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Solar Origin of Cosmic-Ray Time Variations

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The sun is known to be responsible during at least some solar flares for sharp increases in the cosmic-ray intensity on earth. In contrast to the flare pulses, the other principal changes in cosmic-ray intensity are all smaller in amplitude, less steep in energy dependence (extending perhaps to 30 Bev/c), much slower in time scale, and very much more isotropic (worldwide). These latter changes are not correlated sharply with any conspicuous solar event. A common cause for all of the nonflare cosmic-ray changes is here proposed: time (and energy) modulation of the incoming cosmic-ray beam by the random diffusion of the particles through turbulent clouds of magnetized plasma emitted from the sun. The sporadic cosmic-ray storm decreases (Forbush events) occur when the earth is immersed in a strong fresh cloud following a solar flare. The eleven-year variations in intensity and low-energy spectrum arise from the combined effect of much weaker and more diffuse clouds which travel across the solar system to the region of the outer planets. The recurrent 27-day effects depend on the presence near the earth of a region of longer diffusion mean free path, which punches a channel into the pre-existing clouds. The origin of the clouds in active centers and the channels in magnetic monopole regions of the sun is discussed, and parameters obtained which describe the clouds, and their motions, adequate to produce the observed effects and quantitatively, astrophysically plausible. The small but complex diurnal cosmic-ray variations are not discussed in detail, but appear to fit in naturally. The observed variation of all these effects throughout one solar cycle agrees with the picture presented.

I. INTRODUCTION

THE cosmic-ray beam incident upon the earth is grossly time-independent and isotropic. Such a property is natural for any galactic phenomenon, and is more or less necessary if a galactic origin for the cosmic rays is to be believed. But there are, albeit rarely, large variations, and continually there are smaller ones, in the cosmic-ray beam. Until these are explained, no theory of galactic origin remains safe.

The clearest and most marked example of cosmic-ray variation, which must be attributed to the sun, is the sharp intensity increase seen at low cosmic-ray momenta, below 5 Bev/c, in the hours following a few great solar flares, and perhaps after all solar flares.[1] These remarkable events are characterized by their concentration in low energy (they are unseen at the geomagnetic equator), their lack of isotropy, and their large effects, increasing the beam as they do by a factor of five or more at low energy. The strongest arguments have been given to show that they represent actual injection of cosmic rays into space from the approximate direction of the sun. Though there are data to show that the matter is not quite so simple, the motion of newly produced low-energy cosmic-ray particles from the solar neighborhood to the earth's dipole field region in nearly straight trajectories is surely the main feature of these events. The sun then is the only known source of cosmic-rays. But it is certain that these events by themselves do not give rise to any considerable fraction of the cosmic-ray beam, so that a wholly different mechanism must be postulated, if the cosmic-rays are to be ascribed fully to the sun or to solar system processes.

These unusual flare variations, however, by their very differences, strongly suggest an interpretation of many other time variations. The main types of variation to be discussed in the present paper are the sporadic cosmic-ray storms (Forbush events) the 27-day recurrent maxima in the cosmic beam, and the eleven-year variations in intensity (and in the low-energy spectral shape). All of these effects, broadly speaking, form a single class, quite distinct from the flare spikes. In contrast to the flare pulses, these variations are all: (1) much smaller in amplitude, amounting to some 5 or 10% in the meson beam at sea level in middle latitudes, or perhaps 20–30% for particles from some 1–5 Bev; (2) much more slowly energy-dependent, showing a considerable effect all the way up to 20 or 30 Bev/c, clearly visible in the mu-meson beam both at the magnetic equator and at the pole; (3) much slower in time scale, taking days to perhaps weeks for important initial changes, and persisting for years in some cases; (4) at best loosely time-correlated with known solar phenomena; (5) mainly isotropic, being worldwide in effect. (We will nowhere discuss the complicated but rather small diurnal effects, which do reflect some anisotropies of these various phenomena.)

Since by all means the most violent phenomena of the solar "climate" are the great flares, it seems physically at least improbable that particles of higher energy should be accelerated in the much less spectacular and slower variations of the present class. Since the slow increases and also decreases of the beam are never major, with no indication of manyfold increases as in the sudden flare events, it is plausible to ascribe them to a modulation of a generally constant cosmic-ray beam, rather than to an additional injection. Since the effects are worldwide, and not strongly longitude-dependent as are the flare events, it is necessary to ascribe them to causes less well-defined in direction than is the sun itself, and indeed to a nearly isotropic modulation of the cosmic-ray beam.

