# PROTON MODULATION NEAR SOLAR MINIMUM PERIODS IN CONSECUTIVE SOLAR CYCLES

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## Abstract

Observations of the Pioneer/Voyager missions during 1985/1986/1987, together with observations at Earth in 1976/1977 and 1987, are compared with predictions of a steady-state modulation model. The qualitative features of the modulation are well understood, but to get quantitative agreement with observations, drastic modifications have to be made to the Parker spiral magnetic field above the solar poles

**1. Introduction.** During the 1986/87 solar minimum, Voyager 2 had reached the approximate radial position of 25 AU, while cruising near the ecliptic plane; Voyager 1 was at ≈ 30 AU and ≈ 30° North of the ecliptic; and Pioneer 10 was at ≈ 40 AU, near the ecliptic plane. Together with observations at Earth, the large separation between these spacecraft offers an opportunity to study the spatial dependence of the modulation during and near this solar minimum. The most outstanding modulation feature during this time was the significant negative latitudinal gradient observed between Voyagers 1 and 2.

It is shown that the qualitative features of the observed modulation, together with those observed in the previous cycle (of opposite magnetic polarity), can be explained primarily by drift effects in the IMF. As in an earlier study of Webber *et al.* (1989), the calculations indicate that the change in neutral sheet tilt angle may indeed be a major -- if not the dominant -- modulator of the cosmic ray intensity.

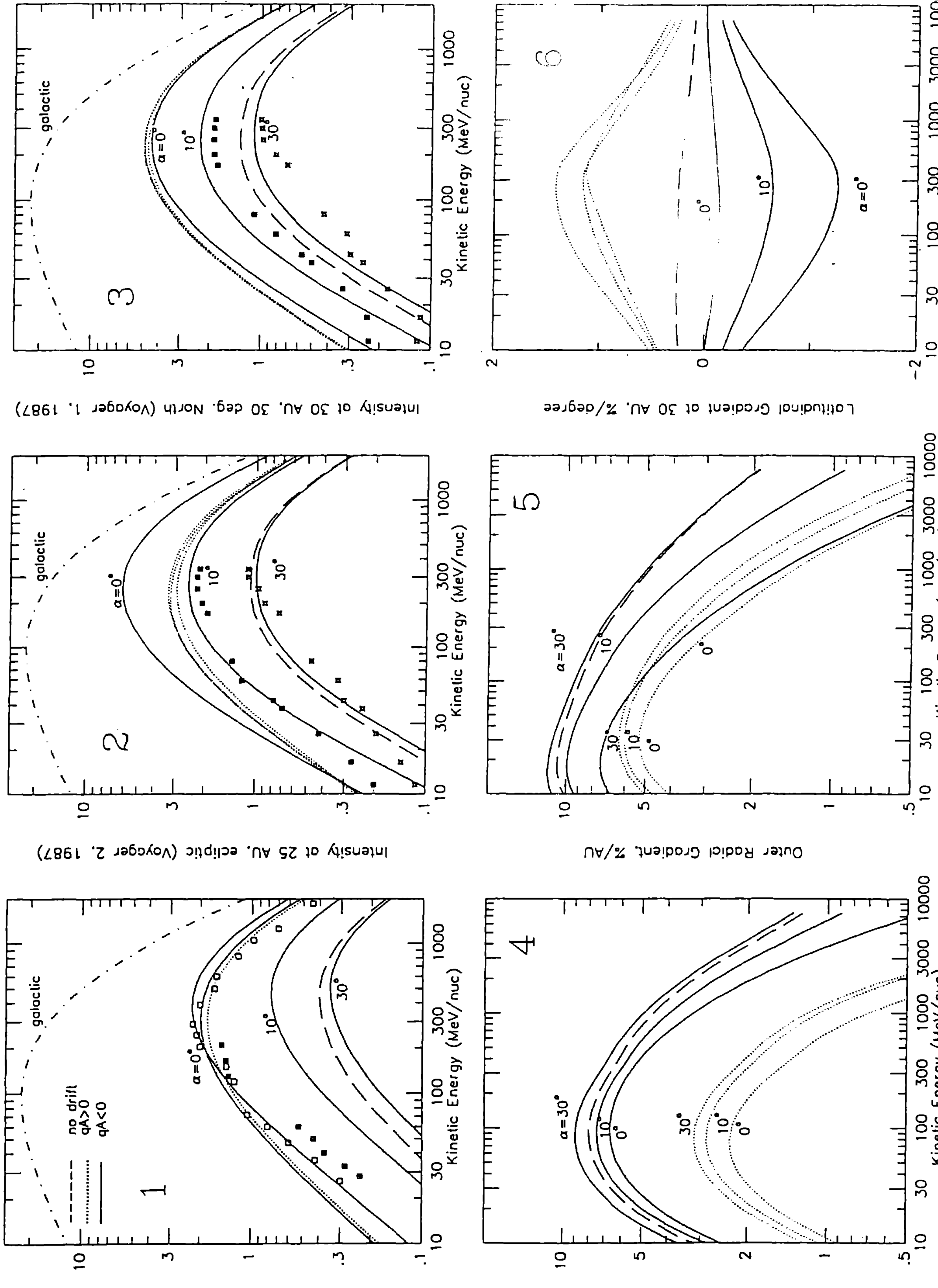
**2. The Model.** The steady state, two-dimensional (radial distance, polar angle) transport equation was solved numerically in the standard fashion as described in detail by, *e.g.*, Webber *et al.* (1989). The boundary distance was chosen at 61 AU, where an interstellar proton spectrum of the form described by Webber *et al.* was imposed. The solution ran from the heliospheric North to South Pole ($\theta = 0°$ to $180°$). The only difference with previous two-dimensional models is that the actual wavy geometry of the neutral sheet was retained. (Although wavyness of the sheet is strictly a three-dimensional phenomenon, extensive experience has shown that its exact treatment is of little consequence, as long as the correct drift flux is carried along it on average; see, *e.g.*, Burger and Potgieter, 1989).

