the cosmic-ray trajectories in the field of the earth's magnetic dipole shows that the particles from the sun which come in at Climax at 4 A.M. have a magnetic rigidity of 4 Bv.

The small flare effect appears to be a frequently occurring phenomenon; and if it represents production of cosmic rays on or near the sun, then the possibility arises that this effect has an important bearing on the question of the origin of cosmic rays. Before discussing any such implications, however, it is first necessary to obtain a numerical estimate of the production rate of (4-Bv) cosmic-ray particles at the sun. This is the main purpose of the present paper and is the subject of the following section. It should be emphasized that the calculation is based on the experimental data; we do not consider here the question of possible production mechanisms. In the remaining sections of the paper we discuss in a general way the implications of our result

* Assisted by the Office of Scientific Research, Air Research and Development Command, U. S. Air Force.

† Present address: Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.

1 Forbush, Stinchcomb, and Schein, Phys. Rev. **79**, 501 (1950).

2 J. W. Firor, Phys. Rev. **94**, 1017 (1954).

3 See Simpson, Fonger, and Treiman, Phys. Rev. **90**, 934 (1953) for a description of the experimental apparatus. Neutron pile monitors *D*-1 and *D*-3 were used for the solar flare effect studies.

for hypotheses on the origin of cosmic rays. In particular, we consider in some detail the implications for solar-origin hypotheses, although we do not ourselves wish to propose here any comprehensive theory nor suggest that the solar flare effect points uniquely to a solar-origin theory of cosmic rays.

II. PRODUCTION RATE AT THE SUN

Suppose that the particles which give rise to the solar flare effect approach the earth over a broad front, traveling essentially along the sun-earth line. (A possible small spread in direction has no effect on the following discussion.) Let $i_b d\Omega_b dN$ be the flux of these particles in element of solid angle $d\Omega_b$ and element of magnetic rigidity dN ($N=pc/Ze$, where p is the particle momentum and Ze is the charge). It is reasonable to suppose that the intensity is constant over a dimension much larger than the diameter of the earth; and it is likewise proper to assume that over this dimension the particles all travel in the same direction (before the geomagnetic field becomes significant). Outside the geomagnetic field,

$$i_b d\Omega_b dN = I(N)\delta(\Omega_b - \Omega_b^0) d\Omega_b dN, \qquad (1)$$

where I is the flux (particles per unit time, area, and rigidity) and Ω_b^0 defines the direction of travel of the beam.

Let $i_e d\Omega_e dN$ be the flux of these particles at a particular location on the earth. By Liouville's theorem: $i_e = i_b = I\delta(\Omega_e - \Omega_e^0)$, where Ω_e^0 is the direction of arrival at the earth corresponding to the direction Ω_b^0 of the beam; Ω_e^0 depends on N and on the particular earth location. The flux from all permitted directions at the top of the atmosphere is, therefore,

$$\int\int I\delta(\Omega_e - \Omega_e^0)(d\Omega_e/d\Omega_b) d\Omega_b dN = \int I (d\Omega_e/d\Omega_b)_0 dN, \qquad (2)$$

where $(d\Omega_e/d\Omega_b)_0$ is the ratio of the elements of solid angle as seen from the earth and in the beam for particles of given N. This factor takes into account the possibility that there may be a few directions of arrival Ω_e^0 corresponding to the given beam direction. Expression (2) may be written

$$I\langle d\Omega_e/d\Omega_b\rangle \Delta N, \qquad (3)$$

where ΔN is the spread in magnetic rigidity (due to the spread in directions of arrival Ω_e^0) for the particles which arrive at the given earth location: and $\langle d\Omega_e/d\Omega_b\rangle$ is the average value of the quantity defined above. This latter quantity is difficult to estimate and represents the largest uncertainty in the present calculation. Our estimate is based on the trajectories which were

