RAPID REDUCTION OF COSMIC-RADIATION INTENSITY MEASURED IN INTERPLANETARY SPACE*

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In a recent Letter[1] we showed that the mechanism responsible for the rapid decreases of galactic cosmic-ray intensity was located beyond 8 Earth radii, and that this result excluded all existing geocentric theories for this phenomenon. We have extended these experiments out to distances of 8×10^6 km and now can prove that there is no possible association of this phenomenon with the earth and its magnetic field. We also find strong evidence that there is a bulk motion outward from the sun of conducting solar plasma ejected in association with a solar flare which either carries magnetic fields within itself, or manipulates an interplanetary magnetic field to remove convectively the galactic cosmic radiation from a limited volume of the inner solar system.

The experimental apparatus was carried in the space probe Pioneer V launched March 11, 1960 on a trajectory inside the orbit of the earth and towards the orbit of Venus. The apparatus is identical with equipment on Explorer VI; namely, a wide-angle, triple coincidence counter telescope surrounded by 5 g/cm² lead which detects protons with energies in excess of 75 Mev and electrons of more than 13 Mev. Bremsstrahlung due to electrons in the energy range 0.2 - 13 Mev is measured independently. The details of the experiment have been described in earlier communications.[1,2] To compare simultaneously the changes of cosmic-ray intensity at the earth and at the position of the vehicle in interplanetary space, the recordings of nucleonic component intensity monitors were used. The telemetry limitations for Pioneer V confined the data recording to relatively short intervals several times each 24-hour period. Therefore, the correlation method used previously for Explorer VI data[1] cannot be applied to Pioneer V results. Consequently, averaged, simultaneous observations in the space probe and at the earth are used to determine the relative change in galactic intensity at the probe and at the earth both before the intensity decrease, and after the decrease reached its full extent.

Although several intensity decreases have been detected in the Pioneer V data,[3] the largest and most readily analyzed event occurred on March 31, 1960, at which time the probe was nearly on the Sun-Earth line and 5.2×10^6 km inside the orbit of Earth. The changes in the nucleonic component at the earth—representing changes in the primary beam of particles with magnetic rigidities > 2.4 Bv—are shown in Fig. 1. The corresponding data for Pioneer V are shown in Fig. 2(a).

It is almost certain that the ejection of plasma from the solar flare[4] of importance 2 at 1455 - 1858 U. T. on March 30 led to the commencement of the geomagnetic storm and the beginning of the cosmic radiation intensity decrease at about 1200 U. T. on March 31. From this time delay we compute an average radial velocity of 2000 km/sec for the advancing "front" of conducting plasma. The expected time difference of ~40 - 50 minutes between the arrival of the plasma at Pioneer V and at the earth could not be observed due to the intermittent reception of data.

After extrapolating the neutron intensity monitor data of Fig. 1 to the top of the atmosphere,[1] we compute the ratio of the relative intensity change at the space probe and at the earth as

$$\frac{\text{Relative change in Pioneer V detector}}{\text{Relative change at the earth}} = 1.3 \pm 0.15$$

on April 1, 1960.

The larger decrease measured by the Pioneer

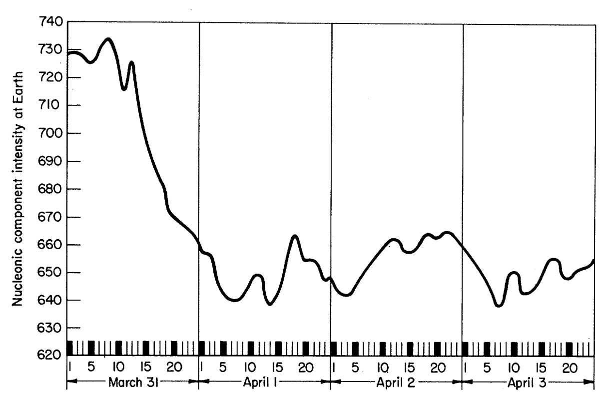

FIG. 1. The changes in galactic cosmic-ray intensity for particles above 2.4-Bv magnetic rigidity. The neutron monitor is located at Climax, Colorado.

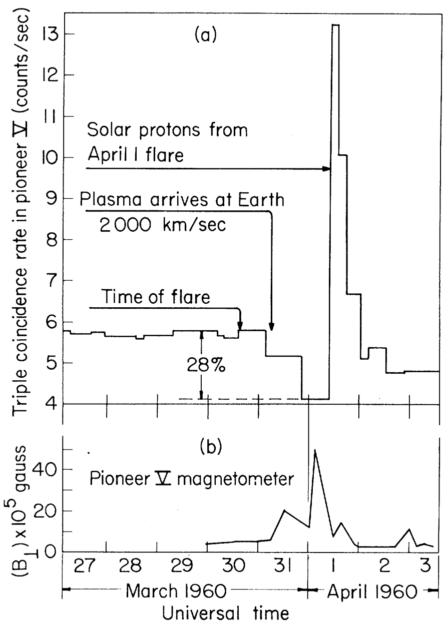

FIG. 2. Telemetered data from the space probe Pioneer V at distances $4 - 5.5 \times 10^6$ kilometers from the earth. The errors for each bar are less than 1%. The time for the first arrival of solar protons April 1 was determined by the onset of enhanced ionization from protons at the polar cap.[8] The magnetometer measurements in Pioneer V are published by Coleman et al.[7]

V detector arises from the removal of cosmic radiation with magnetic rigidities below the cutoff for the detector at the earth (2.4 Bv) but not below the threshold of the probe detector. Indeed, this removal of low-energy particles persisted for more than 30 days after April 1 although the relativistic particle flux by that time had returned to the intensity prevailing before the decrease.[5] From analysis of our neutron monitor data extending to the geomagnetic equator where the cutoff reaches ~15 Bv, we find independent evidence that the intensity decrease was more strongly dependent upon particle magnetic rigidity than for the event of August 19 - 20, 1959 previously reported.[1]

These results prove that the rapid reduction in galactic cosmic radiation is a phenomenon of solar origin taking place in interplanetary space and is not related to the presence of the earth or its magnetic field. Since the observed intensity decreases only follow solar flares on the visible side of the sun, the reduction of cosmic-ray particle intensity is confined to a limited volume of the inner solar system. We also eliminate all electrostatic field deceleration models for this effect.