The possibilities for modulation are not very numerous. A slow change of the earth's dipole field, or of the sun's or of some similar symmetrical and essentially

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[1] J. W. Firor, Phys. Rev. 94, 1017 (1954).

time-constant field will modulate the beam around its asymptotic value by shifting the set of accessible directions for a given magnetic rigidity. Such a change will be strongly energy-dependent, for at a point where accessible directions have been reduced so much that atmospheric or instrumental absorption, or the original spectral distribution, causes an apparent cutoff, no further decrease is possible. This general argument[2] has excluded the geomagnetic theories earlier favored. Electric fields, near the earth or far out in space, cannot be so generally excluded, but they require such large potential drops, or such extended fields, that they seem implausible. Specific[3] models seem to give again rather too steep energy dependence. Energy modulation rather flat over the whole range from a few to 20 or 30 Bev is hard to produce, especially when nearly isotropic.

The statistical magnetic modulation here proposed can be understood physically from a simple account. It is plain that deep within the convective mantle of the sun the cosmic-ray flux is zero, absorption having prevented access. If a magnetized volume of gas rises to the solar surface, it will come to a point where the external cosmic-ray flux can enter. But if the field in question extends, with some roughly dipolar shape, over a typical distance with strength as observed (few gauss, $0.1R$), the slowly moving magnetic region will contain much volume nearly inaccessible to the cosmic-ray flux, and may be considered as empty of cosmic rays. Now suppose that such a cloud of ionized hydrogen is expelled from the sun into space, bearing with it magnetic fields (produced by net currents flowing in the neutral mass of plasma). Because of Liouville's theorem, the cosmic-ray flux will eventually reach its asymptotic value at all points accessible to the particles of a given rigidity. Without the solidity of the earth, or the compressive strength of the inner solar layers, the gas cloud is very unlikely to maintain any particular shape and field distribution. It will possess a chaotic and not a coherent field. At each point within it, there will in time be plenty of accessible directions for the external cosmic-ray beam at any energy. It has, moreover, no absorption to shield some volumes from certain directions. Eventually it must fill to the full cosmic-ray flux almost everywhere. But this filling takes time and during the time taken for random diffusion of the cosmic-rays through the chaotic field of the turbulent cloud, the cosmic-ray flux will be below its asymptotic value. The cosmic rays which do not penetrate are reflected away from the cloud, which has thus a certain albedo for cosmic rays of any energy. We regard the observed variations as samples taken when the earth passes through such clouds. The intensity increases as the cosmic rays diffuse into the originally more or less empty clouds of magnetized gas as the clouds move out from the sun, and in the end the flux within approaches the asymptotic value. As new clouds cross a point in space they preserve a lower cosmic-ray density there; the value present at any point is set by a competition between the age of the empty clouds and the rate of diffusion of the cosmic rays into them. The scale of the turbulence, which will determine the scale of coherence of the magnetic field, and the strength of the magnetic field, will determine the mean free path of cosmic rays for any energy. The whole modulation will be isotropic to the first approximation of diffusion theory, with an anisotropy measured by the mean free path compared to the cloud size, except at the boundaries where larger transient effects occur. The time scale and the amplitude of the modulation (which always depends upon a decrease from the assumed asymptotic value) found within a cloud, will also be determined by the size of the clouds, and by the mean free path for cosmic-ray diffusion. The diffusion times are much greater than the straight-line transit time because of the random walk of the cosmic rays into the chaotic magnetic field.

This introductory account now leads into Sec. II, a discussion of the several observed time variations, in an effort to obtain for each some estimate of the cloud sizes and magnetic properties which would account for the observed changes. These necessary parameters are then to be discussed, in Sec. III, in the light of the present rather slight knowledge of the corpuscular emission from the sun and the physics of a turbulent magnetized gas, to test their astrophysical plausibility.

It is convenient to list a few magnitudes which will be of importance: 1 astronomical unit (a.u.) = earth-sun distance $=1.5\times10^{13}$ cm; solar radius $=R_\odot=7.0\times10^{10}$; earth's radius $=R_e=6.4\times10^{8}$ cm; radius of curvature R_B in magnetic field of B gauss, for particle charge e and momentum $\mathbf{p}$ Bev/c:

$$R_B=3.3\times10^{6}\mathbf{p}/B\text{ cm}$$

equipartition magnetic field B_{Av}: $\rho v^2=B_{\mathrm{Av}}^2/4\pi$, so that $B_{\mathrm{Av}}=4.6\times10^{-4}\rho^{\frac{1}{2}}v$ gauss for a particle density of ρ hydrogen atoms per cm^3 and a mass velocity of v thousand km/sec.

II. TYPES OF TIME VARIATION

A. Cosmic-Ray Storms

Loosely associated with nonrecurrent and moderate to severe geomagnetic storms, there have long been noticed worldwide decreases in cosmic-ray intensity. These have been called cosmic-ray storms by the Japanese workers, and have also been known as Forbush events. It is quite certain[1,4] that the geomagnetic effects cannot of themselves cause these decreases. They tend to follow strong flares of class 3 and 3+, showing about twenty hours delay before the cosmic-ray decline, as before the sudden geomagnetic commencement when it occurs. This relation is not an invariant one; flares can fail to cause cosmic-ray storms as they can fail to cause geomagnetic storms. Since 1936, 33 type 3+ flares have

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[2] S. B. Treiman, Phys. Rev. **89**, 130 (1953).