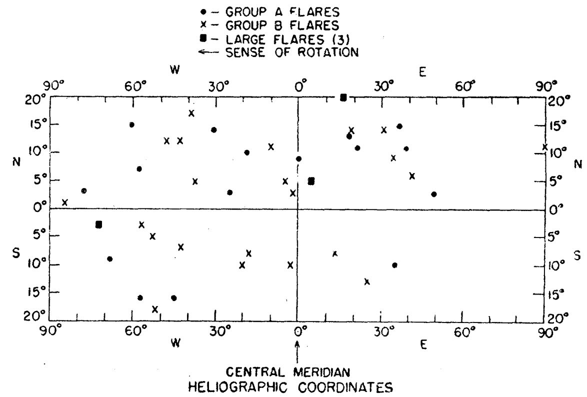

FIG. 1. The location of small and large flares is shown on the visible hemisphere of the sun. Flare Groups A and B are small flares studied in detail in reference 2. Group A flares occurred at times when the Climax neutron pile monitor was in the 4-Bv particle impact zone; they were associated with increases of cosmic ray intensity. Group B flares occurred at times when the detector was outside the impact zone, and, therefore, were not associated with increases. The three large flares were already reported.

obtained in the terrella experiments of Malmfors.[4] These pertain to a latitude of 58°, whereas the latitude of Climax is 48°, and further, they pertain to a different impact zone for particles from the sun. Nevertheless, because of other similarities between the two impact zones in question, we believe that our estimate of $\langle d\Omega_e/d\Omega_b\rangle$ is not in error by as much as a factor of five. Our numerical estimate will be quoted in context below.

The fractional change in the omnidirectional cosmic-ray intensity at the top of the atmosphere is given by

$$f = (I\Delta N/J)\langle d\Omega_e/d\Omega_b\rangle, \qquad (4)$$

where J is the normal omnidirectional flux (at Climax). This value of f is not the same as the observed value deep in the atmosphere; it is probably not very different, however, since the average specific yield at Climax[3] (averaged over the normal spectrum) is similar to the specific yield for particles of rigidity 4 Bv.

Suppose that during a flare cosmic-ray particles are emitted in a cone of solid angle w normal to the surface of the sun. At first sight it would seem that the probability that the earth lies in this cone is $w/4\pi$. But flares actually occur in a limited range of helio-latitudes, so that this probability is better written as w/W, where W is the total solid angle within which most flares emit particles. As reported in reference 2, the cosmic-ray emission during flare events lasts for a period of about 2 hours. If we multiply this length of time by the average rate of flare events on the sun, we obtain the

[4] K. G. Malmfors, Arkiv. Mat. Astron. Fysik **32**, No. 8 (1945). This paper gives plots of the "asymptotic" longitude and latitude for trajectories which arrive from various directions in the sky at the location of Stockholm. From these curves the ratio of the elements of solid angle at the earth and in the beam were obtained for various directions of arrival; and this ratio was then averaged over all directions.

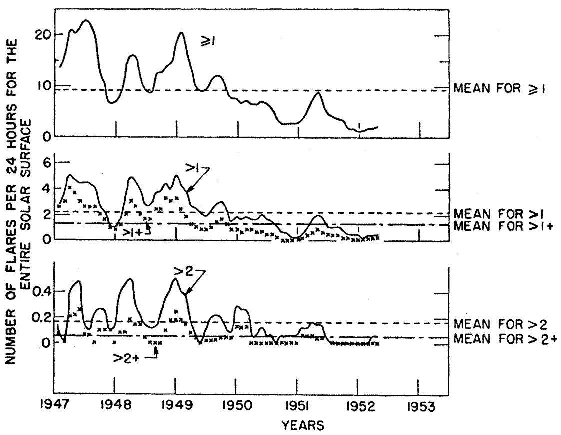

FIG. 2. The monthly averages of solar flare rates were determined from the worldwide reports of the International Astronomical Union Quarterly Bulletin on Solar Activity (published by Eidgen. Sternwarte, Zurich, Switzerland). Flares are roughly classified by their importances into groups of increasing size; namely, 1, 1+, 2, 2+, 3, and 3+ (for details see reference 2). The flare rates are corrected for the observing times of the individual observatories.

fraction of time F during which the sun is emitting particles.

