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OBSERVATIONS OF COSMIC RAYS IN THE OUTER HELIOSPHERE

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Abstract

Outward propagating cosmic ray modulation features seen in the outer heliosphere include Forbush decreases, the minimum of the 11 year cycle, and intervals of set recovery rate. The best theoretical model may not be the same for all these features. Some modulation features have been modified or have disappeared between Pioneer 11 and Pioneer 10 as if by the action of an interplanetary low-pass filter. Azimuthal symmetry still applies, and the radial gradient for nucleons $>\sim 500$ MeV/nucleon is $\sim 1\%$/AU.

1. Outward Propagating Modulation Features. In the outer heliosphere the rise of the current cosmic ray cycle, from 1982 to 1986, can be described as a series of distinct ramp segments, each having its own constant value of $d(\ln U)/dt$. The creases where the ramps intersect (and $d(\ln U)/dt$ changes) propagate outward with roughly the solar wind velocity. (See Figure 1.) This propagation lag is reminiscent of the decline of the last cycle from 1978 to 1982, when a series of negative steps propagated outward in the same manner [1,2,3,4]. Most observers attributed the negative steps to narrow barriers propagating outward in the solar wind, and Lockwood and Webber [5] pointed out explictly that the agency for the modulation must be localized radially, because the modulation state at a given observer changes at such a recognizable and short time.

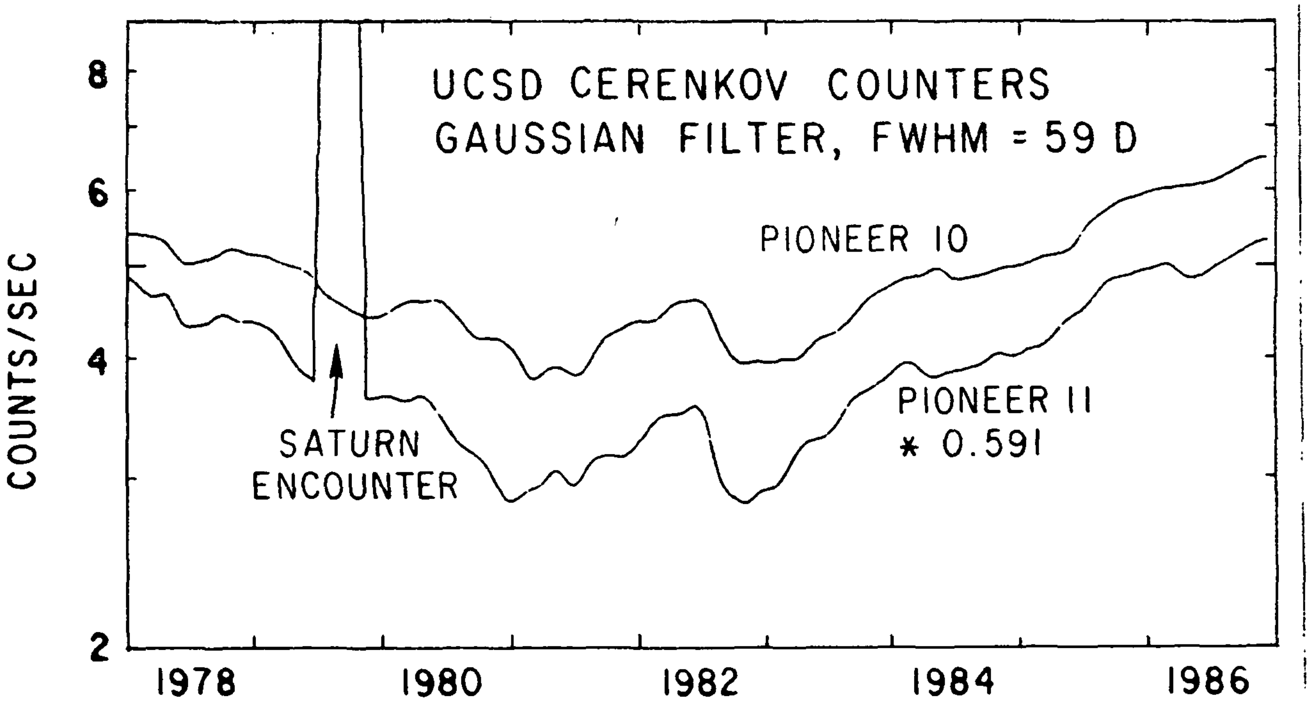

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Fig 1: Normalized counting rates from the UCSD Cerenkov counters aboard Pioneers 10 and 11, responding to cosmic ray nucleons of energy >500 MeV/n. The data have been smoothed by a running Gaussian filter of FWHM=59 days. From 1978 through 1986, the radial distance from the sun to Pioneer 10 increased from 15 to 40 AU and, to Pioneer 11, from 6 to 22 AU.