[3] K. Nagashima, J. Geomag. Geoelec. **5**, 141 (1953).

[4] R. L. Chasson, Phys. Rev. **96**, 116 (1954).

been seen, of which 23 were followed by marked cosmic-ray storage with about a day or two delay. Only one flare was definitely not so followed; for 7 flares, overlapping effects prevent a clear decision. The storms produce about a 5% decrease in the meson beam, reaching up to a momentum of some 30 Bev/*c*, as seen from the small latitude effect, and typically a five or six times larger decline in the nucleon component, at energies from 2–5 Bev. These declines are never matched by any similar increases.[5] They set in rather rapidly, in a day or so, and slowly relax, taking about five or ten days to return to the background level in typical cases. Longer durations are seen, and a slight recurrence has been observed over perhaps one or two solar rotations, or even longer.[6] The isotropy of these storms is high, unlike the solar flare cosmic-ray peaks. A typical strong cosmic-ray storm displays an anisotropy which reaches at most a fifth of the total decrease, showing a maximum in the local forenoon. But appreciable anisotropy is generally of much shorter duration than the intensity decline. The separation of the storm anisotropy from the rather complex diurnal variations is beyond the scope of the present discussion.

Nagashima[3] has sought to give an explanation of the whole phenomenon in terms of a varying electric field in space which modulated the energy of the beam. We take here the view that the not very well-known spectral changes do not agree with the rather specific predictions of Nagashima, and that the needed fields in space are implausible. The theory of Nagashima is not yet disproved by experiment; what both Nagashima and the present arguments do exclude is a terrestrial effect, whether magnetic or electric. The present model is offered as an alternative to Nagashima's; it lacks the specific detail of his proposal, but this weakness perhaps allows better experimental agreement.

We interpret the cosmic-ray storm as the result of the passage of the earth into a cloud or beam of magnetized plasma, emitted from the sun in a wide cone beginning at or near the time of great solar flares, and perhaps at other times. The sharp decline represents the passage of the earth into the cloud; the relaxation time is the time required for the earth to pass through the beam, which occupies a fair fraction of the earth's orbit. Taking ten days for the decline, we get a diameter for a large cloud of about 1–2 a.u. The cloud persists throughout this time, and may be weakly effective from the same emitting source on the sun even after several solar rotations. Now diffusion theory predicts for a flux $j(t)$ at the center of a spherical region, initially empty, into which an external flux j_∞ diffuses in a time t, the value

$$j(t)=j(\infty)\left[1-2\sum_{1}^{\infty}(-)^{n-1}\exp(-n^2\pi^2\lambda ct/3R^2)\right],$$

where R is the radius of the region, λ the transport mean free path, c the particle velocity (velocity of light). The intensity decline at full immersion is the result of the cosmic-ray diffusion into the empty cloud, in a time a little greater than the transit time from sun to earth, say 10^5 seconds. Using the diffusion expression, the mean path satisfies the relation

$$1-[j(p,t)/j(p,\infty)]=2\exp(-\pi^2\lambda ct/3R^2),$$

for a given momentum p. The results, for a radius $R=1$ a.u., become

p	$j(p,t)/j(p,\infty)$	λ
30 Bev/c	0.95	6×10^{10} cm
4 Bev/c	0.75	3×10^{10} cm.

The order-of-magnitude estimates are of course not to be relied upon literally. The slow variation of the mean free path with momentum suggests diffusion through a medium in which rather highly fluctuating magnetic fields are present. If knots of strong field were separated by a region of very weak field, the mean free path would in the limit be constant with momentum, until the Larmor radius in the strong fields became larger than their dimensions. A slow variation in free path, in the expected sense, is plausible, but the theory really makes no prediction about the energy dependence. It is important to observe that the maximum fields need be no larger than that given by $R_B<\lambda$, which fixes a field in the scattering part of the magnetic cloud of about 1.5×10^{-3} gauss. The event discussed is, in fact, a rather strongly marked one, by no means a commonplace happening; such fields would not be inconsistent with the observed terrestrial magnetic variations in times of disturbance. A marked anisotropy at entry is to be expected from this picture, as well as its later decline, but the question of small anisotropies goes beyond such a simple model of homogeneous and isotropic diffusion. Only considerations on much smaller scale will allow clear conclusions about short-time anisotropy.

The cosmic rays which do not reach the earth during the presence of the diffusing cloud are of course reflected away, out into space. Since the mean free path of the outer space may be taken as quite a good deal larger, no appreciable rise of intensity due to the albedo of the moving cloud will precede its arrival. Some small anticipatory effect ought to be present; along these lines some tests of the model can be developed.