The product $h=Fw/W$ is best obtained empirically from the Climax data, since it represents the fraction of all days on which a solar flare effect is registered at Climax during a transit through the impact zone. The time-averaged rate PdN (averaged over an 11-year solar cycle) at which the sun emits particles in the rigidity interval dN centered at 4 Bv is, therefore, given by

$$PdN=hWR^2\frac{fJ}{\Delta N\langle d\Omega_e/d\Omega_b\rangle}dN, \tag{5}$$

where R is the earth-sun distance (we assume that the particles travel in essentially straight lines from the sun to the earth's vicinity).[5] We have adopted the following numerical estimates: $f\approx 0.005$ (0.5 percent cosmic-ray intensity increase at Climax); $J\approx 1$ particle/cm^2-sec (omnidirectional flux at the top of the atmosphere above Climax); $W\approx 2\pi$ (this estimate of the solid angle of emission of cosmic-ray particles from the sun is suggested by the evidence quoted in the introduction and is almost certainly not off by more than a factor of two); $\Delta N\approx 0.5$ Bv (this estimate is obtained from references 2 and 4); $\langle d\Omega_e/d\Omega_b\rangle\approx 20$ (as discussed earlier, this estimate is based on the results of Malmfors and could be off by as much as a factor of five); $h\approx 0.3$. (The fraction of days on which a cosmic-ray effect was observed at Climax, during the period studied, was about 0.1. This fraction is obtained from Fig. 10 in reference 2. These data were obtained in a period of rapidly declining solar activity, the minimum of which is expected about 1954. Over an 11-year solar cycle, the average rate of occurrence of flares is about three times the average rate during the period studied, i.e., May, 1951–August, 1953, as can be seen in Fig. 2. Our estimate of P is meant to represent a time-averaged value over an 11-year solar cycle.) We obtain now the result $P\sim 2\times 10^{23}$ particles/sec-Bv, for particles of rigidity 4 Bv.

III. RELATION TO ORIGIN THEORIES

The foregoing calculation has led to an estimate of the production rate of 4-Bv particles at the sun, averaged over a period of time comparable with the sunspot cycle. Observation of solar flare effects at other geomagnetic latitudes should eventually lead to similar estimates of the production rate at other magnetic rigidities in the latitude-sensitive range.

The question now arises as to the bearing of this result on a possible solar origin of cosmic rays. For one thing, it is clear that—by whatever mechanism—the sun *does* produce particles of cosmic-ray energies. But our analysis does not reveal what fraction of the observed cosmic radiation at the earth comes from the sun. At one extreme, if the particles produced at the sun escape toward outer space along straight lines, then the time-averaged solar contribution to the cosmic-ray intensity at the earth is negligibly small. At the other extreme, if the particles are trapped in the neighborhood of the solar system by suitable magnetic fields, then a solar-origin theory becomes possible.

(a) Galactic Origin

There is one point concerned with galactic theories of the origin of cosmic rays which requires special mention here. It is sometimes asserted that the observed production rate of cosmic rays at the sun may be typical of production by other stars of our galaxy. It is easily shown, however, that this suggestion fails quantitatively. If the cosmic-ray number density n is to be maintained by stellar sources, the average stellar production rate is given by

$$n/\rho\tau, \tag{6}$$

where ρ is the number density of stellar sources and τ is the mean life of cosmic rays in our galaxy. In our vicinity of the galaxy the density of observable stars is about 1 per 1000 cubic light years, and the number density of 4-Bv particles is $10^{-11}/cm^3$-Bv. The chemical composition of the cosmic radiation observed at the earth indicates that the mean life τ is no larger than about 10^6 years.[6] Thus, the average production rate of 4-Bv particles must be $\sim 10^{33}$ particles/sec-Bv. This is larger than the production rate at the sun by a factor of 10^{10}.

We have here compared the rates of production and loss of particles of a specified rigidity, 4 Bv. If, as in Fermi's theory, cosmic rays are accelerated gradually,

[5] S. B. Treiman, Phys. Rev. **94**, 1017 (1954).

[6] Morrison, Olberti, and Rossi, Phys. Rev. **94**, 440 (1954).

the appropriate comparison would be between the rate of loss of cosmic-ray particles of all energies and the production rate of particles of all energies above the threshold, or "injection" value. We have no information on solar production rates at very low energies; but it is certain that no large increase (factor of 10^{10}) occurs between 4 Bv and at least 1.5 Bv (the cutoff at the earth). On the other hand, in the galactic model of Morrison *et al.*,[6] for example, the threshold energies are extremely small ($\sim$1 Mev for protons). This is not very much larger than the energy of auroral particles. We cannot say, therefore, that the sun may not represent a typical stellar source for injection of particles into an extended acceleration mechanism; but the solar flare effect, in itself, gives no indication that this is the case.

