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II-4-32. The Cosmic Ray Intensity Gradient in Space during Solar Modulation*

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Measurements of cosmic radiation intensity have been made to ~0.1 a.u. from the earth in Pioneer V for investigating the heliocentric properties of the eleven year and Forbush decrease modulations of cosmic ray intensity by magnetic fields in interplanetary space. It is shown that during a Forbush decrease at 0.03 a.u. the cosmic ray spectrum undergoes a sudden change wherein approximately 10% of the total flux (mostly low energy particles) is removed from the spectrum. A second decrease at 0.1 a.u. (30 days later) shows that this low energy component does not return to the vicinity of Pioneer V. It is shown that this change in spectrum is important for determining the gradient of cosmic ray intensity in space at the time of solar maximum. The gradient for the eleven year intensity variation is $(0.0\pm2.0)\%/0.1$ a.u. This result shows that if the cosmic ray flux at solar minimum approximates the galactic flux of cosmic rays, then the main heliocentric gradient in space lies beyond the orbit of the Earth.

§1.

Although it was proved over a decade ago that the major changes of cosmic ray intensity were a property of the primary radiation controlled by solar activity, it was not possible until recently to measure directly modulation and production of cosmic ray particles in space free from the environment of the Earth. In this paper we discuss further simple experiments which have a bearing upon our present idea of interplanetary models invoked to describe the solar control of the primary cosmic ray intensity at the earth. We limit our discussion first to the rapid decreases of intensity—the Forbush decreases—and secondly, to the eleven-year changes of cosmic ray intensity and spectrum. We further confine our attention to the question of the heliocentric, radial dependence of these phenomena. Beginning with the assumption that at the orbit of the earth the cosmic ray intensity and spectrum at solar minimum represents an approach to the galactic spectrum, and that the reduced fluxes at solar maximum activity represent the removal of particles, it then follows that the radial dependence of the removal mechanism originating at the sun depends upon electrodynamical mechanisms which may be operative at solar maximum. Therefore, the experiment consists in measurements at a time near solar maximum of the gradient of the Forbush decrease in space and the gradient of the eleven-year effect. Some preliminary results on these measurements have already been reported[1,2].

The measurements were made in the deep space probe Pioneer V (launched March 11, 1960) which provided valuable data to a distance of ~0.1 astronomical unit (a. u.) from the Earth. The instrumentation consists of a proportional counter telescope which has a low energy cut-off for protons of 75 Mev. Details of the instrumentation are given elsewhere[3]. Neutron intensity monitors on Earth were used for simultaneous measurements of the relativistic component of the cosmic ray flux so that corrections could be made for changes of intensity with time.

The first two weeks following the launch of Pioneer V was a period of low solar activity. Thereafter, one of the most active regions in this solar cycle developed and

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was studied for two solar rotations with Pioneer V instrumentation.

§ 2. Forbush Decreases in Space

It has been shown that the Forbush decrease is heliocentric over a limited region of the inner solar system which includes the sun and the Earth[1]. The question then arises, what is the relative magnitude of a Forbush decreases with heliocentric range? Two large decreases were observed during the measurements. The first was 0.03 a.u. from earth (31 March 1960); the second was 0.1 a.u. from earth (30 April 1960). The intensity levels in Pioneer V and at the Earth during the first several days after launch were chosen as initial intensity levels at Earth and at Pioneer V. We then determined the percent change in these detector system levels. The results are shown graphically in Fig. 1. The decrease of 31 March was first detected as a loss of about 10% in the cosmic ray flux at Pioneer V without a corresponding obvious decrease of relativistic particles at the Earth. The first increase in the component of the interplanetary magnetic field perpendicular to the sun—earth line began near this time[4]. Thereafter, the intensity decreased both at the Earth and at Pioneer V consistent with the ratio of intensity changes of 1.0±0.2. The recovery of intensity over the period 1 April to 23-26 April as seen in Fig. 1 provides additional, strong evidence that the ratio is close to unity for the change in relativistic flux at the Earth and at the position of Pioneer V provided the initial 10% drop of particle intensity in space is first subtracted from the Pioneer V measurements.

The most important result of these observations is the loss of the 10% flux initially present of Pioneer V which did not return during the recovery phase of the Forbush decrease to full intensity at Earth by 23 April. Indeed, the recovery at Pioneer V is to the same level as the intensity at the Earth under the assumption that the initial 10% flux remained absent throughout the period of the observations.