The weak correlation with geomagnetic storms is plausible on this picture. Some clouds, presumably those which for some reasons of internal structure or relative motion set up strong ring currents around the earth, produce marked magnetic storms. But the cosmic-ray storm is due to a long-range phenomenon, and need not invariably accompany a much more local cloud, which can yet produce a ring current with dimensions of a few R_e. Large clouds, following great flares which are aimed past the earth, will on this picture always produce cosmic-ray storms, and usually magnetic ones

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[5] A. R. Hogg, Canberra. Commonwealth Solar Observatory Memoirs, **10** (1949).

[6] Communication to International Association for Terrestrial Magnetism and Electricity Meeting, Rome, 1954. Working Association of Primary Cosmic-Ray Research, Japan.

as well. This is consistent with experience (one exception was mentioned above), but it is to be emphasized that the cosmic-ray storm does not directly imply any marked geomagnetic one; the two have a common cause in the solar beam, but the spatial and magnetic paramenters involved are wholly different.

B. Eleven-Year Variations

The recent work on the low-energy cutoff[7,8] and the long-term series of meson intensities published by the Carnegie Institution[9] leave no doubt that there is an important variation in the cosmic-rays over the solar eleven-year period. The Forbush series of monthly means shows a 3% change in the meson intensity from the maximum in 1944, the time of sunspot minimum, to the minimum of late 1947, about the epoch of greater solar activity. The cut-off data indicate a considerably greater effect for momenta below 1–2 Bev/c, but quantitative information over a full cycle is still not at hand. It is likely[10] that the cut-off changes affect particles of a given magnetic rigidity, and not of a given velocity, making a magnetic origin of these changes entirely plausible.

Inspection of the meson intensities shows that the decline of the cosmic-ray beam during solar activity is not a slow, regular effect. On the contrary, most of the decline from the maximum was due to two sharp falls, each followed by a long, slow partial relaxation back upward towards the mean. One of these drops amounted to about $2\frac{1}{2}$%, in February, 1946, and relaxed away to about half that decline by the end of the year. It was followed by a somewhat less abrupt fall, lasting from March to July of 1947, relaxing back in turn toward the rather constant values of 1948–1952. This behavior is so analogous to the behavior of the cosmic-ray storms that the same general model is suggested. The model, moreover, accounts qualitatively for the weak latitude dependence, for the dependence upon magnetic rigidity alone, and for the stronger effects shown at the lowest rigidities, i.e., the variation of the cutoff.

Again the effect is considered as a screening of the earth by the scattering effect of a turbulent magnetized cloud in which it is immersed. The empty cloud again leaves the sun, and the cosmic rays diffuse slowly into it. But the time scale is very different. It takes the cloud not a day but weeks to become well established. We will defer to the next section a discussion of the reason for assuming a velocity for this type of cloud which is on the average smaller than the flare-emitted cloud of the cosmic-ray storm. In any case, the velocity is taken only a factor of five smaller. Indeed, in the February, 1946 drop, the clouds may well have been the same. But now we shall postulate that the cloud, bearing usually lower density and field than the cosmic-ray storm beams, and traveling slower, finally fills up, not merely the neighborhood of the earth's orbit, but a volume with a radius of tens of a.u., to the orbits of the outer planets or beyond. Into this whole volume, cosmic-ray diffusion must now take place. The large size of the region means that the rather erratic but continual emission of clouds from various parts of the sun will in the end build a more or less uniform diffusing cloud far away, though it may well be filled with holes and channels in the interior, especially in distances within a couple of a.u. from the source. The diffusion time is now perhaps a hundred times as long, but the diameter of the diffusing region is larger by a similar factor, and the effect smaller (for the higher momenta), so that the diffusion relation

$$\lambda = 2R^2/ct \quad (\text{for } p = 30 \text{ Bev}/c)$$

now implies a considerably longer mean free path, and hence a smaller maximum magnetic field. A value of $\lambda = 3\times 10^{12}$ cm, and thus $B \cong 3\times 10^{-5}$ gauss, would be fully consistent. Such a small field would still have a considerable transient effect on really low-energy cutoff, perhaps preventing particles with p only a fraction of one Bev/c from ever diffusing to the earth during a normal solar cycle. It is not possible to estimate at what momentum this cutoff will appear without a model of the turbulent field. But the possibility of such a cutoff, maintained purely statistically, is clear.