From the simultaneous measurements in Pioneer V and at the earth we may also deduce some of the properties of these modulating magnetic fields:

(a) It has been known for many years that the rate of decrease of cosmic-ray intensity may be as high as 5% per hour for some events. On the basis of our Explorer VI studies[1] and the present results, we now conclude that this high rate applies to the removal rate of particles and, hence, to the transient magnetic field parameters in the interplanetary medium. Since telemetered data from Pioneer V on March 31, 1960 did not provide details on the rate of intensity change, we refer to the neutron data in Fig. 1 for these measurements. Approximately 28% of the particle flux detected by Pioneer V disappeared in less than 20 hours, with half of this decrease occurring in less than six hours. From these data and the computed radial velocity of 2000 km/sec for the advancing "front" of solar plasma, it is clear that a penetration to ~0.3 a.u. behind the front is required to reduce the intensity by 14%—half the full intensity decrease. For other events of this kind where the rate of decrease may be as high as 5 to 6% per hour the corresponding depth of penetration may be smaller by a factor of 3. This requires the rapid appearance of enhanced interplanetary magnetic field intensities; the magnitude of the changes and the degree of disordering of the required fields depends upon initial conditions and specific models which are not discussed here. Whereas our results describe large-scale transient magnetic fields over great distances from Pioneer V, the magnetometer in Pioneer V registers field changes at the position of the vehicle perpendicular to its spin axis.[6,7] These data[7] are shown in Fig. 2(b) where magnetic field increases of a factor 10 - 20 times the quiescent field conditions occur at the time for which we deduce the existence of large-scale magnetic fields from the changes in cosmic-ray flux. Both kinds of observations show that magnetic fields are being moved or generated in interplanetary space as a consequence of the solar flare on March 30. The only known way by which these transient fields could be established, or existing fields manipulated, is by moving, conducting plasma of solar flare origin. Therefore, we believe these Pioneer V results provide the most direct evidence to date for the existence of conducting gas ejected at high velocity from solar flares—a concept strongly supported already by many solar and terrestrial observations. Convective removal of galactic cosmic radiation by particle collisions with advancing magnetic field irregularities, such as a shock front, is the most likely explanation at this time. We do not discuss here the many models which may fulfill some of these conditions.

(b) By 0600 April 1 the advancing region which produced the full decrease of intensity had passed outward beyond Pioneer V and the earth. What were the magnetic field conditions remaining immediately thereafter in space between the sun and Pioneer V, i.e., behind the advancing "front"? This question may be investigated by examining the propagation of solar flare protons on April 1 which penetrated the volume of space between the sun and Pioneer V only four hours after the full reduction of galactic cosmic-ray intensity. The solar flare was observed to begin at 0845 and extend through 1222 U. T., with the first solar particles arriving to produce ionization in the polar ionosphere at 0945 U. T.[8] Thus the upper limit for the transit time is one hour. The solar particle increase is shown in Fig. 2(a) for protons > 75 Mev (but less than 1 Bev since no increases were observed by neutron monitors at the earth). Maximum intensity was reached within 50 minutes.[8] The subsequent decline of intensity with time t closely follows a power law $1/t$.

These data show that the interplanetary magnetic field conditions behind the advancing front are either smooth and radial or weak, irregular fields ($B_{rms} < 5\times10^{-6}$ gauss), otherwise the low-energy solar protons would not penetrate to the orbit of the earth in less than one hour.

Bremsstrahlung-producing radiation was also observed by our single, lead-shielded counter in Pioneer V[3] and by the University of Minnesota detectors[9] beginning about two days before and during the Forbush decrease. The measurement of detector efficiency is under way and these results will be reported at a later date.

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[1]C. Y. Fan, P. Meyer, and J. A. Simpson, Phys. Rev. Letters 4, 421 (1960), and references therein.

[2]C. Y. Fan, P. Meyer, and J. A. Simpson, Proceedings of the First International Conference on Space Research (North-Holland Publishing Company, Amsterdam, 1960); I. G. Y. Satellite Report No. 11, p. 115, June, 1960 (World Data Center A).

[3]C. Y. Fan, P. Meyer, and J. A. Simpson, J. Geophys. Research 65, 1862 (1960).

[4]Solar and Geophysical Data, National Bureau of Standards, Central Radio Propagation Laboratory Series-F, Part B (1960).

[5]See C. Y. Fan, P. Meyer, and J. A. Simpson, following Letter [Phys. Rev. Letters 5, 272 (1960), Fig. 3.

[6]P. J. Coleman, Jr., L. Davis, and C. P. Sonett, Phys. Rev. Letters 5, 43 (1960).

[7]P. J. Coleman, Jr., C. P. Sonett, D. L. Judge, and E. J. Smith, J. Geophys. Research 65, 1856 (1960).

[8]H. Leinbach [private communication and preprint, June 21, 1960 (unpublished)].

[9]J. R. Winckler (unpublished communication).