(b) Solar Origin

If the observed solar production is to be considered as a significant process for the production of cosmic rays, we must turn to a model in which the solar-generated particles are retained in the neighborhood of the solar system by suitable magnetic fields (see, for example, the paper by Alfven[7]). The loss of cosmic-ray particles would then be ascribed either to leakage out of the trapping volume or to collisions with bodies in the solar system (only the sun need be considered in this connection). We assume that the lifetime of the cosmic-ray particles is sufficiently small so that collisions with interplanetary matter are negligible.

If the sun has no general magnetic field, then its absorption cross section is simply equal to the geometric cross section. In this case, the rate of capture of 4-Bv particles is given by

$$A=4\pi(\pi a^2)j=6\times 10^{21} \text{ particles/sec-Bv},$$

where a is the solar radius, and where we have assumed that the cosmic-ray differential intensity at the sun is the same as the intensity j at the earth. If, on the other hand, the sun has a dipole field, the absorption cross section becomes dependent on the magnetic rigidity and is in general smaller than the geometric cross section. One can easily show that the absorption cross section is given approximately by

$$(\pi a^2)a(N/M)^{\frac{1}{2}},$$

where M is the dipole moment and N is the magnetic rigidity. The above equation is valid in the approximation $a(N/M)^{\frac{1}{2}}\ll 1$. The solar flare effect provides evidence that the solar dipole moment has as an upper limit the value 5×10^{32} gauss-cm^3.[5] For a dipole moment of this value, the absorption cross section for 4-Bv particles would be smaller than the geometric cross section by a factor of $\sim$100. However, any large-scale magnetic perturbations, such as might be associated with assumed ion beams from the sun or with the assumed trapping field itself, would tend to open up the allowed Stoermer cones and increase the absorption cross section. The assumption of a geometric cross section may, therefore, be quite reasonable.

[7] H. Alfven, Phys. Rev. **77**, 375 (1950).

We conclude that the production and absorption rates of 4-Bv particles at the sun are comparable. The difference lies in the right direction for a solar-origin theory of cosmic rays, since losses must also occur by leakage from the trapping volume. Within the experimental and theoretical uncertainties, however, the two rates could be considered to be in agreement. This near agreement may of course be fortuitous, but it is at least suggestive of a solar origin of cosmic rays.

Limits on the Dimensions of the Trapping Volume

If we assume that the cosmic radiation is retained in the vicinity of the solar system by magnetic fields, then it is possible to set rather close limits on the size of the trapping volume. If we suppose that the cosmic radiation is distributed with essentially uniform density throughout the trapping region, then we can obtain a relation between the volume V of the trapping region and the mean life τ of the cosmic radiation; evidently,

$$V=P\tau/n, \tag{7}$$

where n is the number density and average P is the production rate of 4-Bv particles.

Taking for τ the upper limit 10^6 years, we find for the linear dimension of the trapping volume ($V=L^3$) the upper limit

$$L<8\times 10^{15} \text{ cm}.$$

A lower limit on the lifetime of particles in an assumed trapping volume can be obtained by noting that the rate of occurrence of solar flares follows the general changes of solar activity over successive 11-year cycles (see Fig. 2). In order to account for the approximate constancy in time of cosmic-ray intensity at the earth, it must be assumed that the lifetime of the particles in the trapping volume is large compared to 11 years. It is known from long time observations with ionization chambers that the cosmic-ray intensity over a period of many years does not vary by more than $\sim$4 percent.[8] Since ion chambers at sea level have a low sensitivity for measuring variations in the low rigidity portion of the primary spectrum, it is possible that the long time variations in intensity of 4-Bv particles could be as large as 10–20 percent over an 11-year cycle. However, the variation in the rate of occurrence of solar flares is considerably larger than this. A rough measure of the lower limit on τ can, therefore, be obtained by setting

$$11 \text{ years}/\tau \lesssim 0.2,$$

from which we find $\tau \gtrsim 60$ years. The corresponding

[8] S. E. Forbush, Duke University Cosmic Ray Conference, 1953 (unpublished). A. R. Hogg, Mem. Commonwealth Observatory **10**, July, 1949.