The sun then presents to the distant isotropic cosmic-ray beam a reflecting surface, probably a disk rather flattened towards the solar equatorial plane, because of the concentration of solar activity at low solar latitude. That this disk is not very strongly flattened is at least suggested by the wide range of flare positions from which the cosmic-ray storm beams can come to earth. One may picture an ellipsoid about a hundred a.u. in radius, and perhaps a third or a half that thick at middle distances from the sun, tapering to a narrower volume towards the center. This model suggests an anisotropy at low energy across the solar equatorial plane, rather difficult to observe in the presence of other diurnal effects. The outer boundaries have a high albedo for low-rigidity particles. This volume, constantly renewed by new solar clouds, may very well be limited by fields of galactic origin, against which the solar clouds in part may bounce, and into which they may eventually flow, to add to the interstellar gas. The limiting fields of some 10^{-5} gauss suggest such possibilities. The whole picture loses meaning for particles above 10^{12} ev, for such particles cannot be scattered seriously by magnetic fields of the strength here contemplated in the distances available.

The fact that long-term periods of greatest solar activity coincide with the minimum of cosmic-ray intensity and the sharpest low-energy cutoff, strongly argues for a modulation, and against a solar production of the cosmic rays. The trapping fields here described require no special structure or much coherence, op-

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[7] H. V. Neher and E. A. Stern, Phys. Rev. **98**, 845 (1955).

[8] P. Meyer and J. A. Simpson, Phys. Rev. **99**, 1517 (1955).

[9] S. E. Forbush, J. Geophys. Research **59**, 525 (1954).

[10] Ellis, Gottlieb, and Van Allen, Phys. Rev. **95**, 304(A) (1954).

erating by purely diffusive mechanisms. On the picture here described, the solar trapping time at most amounts to a small fraction of one solar cycle, perhaps 0.1 year, and the flare-emitted flux can contribute less than one-thousandth of the observed low-energy intensity,[11] which would be a small effect compared to the modulation of the beam. If these considerations are correct, the solar contribution to all cosmic-ray phenomena is limited to a very minor sporadic production in flares, and a continual and important modulation of the over-all beam, acting in opposite senses as solar activity changes. High-energy cosmic rays are affected by neither solar phenomenon.

The "blowing away" of the cosmic rays and of the external magnetic fields by the sun's particle emission guarantees that any large-scale fields present in interstellar space will be wholly changed in the solar neighborhood. This helps make clear how it is that, at least at times, a field-free region exists between earth and sun, occupying an appreciable solid angle, in which the field is less than a microgauss, averaged over distances comparable with 1 a.u. Local but small-scale fields of higher strength are not excluded by the evidence, which rests wholly on the fact that the flare spikes can in part come more or less directly to the earth. The fact that there are also scattering regions in the neighborhood is made equally clear in the very same events, as Schlüter and Firor have emphasized, because of the "ringing" (slow decay) of the flare cosmic-ray pulse and the evidence that at high latitudes some scattered beam is received.[12]

C. 27-Day Recurrent Variations

The sporadic Forbush-type cosmic-ray storms are well-marked in many cases by the sharp decline and slow relaxation of the cosmic-ray intensity. However, even more important but less well-marked rises and declines in the cosmic-ray beams have been shown to recur with the solar rotation period, about 27 days from the earth's point of view. The onset of a recurrent event is not easy to pick up, but the fully-developed sequence has been much studied (especially by the Chicago group[13]). More or less jagged, but broadly symmetric maxima and minima recur with the 27-day period. Interlacing sequences occur, with different amplitudes. A strong sequence may persist for quite a few rotations, as can be seen by inspection of the Carnegie Huancayo meson data from April to September of 1952, for example. The slow spectral dependence up to 30 Bev/c or so, increasing in effect at low momenta, and the over-all isotropy, are very similar to the cosmic-ray storms. Like the cosmic-ray storms, and unlike the long-run intensity, the recurrent effects are highest in amplitude at the time of solar activity maximum, though they are not so obvious in the much more irregular intensity curves of such year. The amplitude of the intensity change varies from about $\frac{1}{2}$ to 1% in 1944 to above $2\frac{1}{2}\%$ in 1947, using meson data. The nucleonic (low-rigidity) effect is three or four times larger.

TABLE I. Time of 27-day recurrent effects compared to cosmic-ray maximum.

Effect	1952	1953
K_p minimum	-2 days	-1.5 days
Cosmic-ray maximum	0 days	0 days
K_p maximum	$+2\frac{1}{2}$ days	$+3$ days
Meridian passage of coronal intensity maximum (active center) (16)	$+6\frac{1}{2}$ days	-4 days
Meridian passage at monopole region	not observed	-1 day

It is already clear from these purely cosmic-ray data that the cause of the 27-day change is related to some persistent structure on the sun. The magnetographic studies at Mt. Wilson[14] have shown that during the well-marked recurrent changes of the summer of 1953, the cosmic-ray maxima occurred within about a day of the central meridian passage of a magnetic monopole region in the chromosphere (called a *UM* region by those authors). We identify this region with the cosmic-ray maxima, because of the time coincidence, and from plausible hydromagnetic arguments, which we defer to the next section.