A simple mathematical model articulates the barrier interpretation of these observations. Barriers can be incorporated in the cosmic ray transport equation as distinct regions where the diffusion constant, k'', is much less than the undisturbed value, k' [6]. Thus the approximate solution for the spherically symmetric case,

$$U(R) = U_o \exp\left(-\int_R^{R_o} \frac{V}{k(s)}\, ds\right)$$

can be retained in the form of the undisturbed solution multiplied by the cumulative effect of the barriers.

$$U(R) = \left(\prod_i B_i\right) U_o \exp\left(-\int_R^{R_o} \frac{V}{k'}\, ds\right)$$

The effect of the ith barrier is

$$B_i = \exp\left(\left(S(R_i-R_o) - S(R_i-R)\right) \int_{\Delta R_i} \frac{V}{k_i'''}\, ds\right)$$

with $k_i''' = (1/k''-1/k')^{-1}$. Its position is $R_i = V*(t-ti)$ and its width is ΔR_i. The step functions $S(R_i-R) - S(R_i-R_o)$ define the window, between the observer at R and the modulation boundary at R_o, where the barriers are effective. This model is appealing for its simplicity. To evaluate the modulation, we need only count up the barriers. The number of barriers in the window follows from the rate at which they are launched from the sun at R = 0.

Although the negative steps from 1978-82 immediately suggest barriers, the ramps from 1982-86 do not. To stick with the barrier model here, one can postulate infinitessimal barriers, individually too small to be seen, but in sufficient numbers to produce modulation. These might also be needed in case the large, identifiable events do not produce all of the modulation. One can devise a barrier creation rate that will synthesize the observed modulation features, including ramps and an outwardly propagating minimum between cycles. Of course, dealing with infinitessimal barriers is equivalent to letting the modulation integral,

$$\int_R^{R_o} \frac{V}{k(s)}\, ds$$

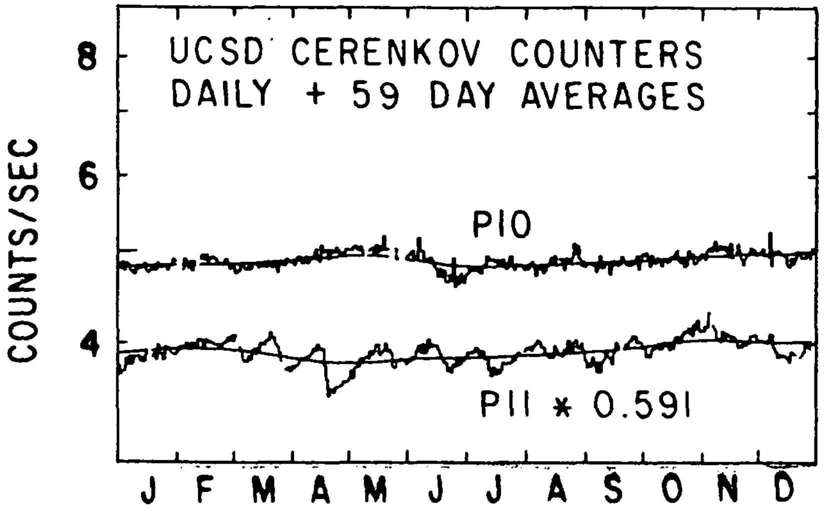
vary continuously. For this part of the observational record, then, barriers are no real help as modeled here.