limit on the linear dimension of the trapping volume, from Eq. (7), is therefore

$$L \gtrsim 3\times10^{14}\ \text{cm}.$$

The Anisotropy of Cosmic-Ray Intensity at the Earth

The near isotropy of cosmic-ray intensity at the earth sets an independent limit on the volume V for any given value of τ. Let $(1+\gamma)/(1-\gamma)\approx 1+2\gamma$ represent the ratio of the cosmic-ray fluxes passing respectively out of and into a sphere of radius R_e equal to the radius of the earth's orbit; γ is then a measure of the anisotropy. If the cosmic-ray particles move at random within the volume V, then[7]

$$V=2\pi R_e^2 c\tau\ \gamma. \tag{8}$$

For particles of low rigidity ($\sim$4 Bv), the anisotropy γ could be as large as 10^{-2}. In this case, however, the limit set by Eq. (7) is more stringent than that set by Eq. (8); i.e., our requirements on isotropy are automatically satisfied by Eq. (7).

IV. DISCUSSION

Even if a trapping field is postulated for the low-energy particles, the principal difficulties for any solar-origin hypothesis are the source of very high-energy particles and the retention of these particles in a trapping field.

On the basis of the four large flare events, it has been widely assumed that the energy spectrum of the particles associated with flares is considerably steeper than the time-averaged cosmic-ray spectrum. It is not certain, however, that this is the case. For example, the ion chambers and counter telescopes which detected the large intensity increases were distributed partly in and partly out of the impact zones for the incoming radiation. Intensity differences due to the effect of the geomagnetic field therefore make any estimate of the spectrum uncertain. Further study of the small flare effect at various latitudes should eventually provide a better estimate of the spectrum.

A related question has to do with a possible upper limit on the energy spectrum of solar-produced particles. The upper limit has been estimated to be $\sim$10 Bv; since for the four large flare events, no cosmic-ray effect was observed at the equator. On the other hand, possible evidence for higher rigidity particles coming from the sun is provided by the results of Dolbear *et al.*[9] who find a close association between cosmic-ray intensity increases and sudden ionospheric disturbances (which are often associated with solar flares) during local daytime hours. At present, however, it is not certain that these observations represent an extraterrestrial effect.

A necessary condition for the trapping of particles in a magnetic field is that the radius of curvature for the particles of highest rigidity be small compared to the linear dimension L of the trapping region. For the largest known cosmic-ray rigidities ($\sim 10^6$ Bv), the magnetic field would have to exceed $\sim 4\times10^{-4}$ gauss. It is not known whether or not extensive fields of this magnitude exist; and it is even less clear whether or not the assumption of a field distribution suitable to permit trapping is reasonable.

The difficulties with a solar-origin hypothesis, as we have seen, are most pronounced for the high energies. On the other hand, our results on the solar production of low-energy particles are at least suggestive of a solar origin of the cosmic radiation. It may be that the observed cosmic-ray spectrum is obtained from the combined effect of low-energy particles from the sun plus high-energy particles produced elsewhere. Present experimental evidence indicates the rigidity spectrum is fairly smooth up to at least 10^4 Bv. The smooth joining of spectra from two different origins may present a difficulty for this hypothesis.

V. SUMMARY

In this paper we have determined the average production rate of 4-Bv particles at the sun and associated with solar flares. If this production is to account for most of the observed cosmic radiation intensity a trapping magnetic field is required. Whether or not such a magnetic field exists and is capable of trapping particles of all observed rigidities is unknown at present.

In addition there are many questions which a solar-origin hypothesis, indeed any hypothesis, must answer. For example, how are the stripped heavy nuclei accelerated; can they be accelerated in the mechanism associated with the solar flare? If the source is postulated to be nearby, why are not high-energy electrons abundant in the primary cosmic radiation? These and other questions will require answers before a satisfactory theory of the origin of cosmic radiation can begin to develop.

The authors wish to thank Dr. R. P. Kane for tabulating and computing the flare rates in Fig. 2.

[9] Dolbear, Elliot, and Dawton, J. Atm. Terrest. Physics 1, 187 (1951).