The identification of such a relationship by time coincidence alone is, of course, risky. Earlier efforts[15] to relate the cosmic-ray maximum to active centers also showed persistent correlation. Table I indicates why the active center is excluded. Calling the time of the cosmic-ray maximum day 0, we list the times for various recurrent phenomena, found by averaging superimposed values over a good many months (April–October, 1952; June–October, 1953).

The table shows that for two years, at least, the recurrent geomagnetic effects and the cosmic-ray maximum showed the same relationship, familiar as well at least roughly from available earlier data. But the active center, as marked by the coronal intensity maps of the Climax High Altitude Observatory[16] shows no constant relationship to either. Since only one monopole study has been published, it is not possible to be sure that here too there is not a false identification, but (i) the physical arguments do make the connection plausible, (ii) the likelihood that a monopole cannot coincide in solar position with an active center makes it reasonable that the cosmic-ray maximum should dodge

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[11] Firor, Simpson, and Treiman, Phys. Rev. **95**, 1015 (1954).

[12] J. W. Graham and S. E. Forbush, Phys. Rev. **98**, 1348 (1955).

[13] P. Meyer and J. A. Simpson, Phys. Rev. **96**, 1085 (1954).

[14] Simpson, Babcock, and Babcock, Phys. Rev. **98**, 1402 (1955).

[15] J. C. Parker and W. O. Roberts, J. Geophys. Research **60**, 33 (1955).

[16] Dorothy Trotter and W. O. Roberts, Reports of the High Altitude Observatory, Boulder. Solar Activity Summaries (unpublished).

the active center as it does, and (iii) it is in any case sure that by now unpublished data on 1954 and 1955 events have settled the matter observationally. We here assume, then, that the monopole meridian passage is the cause of the cosmic-ray maximum, with perhaps a day delay or so.

Accepting this connection, it is now evident that the cosmic-ray phenomenon is very different from that of a cosmic-ray storm, though it shows a similar spectral and time behavior. The recurrent effect is a maximum when the solar beam (assumed from the monopole) envelops the earth, and not a minimum as before. Moreover, the amplitude of the effect becomes largest when the cosmic-ray over-all intensity is smallest, at the maximum of the solar activity cycle, and conversely. During active times, however, a single monopole region does not persist for many rotations. The longest lasting sequences of some importance appear to occur in years just before sun-spot minima, as in 1940–1941, 1951–1952. This property is well-known for recurrent geomagnetic storms, too.

The cosmic-ray maximum can be explained if the monopole region is taken as the origin of a volume of space within which the cosmic-ray diffusion is easier than within the average magnetic cloud. The cosmic rays will diffuse into this region from the interstellar beam, the flux density will rise, and a maximum will be visible as the earth traverses the volume. The height of the maximum will be limited by the degree to which the outer clouds are reflecting the cosmic-ray beam away from the sun, and will thus show its maximum amplitude when the cosmic-ray intensity is lowest over all, and the converse. The earth stays in this "hole" some eight or ten days in a typical case, making the dimensions around 1 a.u., or a little less. The hole is not fully accessible from outside, for the 27-day maxima do not completely destroy the long-term decline of the cosmic-ray intensity.

The 11-year change is about 3% (meson beam), but the 27-day amplitude is smaller. This may be a purely geometrical matter, the hole not extending entirely out of the solar excluded volume. It may as well mean that there is still some turbulent magnetic matter streaming out of the monopole, but material in which the cosmic-ray mean free path is much longer than in the ordinary clouds.

In September, 1944, the cosmic-ray intensity was higher than at any other known time. The 27-day recurrence component (the "tracking" component of Meyer and Simpson[13]) was less than one-eighth of its maximum amplitude. Two separate factors contribute to this reduction: the over-all intensity is little reduced from the asymptotic value, so that cancelling this average reduction can have little effect, and the solar structures which are responsible for the cancellation are small and rare. It is not possible to separate these two simply, but study of the low-energy cutoff and of the associated solar conditions will probably enable the separation, and an estimate of what the asymptotic flux and spectrum really are. The data give the impression, based on rough extrapolations and comparisons, that the cosmic-ray intensity at 30 Bev/c reached within perhaps $\frac{1}{2}\%$ of its true asymptotic value in 1944. At energies low compared to 1 Bev there is no reason to expect such a close approximation to the distant values. The total cosmic-ray energy input to earth, however, presumably does not change by more than 10% over the solar cycle, since the mean energy is some 10 Bev, and the main cut-off changes occur below a fraction of a Bev.