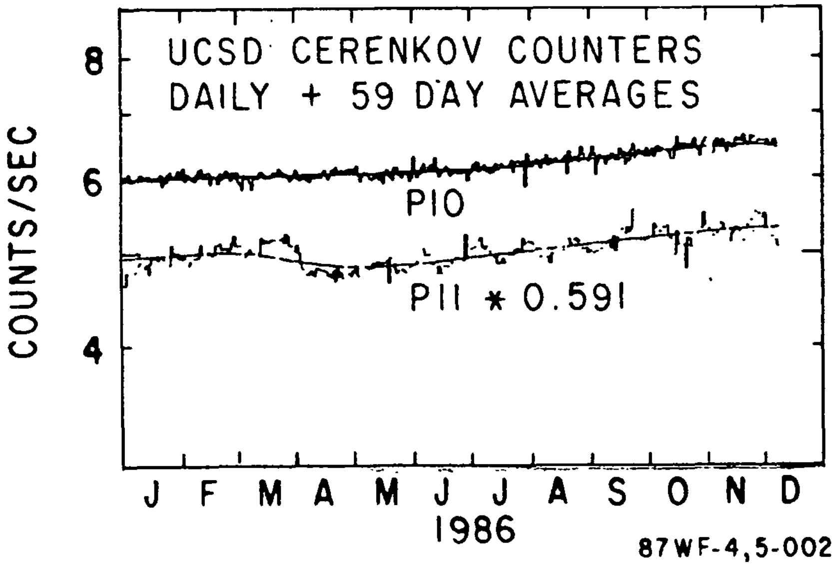
This conclusion might be avoided if the barriers are allowed to decay, as in the more elaborate model of Chih and Lee [7]. Other explanations have also been suggested. Smith and Thomas [8] argued that the tilt of the heliospheric current sheet is the real controlling factor for modulation, via particle drift in the inclined magnetic field [9,10]. They demonstrated that the cosmic ray intensity varies inversely with the tilt angle, and pointed out that sudden increases in this angle coincide with the events that have been attributed to barriers. As it is normal for the inclination of the current sheet to change gradually, it could match the ramped cosmic ray variations more naturally than barriers. On the other hand, the drift theory still does not so readily explain the radial localization and outward propagation of modulation features.

2. Evolution of the Modulation Features. Some modulation features change significantly between Pioneer 11 and Pioneer 10, as seen in Figures 2(a) and 2(b). First of all, there is less variation altogether in the daily Pioneer 10 counting rates. Furthermore, in Figure 2(a), Pioneer 11 has a remarkable 25 day periodicity that lasts for most of 1984; however, Pioneer 10 shows no particular variation at this period. In Figure 2(b), from 1986, the outstanding difference is that the large Forbush decrease that passed Pioneer 11 on about day 90 has no counterpart at all at Pioneer 10.

Figure 2: Counting rates as in Figure 1, with daily averages superimposed.

(a) During 1984, the radial distance from the sun to Pioneer 10 increased from 31.8 to 34.6 AU, and, to Pioneer 11, from 15.2 to 17.6 AU.





(b) During 1986, the radial distance from the sun to Pioneer 10 increased from 37.3 to 40.0 AU, and, to Pioneer 11, from 20.0 to 22.4 AU.

If the critical distinction is spatial, as seems likely, it might be from the difference in longitude, latitude, or radial distance from the sun. The two spacecraft are 180° apart in ecliptic longitude. However, the 25-day wave is obviously rotational, and should be seen at all longitudes. The Forbush decrease certainly originated in the solar disturbance that affected earth in early February, 1986. As this activity lasted for more than 25 days, it is unlikely that longitudinal differences could account for this discrepancy either. The difference in heliolatitude is ~12° (Pioneer 11 is at ~16° and Pioneer 10, 4°), and one can imagine latitude-dependent disturbances that could affect one spacecraft and not the other. However, for the Forbush decrease, at least, published data show that the event was also present at Voyagers I and II on the same side of the sun as Pioneer 11, and at heliolatitudes of 0° and 25° [11]. Thus it seems most likely that the radial distance of 17 AU from Pioneer 11 to Pioneer 10 is the critical factor.

If these modulation features are unable to propagate out as far as Pioneer 10, one must ask whether Pioneer 10 has passed beyond the modulation boundary, as predicted by Randall and Van Allen [12]. Referring to Figure 1, note that the cosmic ray intensity at Pioneer 10 increases monotonically from 1984 through 1986. This is ample evidence of continuing solar modulation, at least on the time scale of the 11 year cycle, and we conclude that Pioneer 10 has not reached the modulation boundary yet.

Although these higher-frequency modulation features disappear between Pioneer 11 and Pioneer 10, note in Figure 2(a) that when the data are smoothed by a filter of width somewhat greater than the solar rotation period (and lagged appropriately) they match well. This is very apparent in Figure 1, also. In Figure 2(b) a better match requires a longer filter than the one shown. It is as if the interplanetary medium has applied a low-pass filter to the cosmic rays similar to the one we applied to the data.

3. Radial Gradient. The intensities in the Figures are normalized, and so we can quickly estimate the radial gradient. In 1986 the difference in intensities, $\Delta(\ln(U))$, is about 23%, and $\Delta(R)$ is ~17 AU. Thus, if the latitude difference is negligible, the radial gradient is about 1%/AU. Azimuthal symmetry still appears to hold, as can be inferred from the correspondence between features propagating from one spacecraft to the other at roughly Vsw.

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