VOYAGER 1 AND 2 MEASUREMENTS OF RADIAL AND LATITUDINAL COSMIC RAY GRADIENTS DURING 1981-84

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ABSTRACT

We have determined the cosmic ray radial gradient during 1981-84 using data from very similar detectors onboard spacecraft Voyagers 1 and 2 (radial separation ~ 6 AU, heliolatitude separation ~ 25^0) and from the earth-orbiting satellite IMP 8. The principal result is that the radial gradient over this period decreased at the rate ~ 0.4%/AU/year, reaching by the end of 1984 a value of ~ 2.0%/AU between 1 and 16 AU and ~ 0.6%/AU between ~ 16 and 22 AU.

1. Introduction: Measurements of galactic cosmic ray intensity gradients, radial as well as heliolatitudinal, play on important role in guiding theoretical models of cosmic ray propagation in the heliosphere. Determinations of integral radial gradients (for a summary, see Venkatesan et al., 1985) using data from Pioneers 10 and 11, Voyagers 1 and 2, and IMP 8 have revealed relatively small values of 2-4% per AU, thus questioning the concept of a spherically symmetric heliosphere. Decker et al. (1984) have estimated for the first time the heliolatitudinal gradient of galactic cosmic ray intensity during early-1981 through mid-1982, a period coinciding with the initial phase of cosmic ray recovery following the minimum reached in late-1980 to early-1981. They found that for all practical purposes, the heliolatitudinal gradient is 0%/deg over the 16° heliolatitudinal separation in the region 8-13 AU during that period of study. This was based on the assumption that the radial gradient during the 1981-82 recovery period remained at the same ~ 2-4%/AU level as determined from multi-spacecraft measurements during the 1977-80 cosmic ray intensity decay period.

2. Experiment: Our study has used the data from the cosmic ray channel (responding to protons integral above 70 MeV) provided by a heavily shielded solid state detector in the low-energy charged particle (LECP) instrument on both Voyagers. Total counts over a 26 day interval are typically $\gtrsim 2 \times 10^4$; thus the statistical error is $\lesssim 0.7\%$. We have also used the data from the charged particle measurement experiment (CPME) anticoincidence scintillator (Ep $\gtrsim$ 35 MeV) on IMP-8. For detector details and analysis refer to Venkatesan et al. (1985).

3. Observations:
(a) Differential Gradient: Figure 1 shows at the top a plot of the 26 day means of the cosmic ray intensity registered by both the Voyagers. Note that the Voyager 1 data has been shifted to the position of Voyager 2 using an average value of 500 km/sec for the solar wind. The

convection of cosmic ray features and the appropriateness of such a solar wind speed has been discussed in detail by Venkatesan et al. (1984, 1985). The close correspondence in the two intensity-time profiles is seen.

In the middle of Figure 1 we have plotted the values of the radial gradient G_r given by $G_r = \left((\ln (R_1/R_2))/\Delta r\right) \times 100\%$, where R_1 and R_2 are the counting rates of Voyagers 1 and 2, and Δr is the radial separation. They are point-by-point computations which assume that the difference in intensity is entirely due to a radial gradient. The points are fitted with the line of least squares; note that G_r decreased from $\sim 2.1\%/AU$ to $\sim 0.6\%/AU$ over the four year period giving a value for $\dot{G}_r$ of 0.38 (± 0.09)%/AU/year.

In the bottom portion of Figure 1 we have plotted the values of the heliolatitudinal gradient G_ψ given by $G_\psi = \left((\ln (R_1/R_2))/\Delta\psi\right) \times 100\%$ where $\Delta\psi$ is the latitudinal difference between the two spacecraft. Again, they are point-by-point computations based on the assumption that the difference in intensity is entirely due to a latitudinal gradient. The points are fitted with a line of least squares; note that G_ψ also decreased from $\sim 0.42\%/deg$ to $\sim 0.13\%/deg$ over the four year period giving a value for $\dot{G}_\psi$ of 0.06 (± 0.02)%/deg/year.

(b) Integral Gradient: We use the terminology "integral gradient" when we use a comparison detector located at 1 AU, such as IMP-8 and "differential gradient" when the two Voyagers are compared with each other. Figure 2 at the top shows the intensity time profiles for IMP-8 and the two Voyagers; the latter data were shifted to 1 AU to compensate for convection of cosmic ray features at the speed of 500 km/sec. Note the similarity among the three profiles.