III. NATURE OF THE SOLAR BEAMS

Only a very tentative account can be given of the mechanisms and conditions on the sun which could be responsible for the sort of cosmic-ray diffusion we have here sought to infer from the cosmic data and a very few solar observations. What information we can work from is mostly very new, inadequately studied and only partially published. The most significant contributions come from the magnetograms of Babcock, and the general solar picture as described, say, in the Kuiper symposium.[17]

We recognize two types of solar structure which can be associated with the various cosmic-ray effects. They are:

1. The classical active center, with enhanced coronal emission, radio noises, plages, flares, spots and spot groups, filaments, and the rest. With these are associated the large regions of magnetic dipole fields seen by Babcock, and called by him *BM*; we will call them *D* regions. The lines of force in these structures arch across perhaps $0.1R_\odot$ to pass from *N* to *S* magnetic pole.
2. The large regions of monopole field seen by Babcock, and called by him *UM*; we will call them *M* regions. (The term "*M* region" has been reserved for twenty-five years for those unknown features of the solar surface which are responsible for the typical recurrent geomagnetic storm. Since we here identify geomagnetic storms with the boundary of the beams sent out from Babcock monopoles, no important confusion can be caused by this notation; if it is confusing, it is also wrong, and best forgotten.) Here the lines of magnetic force leave and return, if at all, only after so diverging that at their points of return no visible magnetic field perturbations are seen on the sun.

The cosmic-ray effects can now be attributed as follows: To an active center, (1), we ascribe the flare event which emits the sun's quota of cosmic rays. The cosmic-ray emission is not understood; it has very likely something to do with the emission of a fast magnetically turbulent beam, which may accelerate cosmic-ray particles in the statistical way as discussed

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[17] G. P. Kuiper, *The Sun* (University of Chicago Press, Chicago, 1953), Vol. 1 Chap. 5, 6.

TABLE II. Properties of a cloud accompanying a great optical flare.

	At sun's surface	At 1 a.u.
B_{Av}	10^3 gauss	$10^{-2.5}$ gauss
L_0 (typical dimension)	10^{10} cm	10^{13} cm
v (streaming velocity)	2×10^3 cm/sec	nearly same
particle density	$10^{7.5}$/cm^3	1/cm^3

by Fermi,[18] or by some other process effective within an hour after the optical flare, and probably within a few R of the solar surface. The long exponential tail in time of the cosmic-ray emission may be a feature of the statistical origin, and may also, since in part it does not come along the same trajectory as the main spike, reflect some diffusion in local diffusing clouds, present in space in the first a.u. and not directly associated with the active center. When the cloud which the active center sends out with the optical flare reaches the earth, in about a day, we have a cosmic-ray storm, which persists for a week or so until the earth has crossed the diffusing region. The center spends itself inside a few solar rotations, and breaks up entirely.

The D regions are closely connected with active centers; indeed, it seems probable that the relation is genetic. The D region is the earliest magnetic manifestation of the active center, which may locally develop fields strong enough to give actual sun spots, and all the characteristic active center phenomena. A widespread D field is visible only with the magnetograph; a concentrated dipole or multipole field eventually becomes visible even in white light by its effects on solar convention, and hence temperature.

From the D fields proper, large-diameter and low-field strength regions, (measured in gauss and not in kilogauss), we may expect that any corpuscular emission from the sun will carry out a turbulent magnetic field. The particle beam will be ejected roughly radially, and thus crosses the lines of force near the sun, where the field is rather strong. The beam can leave the sun, then, only if the kinetic energy density exceeds the magnetic energy density, and if so, then the motion would surely result in a highly turbulent magnetic field. The clouds bearing these fields, moving and expanding as they go, leave the sun, to penetrate to the other solar system, where they collide with and perhaps merge into interstellar gas currents.

We list in Table II plausible properties for the clouds emitted from a small concentrated dipole field, both at the time of a flare and for the general corpuscular emission, using the parameters established from geomagnetic and auroral studies, and from the study of the corona, comets, and zodical light. Here the original streaming energy was much above the magnetic energy. The cloud passes out, with a high Reynolds number, and twists the magnetic field up, expanding and thus stretching the lines of force. Very roughly,[19] for a free isotropic expansion, if the density ratio

TABLE III. Properties of a cloud emitted from a D region.

	At sun's surface	At 1 a.u.	At 30 a.u.
B_{Av}	3 gauss		10^{-6} gauss
L_0	10^{10} cm		10^{15} cm
v	$\frac{1}{3}\times10^3$ cm/sec		less by 1 order of mag.
	10^7/cc	1/cc	10^{-4}/cc

$$\rho_{\mathrm{initial}}/\rho_{\mathrm{final}}=\epsilon^3,$$

then

$$B_i/B_f=\epsilon^2.$$

We take the final dimensions and density from the cosmic-ray effects and from the astronomical data, and the internal field follows. This gives the curvature $R_B(30\ \mathrm{Bev}/c)=3\times10^{10}$ cm, not far from what is required for cosmic-ray diffusion.

