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EVIDENCE FOR REGIONS OF NEGLIGIBLE COSMIC-RAY MODULATION IN THE INNER HELIOSPHERE (< 10 AU)

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ABSTRACT

Gold and Venkatesan [1] report observations of periods during 1974-1976 when extended regions of heliolongitude that emitted lower-than-average solar wind velocities at 1 AU also exhibited higher-than-average cosmic-ray intensities as measured by the E > 35 MeV CPME anti-coincidence scintillator (28 cm^2 omnidirectional geometric factor) on IMP-8. Their observations can be reproduced by a simple model, based on the observed steady solar wind structure, wherein there is little modulation of cosmic rays in the inner heliosphere until they reach the shocked plasma beyond the stream interactions in the outer heliosphere (~ 5-10 AU). Beyond the interaction boundary, the intensity exhibits a constant radial gradient (~ 2%/AU). The model also offers an explanation for the irregular behavior of the rotation-averaged radial gradients observed by inside 10 AU, as well as the significant, but often ephemeral, latitude gradients observed by Voyagers 1 and 2 and IMP-8 [2].

1. Introduction. Gold and Venkatesan [1] present correlated IMP-8 observations of integral cosmic ray intensity (> 35 MeV) and solar wind velocity during the previous minimum in solar activity (1974-6). The use of the anti-coincidence scintillator of the JHU/APL Charged Particle Measurements Experiment (CPME) as a cosmic ray detector was described in detail by Roelof, Decker and Krimigis [2]. They note that long-lived recurrent regions of enhanced cosmic ray intensity fall within recurrent regions of low speed solar wind (although they state that the converse is not necessarily so). They offer a qualitative explanation based on a sketch (reproduced here in Panel (b) of the Figure) of the quasi-stable solar wind structure deduced by extrapolating solar wind velocities outward with constant speed from IMP-8 and Pioneer-11, a technique observationally validated for this period in the study of Mitchell, Roelof and Wolfe [3]. The cosmic ray intensity enhancement of May 1974 occurred on extrapolated stream lines that intersected the furthest reaches of the "cavity" formed by the reverse shock of the preceding co-rotating interaction region (CIR) and the forward shock of the succeeding CIR. Gold and Venkatesan therefore suggest that the modulation is weaker in the "cavity" than in the shocked plasma beyond its boundary.

2. Analysis. Suppose the cosmic ray modulation beyond the cavities formed by the CIR's is described by a uniform radial gradient g (%/AU) so that the intensity j may be written $j = j_o \exp(gr)$. Here j_o would be the intensity at the sun if the modulation region extended uniformly inward to $r = 0$. However, we shall assume that $g = 0$ inside the cavities; we could chose a small, but non-zero value of g inside the shocks, but the simplicity of the suggested model calls for a simple treatment. We assume that the cosmic ray populations are ordered along field lines in the inner heliosphere, as was demonstrated by the Voyager/IMP comparisons in 1977-8 [2]. In a steady solar wind structure, the large-scale interplanetary magnetic field lines follow the solar wind stream-lines, as viewed in a frame co-rotating with the sun. Then the intensity at the Earth when its heliolongitude is ϕ should be the intensity at the cavity boundary where the solar wind stream, extrapolated outward from 1 AU, intersects the forward or reverse shock bounding a CIR. Call the helioradial distance of this intersection $r_s(\phi)$. Then the cosmic ray intensity at Earth at heliolongitude ϕ is simply $j(\phi) = j_o \exp [r_s(\phi)]$.

The calculation of $r_s(\phi)$ is not difficult; the values could actually just be scaled off Panel (b) of the Figure. An extrapolated idealized field line has the equation $r(\phi') = a + V(\phi)(\phi - \phi')/\Omega$, where ϕ is the heliolongitude of the line at 1 AU ($r = a$), $V(\phi)$ is the velocity there, and Ω is the solar sidereal rotation rate. The CIR boundaries can be parametrized by a pseudo-field line with the velocities of the forward (V_F) or reverse (R_R) shock and the extrapolated crossings of those lines at 1 AU (ϕ_F and ϕ_R). The lines in the rarefaction between high (V_H) and low (V_L) speed regions can be idealized as a "dwell" in which the lines appear to emanate from a single coronal longitude (ϕ_o): $r(\phi') = a(\phi_o - \phi')/\phi_o - \phi)$. We compute $r_s(\phi)$ for the four regions of the idealized stream structure shown in Panel (c) of the Figure: I, $V(\phi) = V_H$, intersection of high speed solar wind with reverse shock $V = V_R$; II and III, rarefaction, as shown in Panel (b); and IV, $V(\phi) = V_L$, intersection of low speed solar wind with forward shock $V = V_F$. The resulting formulas are:

$$r_s(\phi) = a + (V_H V_R/\Omega)\,\frac{\phi_R - \phi}{V_H - V_R} \qquad \text{Region I}$$

$$r_s(\phi) = a\,\frac{1 + (V_R/\Omega a)(\phi_R - \phi_o)}{1 - (V_R/\Omega a)(\phi_o - \phi)} \qquad \text{Region II}$$

The corresponding formulas for Regions III and IV are obtained by replacing V_R with V_F, V_H with V_L and ϕ_R with ϕ_F. The result of the calculation is plotted in Panel (a) of the Figure with dashed lines indicating the regions where the over-simplification of the model is most extreme.

3. Comments. As could have been seen directly from Panel (b), the cosmic ray enhancement falls in the longitudes of high values of $r_s(\phi)$ shown in Panel (a); not so evident in Panel (a) is the sharpness of the peak within the rarefaction region. Since $d\phi/dt = -\Omega'$, the synodic rotation rate, the $r_s(\phi)$ plot is just a time plot running backwards (see lower scale). The intensity history, if treated as a fractional change, is $\ln (j/j_1) = g(r_s - a)$ where j_1 would be the minimum intensity predicted by the model. A peak radial distance of 9

AU beyond the Earth with a radial gradient of 2%/AU would give a fractional enhancement of $j/j_1 = 1.20$. This is within the range of maximum/minimum intensities presented in Figure 2 of [1]; note that Figure 2 and Figure 3 of that paper are from different years. Also, the longitude used in Figure 2 of [1] is not the Earth heliolongitude used here, but rather the estimated source longitude of the observed solar wind stream. The latter longitude is inappropriate for galactic cosmic ray studies - for example, it would compress the entire rarefaction region of Panel (a), with its attendant intensity enhancements, into a single longitude on their plot. A more appropriate longitude for labelling field lines in the outer heliosphere is the heliolongitude of the innermost spacecraft being used, as was done here and was discussed in [2].

The exercise of this paper is intended mainly to illustrate the very plausible circumstance that cosmic ray modulation in the inner heliosphere ($r \lesssim 10$ AU) may be quite variable (depending on stream structure evolution) with radial gradients much smaller than in the very different plasma/field regimes of the outer heliosphere. An extremely significant result from the VGR/IMP high time resolution (1 h) intensity comparisons [2] was that there were entire solar rotations devoid of significant gradients between 1 and 3-5 AU! Equally important were the ephemeral latitudinal gradients ~ 1%/deg lasting $\lesssim 1$ rotation (which would go essentially undetected if gradients are computed from 25-day averages as in other measurements done with less sensitive instruments). Our present study suggests an intriguing explanation for latitude gradients in the inner heliosphere. Suppose we compare intensities on two field lines passing through the same longitude (ϕ) at 1 AU, but at different latitudes (θ); this was the technique by which field-aligned latitudinal gradients were found in [2]. If the boundaries of the "cavity" were inclined to the solar equatorial plane owing to latitudinal shears described by terms like $(\partial V/\partial\theta)$ or $(\partial\phi_o/\partial\theta)$ in solar wind velocity structure, then we would have a latitudinal intensity gradient $\partial(\ln j)/\partial\theta = g[(\partial r_s/\partial V_i)(\partial V_i/\partial\theta) + (\partial r_s/\partial\phi_k)(\partial\phi_k/\partial\theta)]$ where, for example, $V_i = V_H$, V_R and $\phi_k = \phi_R$, ϕ_o. A shear of $\partial V/\partial\theta \simeq (100$ km/s)/(10 deg) is not unreasonable [3], and from Panel (a), we see that $\partial r_s/\partial V \simeq$ (5 AU)/(100 km/s) in the peak. Consequently, a latitudinal gradient $\partial(\ln j)\partial\theta \simeq$ (2%/AU)[(5 AU)/(100 km/s)][(100 km/s)/(10 deg)] = 1%/deg, as observed [2], could be produced by shears in the stream/shock structure.

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5. References.