The middle and lower part of Figure 2 show the integral radial gradient determined from the two pairs, Voyager 1-IMP-8 and Voyager 2-IMP-8. Again these are point-by-point computations and in the case of Voyager 1 (where only it is relevant) the assumption is made that the intensity difference arises entirely from the radial gradient. The values of G_r decreased from $\sim 3.5\%/AU$ to $\sim 1.5\%/AU$ and from $\sim 3.8\%/AU$ to $\sim 2.0\%/AU$ respectively; the decreases in the radial gradient are given by $\dot{G}_r = 0.48$ (± 0.5)%/AU/year and $\dot{G}_r = 0.43$ (± 0.07)%/AU/year respectively.

4. Discussion and Conclusions: The following points can be made.

(1) The choice of 500 km/sec for the average solar wind speed to correct the data for convection of cosmic ray features (from Voyager 1 to Voyager 2) in the heliospheric region ~ 8 AU to ~ 22 AU during 1981-84 is appropriate since the two intensity-time profiles at the top of Figure 1 agree fairly well.

(2) The similarity in the long-term trend of G_r and G_ψ in Figure 1 is indicative of the fact that the heliosphere, at least up to a radial distance of ~ 22 AU and heliolatitude of 25°, responds to cosmic ray modulation rather similarly. This is not surprising since it is clear from an earlier study (Decker et al., 1984) that no significant

latitudinal gradient exists. This is still our view, by virtue of the fact that the radial gradient G_r of ~ 2.0%/AU is evident from other multispacecraft studies as well.

(3) A decrease in the radial gradient as a function of increasing radial distance is clearly seen. Comparing the middle part of Figure 1 with the bottom portion of Figure 2, we see for example, at the end of 1984, we have IMP-8 (at 1 AU), Voyagers 1 and 2 at radial distances of 16 and 22 AU respectively. We find that the radial gradient G_r in the region 1-16 AU (IMP8-Voyager 2 pair) is ~ 2%/AU and that in the region 16-22 AU (Voyager 2-Voyager 1 pair) is ~ 0.6%/AU, a lower value. This clearly demonstrates that a comparison of integral radial gradient, over larger distances and at the same time later periods in the solar cycle is somewhat questionable. A value of say 2.0%/AU for the radial gradient over a complete solar cycle and out to a heliocentric distance of over 32 AU (Van Allen and Randall, 1985) could very well consist of the mean of the radial gradient G_r over different regions at different times including a 0.0%/AU gradient in the outermost region at the time of the approaching solar minimum. It is appropriate to mention that McKibben et al. (1985) have also observed a similar decrease in the radial gradient for low energy cosmic rays ($10 < E < 70$ MeV).

(4) The trend of G_r shows that we may be approaching a region of G_r = 0.0%/AU either at greater distances or at the sunspot minimum ($\stackrel{<}{\sim}$ 1987-88) at which time Voyager 2 would be at ~ 22-25 AU and Voyager 1 at ~ 30-31 AU. If the trend persists and our interpretation is correct, we may well be seeing the boundary of cosmic ray modulation at the solar minimum. We note that Voyager 1 is generally moving in the direction of the solar apex, while Pioneer 10 although at a greater radial distance, is moving in the opposite direction. It should be pointed out that this is the first time gradient measurement is being reported during the recovery period of the cosmic ray intensity eleven-year cycle at such large radial distances.

In summary, it seems reasonable to conclude that the region of cosmic ray modulation shrinks and expands possibly in step with the solar activity cycle (minimum and maximum). McDonald et al. (1981) have suggested the dominant source of solar cycle modulation as the "pile up" of propagating shocks in the outer heliosphere.

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References

1. Decker,R.B., S.M.Krimigis & D.Venkatesan, Ap. J., 278, L122, 1984
3. McDonald,F.B., N.Lal, J.H.Trainer,M.A.I. Van Hollebeke & W.R.Webber, Ap. J., 249, L71, 1981
4. McKibben,R.B., K.R.Pyle, & J.A.Simpson, Ap. J., 289, L35, 1985.
5. Van Allen,J.A., & B.A.Randall, J.G.R., 90, 1399, 1985
6. Venkatesan,D., R.B.Decker & S.M.Krimigis, J.G.R., 89, 3735, 1984
7. Venkatesan,D., R.B.Decker, S.M.Krimigis & J.A.Van Allen, J.G.R., 90, 2905, 1985