The Forbush decrease of April 30-May 1

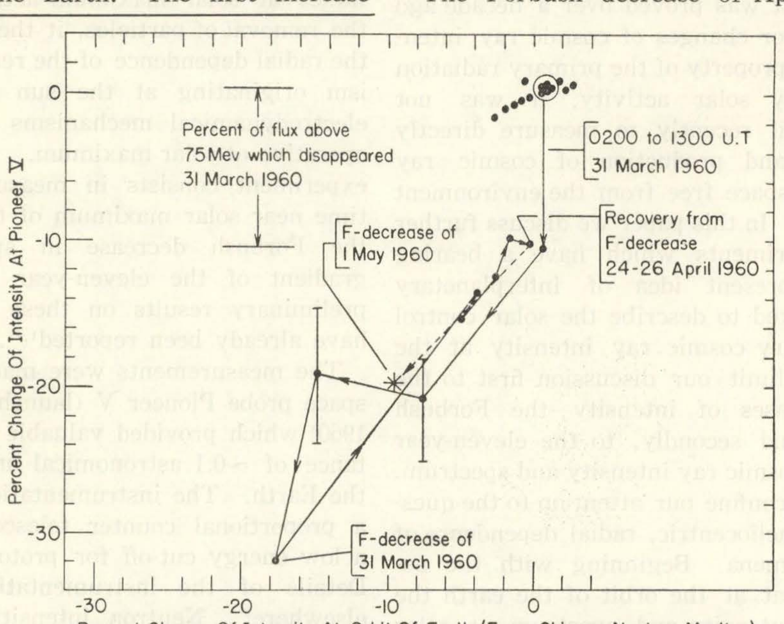

Fig. 1. The arrows connecting the experimental points show the time sequence of the measurements. Only a small portion of all experimental data are shown in this graph. The circle contains some data from the 20-day period prior to 31 March. Small intensity changes with time during this period fall outside the circle. The neutron intensity monitor data have been extrapolated to the top of the atmosphere by multiplying neutron intensity changes by the factor 1.9. Two points having exceptionally large uncertainties are shown—the true values lie between the indicated limits. The star point represents the Forbush decrease of 1 May 1960.

provides a further, sensitive test which shows that the 10% extra flux did not return to the primary spectrum at that late date. The results in Fig. 1 show that the decrease is the same at 0.1 a.u. as at the Earth within the cumulative experimental errors of approximately ±12%.

We believe these results prove that the primary spectrum was changed on 31 March by the modulation mechanism. It is likely that this loss of 10% flux represents mostly non-relativistic particles rapidly removed in the first stages of this Forbush decrease. These particles could not have had their origin as solar flare protons since they were continuously present for at least 20 days prior to their removal. They could either arise from a possible steady solar component, or, more likely represent the return of some low energy galactic flux over the months preceding these measurements.

Due to the relatively large errors in the ratio of the magnitudes of the observed Forbush decreases, it is difficult to place limits at this time on the gradient of the Forbush decrease which decide conclusively among heliocentric models for the modulation mechanism. At 0.1 a.u. the value assigned to this ratio is tentatively $R=1.0\pm12\%$.

§ 3. Gradient in Space of Eleven Year Intensity Change

The preliminary results already reported showed that the 11-year intensity changes are heliocentric, and roughly independent of heliographic longitude within the inner solar system. It was shown that the intensity gradient measurements at Pioneer V along its trajectory out to 0.1 a.u. were interrupted by Forbush decreases which must be taken into account. These consideration led to a preliminary value for the gradient of $-(1.5\pm2.0)$ %/0.1 a.u. Since that time we have analyzed additional data from 0.1 a.u. distance.

The analysis of the Forbush decreases in Fig. 1 now make it certain that the intensity as a function of radial distance free from variations with time must be corrected as we had suggested[2] for the change of spectrum which took place 31 March. Furthermore, we now have the proof *viz.* the Forbush decrease of 30 April that this change in spectrum was *not* followed by a gradual return of the flux removed on 31 March. Thus, the intensity level in space measured by Pioneer V was re-normalized to take account of this loss. Therefore, we find for the gradient in space the revised value of (0.0 ± 2.0) %/0.1 a.u. The error shown is substantially greater than the actual errors we expect to assign finally to this experiment.

There are certainly intensity and gradient fluctuations with time in space at solar maximum, and additional measurements at maximum would have been desirable to determine the spread in values of gradient. However, since they must be small compared with the intensity change of more than a factor 4 during the solar cycle, we consider these observations to be representative of the gradient in space near the time of solar maximum.

Since this small value of the gradient was measured when there was at least a factor of 4 larger intensity in the galaxy than at the earth, we conclude that for any assumed modulation mechanisms the main gradient between the galaxy and Pioneer V must lie beyond the orbit of Earth at solar maximum. The results clearly are in disagreement so far with the modulation mechanism which require appreciable gradients near the orbit of the Earth.

It is important to repeat this experiment when the cosmic ray intensity has increased to about twice its present value and also at solar minimum activity in order to decide whether the magnetic fields responsible for modulation are effective at successively decreasing distances as the sun approaches solar minimum (*i.e.* a gradient may appear at the orbit of Earth), or whether the modulation effect disappears beyond the orbit of the Earth (negligible gradient throughout the solar cycle). Such experiments are important in determining the relative importance of magnetic fields of solar *vs.* galactic arm origin for excluding galactic particles during times of enhanced plasma flow from the sun.

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