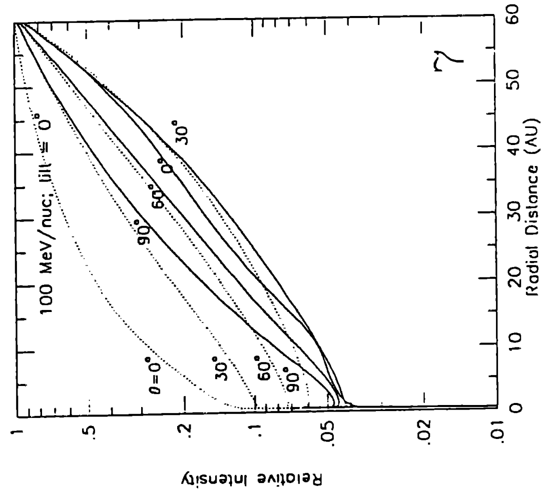
The diffusion coefficients used were of the form

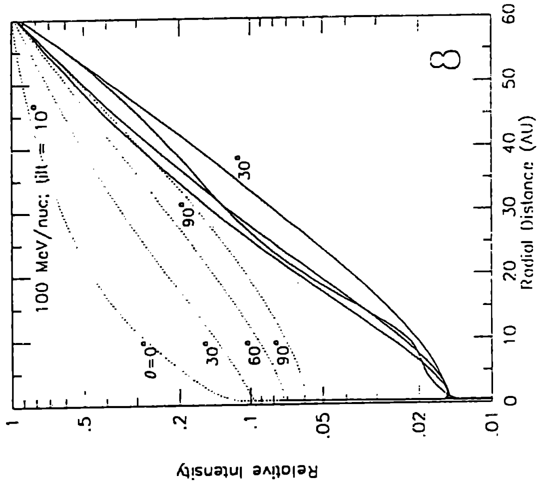
$$K_{\|} = 2.4\times10^{22}\beta P\,|B_e/B|\ \mathrm{cm^2\,s^{-1}} \quad \text{and} \quad K_{\perp} = 2.2\times10^{20}\beta f(P)\,|B_e/B|\ \mathrm{cm^2\,s^{-1}}, \qquad (1)$$

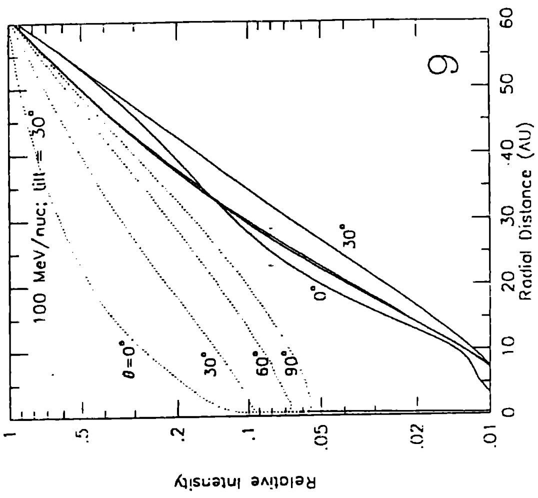
where $P$ is rigidity in GV, $\beta$ is particle speed/speed of light, and $B$ is magnetic field strength, with the subscript "e" referring to its value at Earth. The function $f(P)$ is $f = \sqrt{P}$ if $P > 1$ GV, and $f(P) = 1$ if $P \leq 1$GV. The drift coefficient is $K_T = \beta P/(3B)$, and the magnitude of the drift velocity field was set by selecting $B_e = 8$ nT (see Moraal, 1990 for a calculation of $B_e$ and $K_{\perp}$). The only variable modulation agent in the model is the change in neutral sheet tilt angle, $\alpha$, with results shown for $\alpha = 0°$, $10°$, and $30°$.