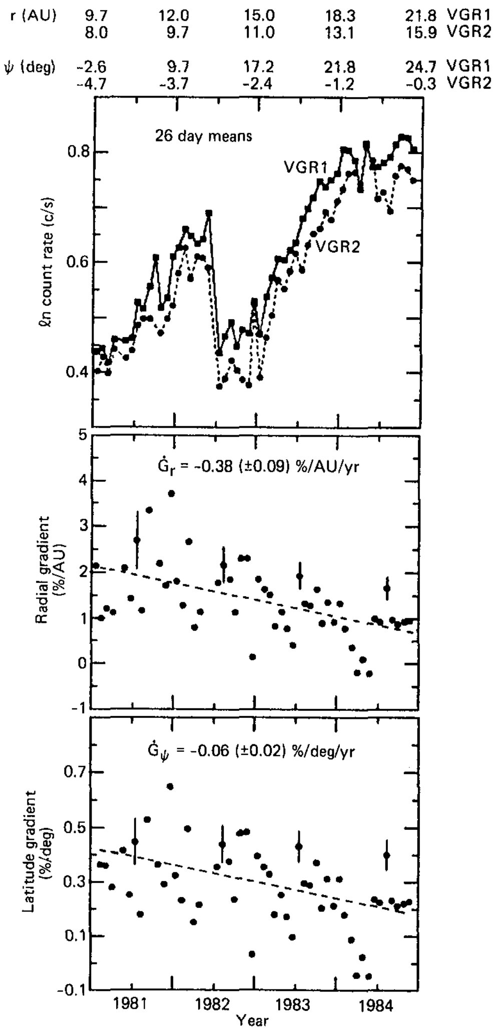

Figure 1

Intensity-time profiles of cosmic ray intensity at Voyagers 1 and 2; Voyager 1 data has been shifted to position of Voyager 2 using a solar wind speed of 500 km/sec. The middle and bottom portions provide the radial and heliolatitudinal gradients between the Voyagers.

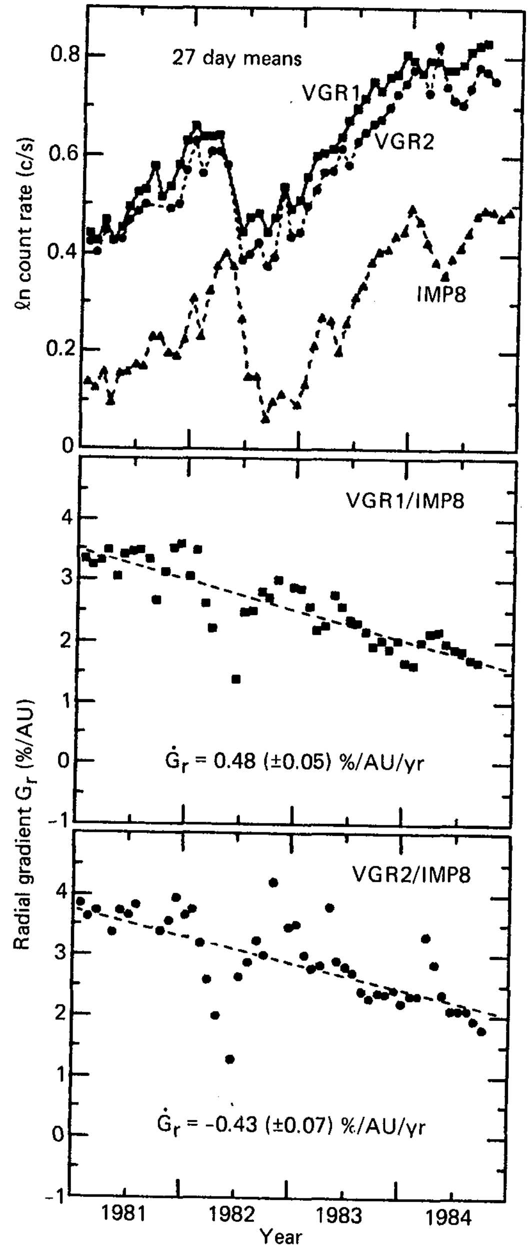

Figure2

Intensity-time profiles of cosmic ray intensity at the Voyagers duly shifted to 1 AU using a solar wind speed of 500 km/sec and IMP 8; the radial gradients are between Voyager 1 and IMP 8 and Voyager 2 and IMP 8.