We may repeat the same considerations for the larger and slower clouds being emitted, on our picture, from various D regions during the whole history of the regions, but with increased frequency at times of high solar activity, when many active centers are present. These are the clouds which drift out to large distances, forming eventually the diffusive barrier to the incoming cosmic-ray flux. The results are given in Table III. Here the low fields extend over such a large distance that again diffusion is adequate to explain the facts; $R_B(30\ \mathrm{Bev}/c)=10^{13}$ cm.[20]

The monopole fields appear to give rise to very different clouds. This is indicated by the cosmic-ray data; it is also plausible because the emitted gas streams will follow the monopole lines of force, not having to cross them until rather far from the sun, where the field becomes very much weaker by divergence, perhaps by a factor 10^2 or even more. So the magnetic fields carried off by such monopole-emitted clouds will be much smaller, and the kinetic energy will remain high. These well-ordered and not very magnetic streams (they must indeed have a small-scale turbulence since the Reynolds number is certainly very high) can sweep the space free of the less energetic but more magnetic clouds already surrounding the region of a few a.u. Then the external beam leaks in, diffusing and reflecting as it goes, and when the earth is immersed in such a volume we see the intensity maxima of the 27-day recurrences.

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[18] V. L. Ginzburg, Doklady Akad. Nauk. S.S.S.R. **92**, 727 (1953); National Science Foundation translation (NSF-tr-207).

[19] G. K. Batchelor, in *Gas Dynamics of Cosmic Clouds* (Interscience Publishers, Inc., New York, 1955), p. 118.

[20] *Note added in proof.*—Professor L. Biermann has kindly informed me that the cloud densities ρ widely cited (e.g., in reference 17) as derived from his work are misinterpreted. In fact, the densities he finds are larger by perhaps one or two orders at magnitude in a case like that of Table III, and by as much as 10^5 in a case like that of Table II. This implies values for B_{Av} correspondingly higher ($B_{\mathrm{Av}}\sim\rho^{\frac{1}{2}}$) and λ smaller. Such a change appreciably relaxes the requirements of size and field shape here imposed, and makes still more likely the assumed cosmic-ray effects of the solar streams.

The origin of the ordinary recurrent geomagnetic storm, or *M*-type storm, is associated with the *M* streams. From the times in Table I, it can be seen that the geomagnetically most disturbed days are those which follow by a few days the earth's arrival in the central part of the *M* stream. It may be taken that the *M* streams have a high stream velocity, about 1–2 thousand km/sec, because the cosmic-ray maxima do not lag the central meridian passage of the *M* region by much more than a day. The most disturbed days, measured by high values for the worldwide disturbance index K_p, are days when the earth is leaving an *M* stream (and perhaps entering a *D* one). The quietest days are those preceding *M* stream central passage, which presumably is a time when the earth is far from such a boundary region. How the earth's field, and the ring current, interact with these streams is outside the scope of cosmic-ray physics; the matter may be very complex. Cosmic-ray diurnal variations, which show both 27-day effects and solar cycle effects, seem to be related to such complicated interactions.

IV. TESTS OF THE THEORY

The most sensitive means yet suggested for detecting weak magnetic fields extending over sizeable portions of the solar system with very low matter density is the study of cosmic rays. Tests of the present model are therefore almost of necessity difficult. Many more cosmic-ray data, such as spectral changes with time during all the types of events here studied, will be of some help. Other means, perhaps using radio-plasma interactions of "whistlers," to sample space a few R_e away, are possible; it is hard to go further. Comets may help, if they ever come back. Particular attention ought to be paid to superpositions of the cosmic-ray effects. The sun emits cosmic-ray particles at times of flares; study of their arrival or nonarrival as a function of the kind of magnetic regime around the earth expected from this picture, for the epoch of the flare, should allow a more or less direct test as soon as flares become frequent enough. If, as it seems likely, flares avoid *M* regions on the sun, the test becomes more complicated. It should also be pointed out that superposition of the processes here considered is by no means linear, a cloud may well change the medium in which it travels. Indeed, this is the assumed nature of the *M* streams.

V. CONCLUSION

The picture, for it is more a picture than a quantitative theory, here suggested cannot claim to have been demonstrated. Yet, it seems to describe the matter in a plausible way, without the assumptions of special structures or processes, or of any physical parameters which are quantitatively absurd. A look at the many years of cosmic-ray data with these ideas in mind seems to make rough order out of the differences among the years, and out of almost all the kinds of wiggles in the curve of mean daily meson intensity. It is hard to ask more at this stage; but it is still very far from a real physical theory. The empirical tests of the theory are still unmade; and a quantitative theory is, with many other astrophysical theories, far away. The close relationship of the physical picture to that of the Fermi-type mechanism for galactic origin of cosmic rays is plain, and equally plain is the way in which the solar modulations fit into a galactic picture of cosmic-ray origin, as they have not been fitted consistently into a picture of solar origin. It is a challenge to the solar theories of cosmic-ray origin to describe plausibly the variations in the cosmic rays, even at low energies. For energies above 10^{11-12} ev it would seem impossible.

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