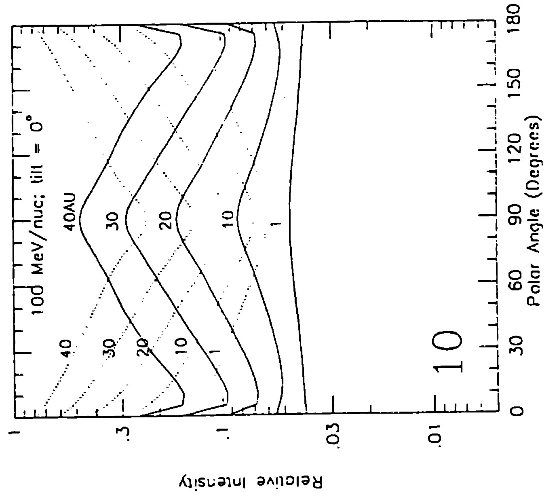
**3. Format of the Solutions.** Figures 1, 2, and 3 show spectra at Earth, at ≈ 25 AU in the ecliptic plane, and at ≈ 30 AU, 30° North (corresponding to the Voyager positions, taking into account their displacement between 1985 and 1987). The solid lines are for the so-called $qA < 0$ (1987 - type ) cycle, while the dotted lines for the $qA > 0$ (1977 - type ) cycle. The dashed lines show no-drift solutions for the purpose of comparison. The 1985 (crosses) and 1987 (filled squares) Voyager observations in Figures 2 and 3 are from Christian *et al.* (1989), and they should correspond to solutions with tilt angles $\alpha \approx 30°$ and $\alpha \approx 10°$, respectively. The 1987 observations at Earth (filled squares) are from McGuire and McDonald (1989, private communication), and those for 1977 (open squares) from Evenson *et al.* (1983). The radial gradients in the ecliptic plane, drawn in Figures 4 and 5, are defined as $g = \ln(j_2/j_1)/(r_2 - r_1)$. The "inner" gradient has $r_1 = 1$ AU, $r_2 = 25$ AU, while for the "outer" gradient $r_1 = 25$ AU and $r_2 = 40$ AU. This definition facilitates direct comparison with observations at Earth, Voyager 2 and Pioneer 10. The latitudinal

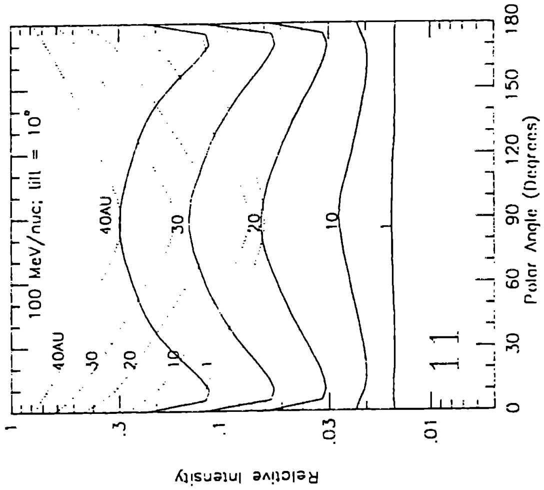

1
2
3
4
5
6
Intensity at Earth (part/m²/s/sr/MeV/nuc)
Intensity at 25 AU, ecliptic (Voyager 2, 1987)
Intensity at 30 AU, 30 deg. North (Voyager 1, 1987)
Inner Radial Gradient, %/AU
Outer Radial Gradient, %/AU
Latitudinal Gradient at 30 AU, %/degree
Kinetic Energy (MeV/nuc)
galactic
no drift
qA>0
qA<0
α=0°
10°
30°
α=30°
0°
10
3
1
.3
.1
10
5
2
1
.5
2
0
-2
10
30
100
300
1000
3000
10000