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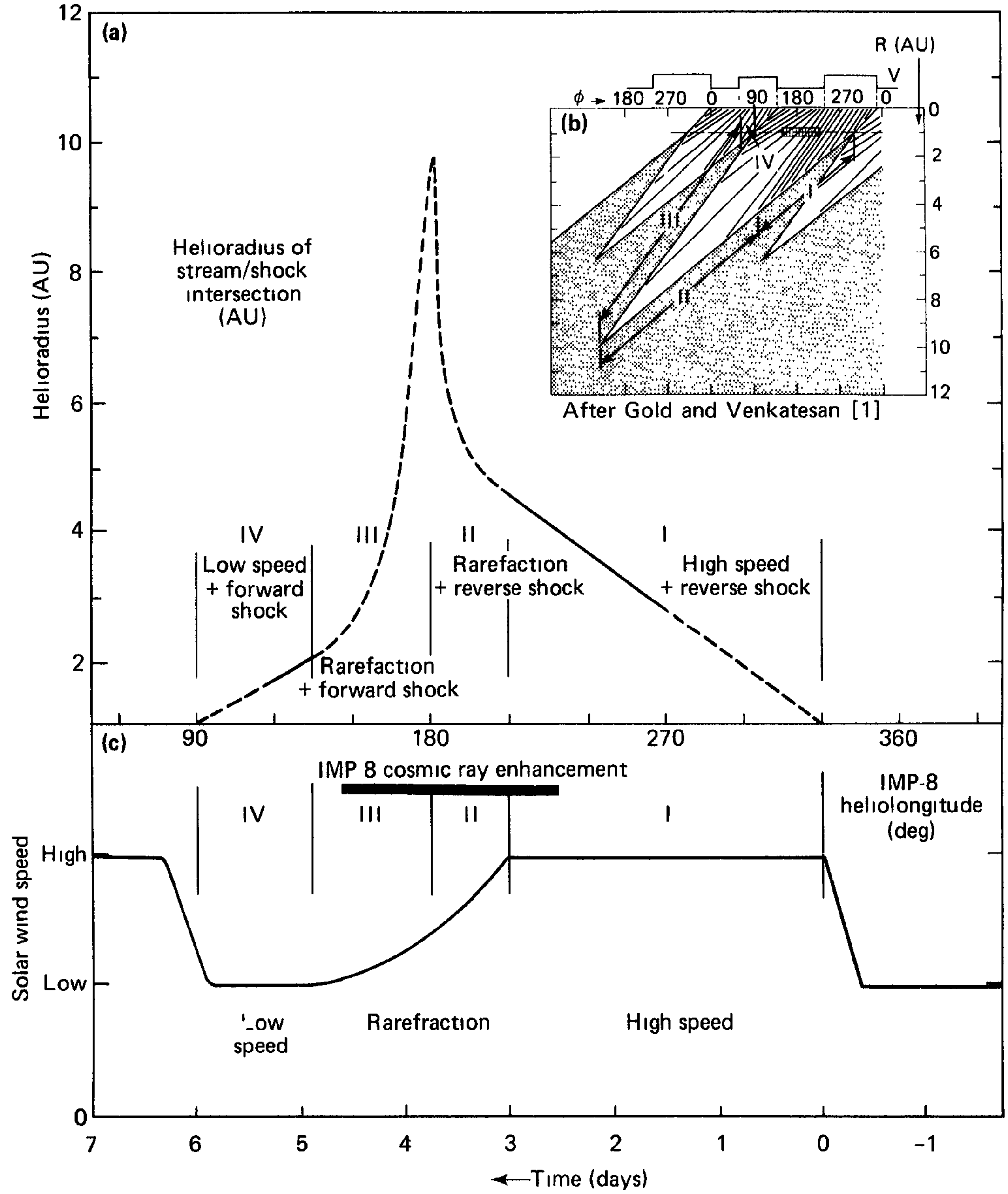

Figure: (a) Outer helioradius $r_s(\phi)$ of intersection of interplanetary field lines from IMP-8 heliolongitude (ϕ) with "cavity" boundary formed by interacting CIR's sketched in (b), as proposed in [1], for the steady solar wind speed profile shown in (c). If there is no cosmic-ray radial gradient within the "cavity" and a constant radial gradient (g) beyond it, the intensity profile at r = a = 1 AU is $j = j_1 \exp [gr_s(\phi) - a]$.