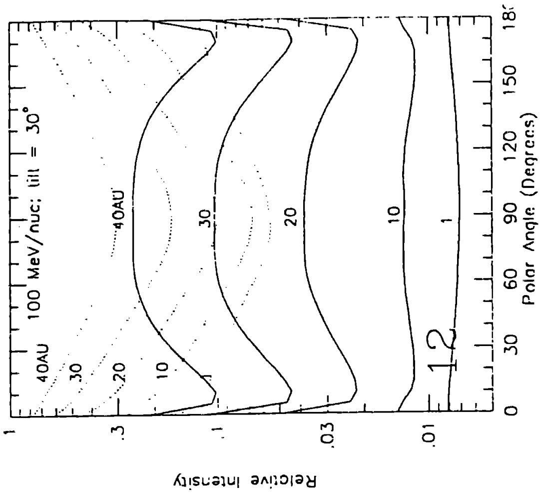

100 MeV/nuc; tilt = 0°
θ=0°
30°
60°
90°
90°
60°
0°
30°
Relative Intensity
1
.5
.2
.1
.05
.02
.01
0
10
20
30
40
50
60
Radial Distance (AU)
7


100 MeV/nuc; tilt = 10°
θ=0°
30°
60°
90°
90°
30°
Relative Intensity
1
.5
.2
.1
.05
.02
.01
0
10
20
30
40
50
60
Radial Distance (AU)
8


100 MeV/nuc; tilt = 30°
θ=0°
30°
60°
90°
0°
30°
Relative Intensity
1
.5
.2
.1
.05
.02
.01
0
10
20
30
40
50
60
Radial Distance (AU)
9


100 MeV/nuc; tilt = 0°
40AU
30
20
10
1
40
30
20
10
1
Relative Intensity
1
.3
.1
.03
.01
0
30
60
90
120
150
180
Polar Angle (Degrees)
10


100 MeV/nuc; tilt = 10°
40AU
30
20
10
1
40AU
30
20
10
Relative Intensity
1
.3
.1
.03
.01
0
30
60
90
120
150
180
Polar Angle (Degrees)
11


100 MeV/nuc; tilt = 30°
40AU
30
20
10
40AU
30
20
10
1
Relative Intensity
1
.3
.1
.03
.01
0
30
60
90
120
150
180
Polar Angle (Degrees)
12

gradient of Figure 6 is similarly defined, but for $r = 30$ AU, and for latitudinal positions in the ecliptic and at 30° North (Voyager 1, 1987). Figures 7 to 12 show the overall radial and latitudinal intensity distributions of 100 MeV protons throughout the heliosphere.

**4. Discussion of the Solutions.** Starting with Figures 10, 11, and 12, they show the dramatic difference in latitudinal distribution in the two cycles of opposite polarity, with extensive negative latitudinal gradients in the $qA < 0$ cycle. Together with the radial distributions of Figures 7, 8, and 9, they display the importance of drift and neutral sheet geometry as modulation agents. Notice that, although the minimum observed tilt values at solar minimum were $\approx 10°$, the flat neutral sheet case is included for demonstration purposes. At the same time, it serves little purpose to show intensities for tilt angles $>$ 30°, because further modulation effects diminish rapidly with higher tilt angles. This is due to diffusion, which progressively lets the particles "break through" the barriers of the increasingly "steep walls", set up by the highly warped wavy sheet.

The intensities and gradients of Figures 1 to 6, at selected positions in the heliosphere, can be interpreted in terms of these global spatial intensity distributions. Note that the $qA > 0$ intensities are almost totally insensitive to the neutral sheet geometry. At this point it should also be remarked that the qualitative features of these solutions are valid for a very wide range of modulation parameters. In particular, the solutions can hardly discriminate between boundary distances in the range 50 to 100 AU. It is, therefore, important to demonstrate to what extent one single set can explain the observations quantitatively.

The 10° and 30° tilt solutions in Figures 2 and 3 provide a reasonable fit for the 1985 and 1987 Voyager observations, with some overshoot at Voyager 1, indicating that the calculated negative latitudinal gradients may be somewhat too small. The 10° solution fits the Pioneer 10 observations at $\approx 40$ AU (McDonald, 1989 priv. comm.) about equally well. At these large radial distances, the $qA < 0$ intensities are determined almost entirely by the geometry of the sheet and the rate of radially inward drift and perpendicular diffusion. The kinked rigidity dependence of $K_\perp$ in (1) is required to fit these spectral shapes.

The constraint that the 1985/1987 intensities in the outer heliosphere must be well represented, leads to compromises at Earth. Figure 1 shows that the $qA > 0$ solutions slightly exceed the 1977 observations, while the 10°tilt, $qA < 0$ solution is clearly lower than the 1987 observations. Also, there is an uncomfortably large jump between the $qA > 0$ and $qA < 0$ inner gradients in Figure 4, which has not been observed. There is also observational evidence (but not for all species and energies) that the radial gradient may decrease with r, which is not reflected in these solutions. This is, however, the best agreement that could be found, and it was achieved only by modifying the Parker spiral field above the solar poles drastically, as was suggested by Jokipii and Kota, (1989): The spiral field was multiplied by a hyperbolic cosine in $\theta$, having values 1 (no change) at $\theta = 90°$, 2 at $\theta = (30°, 150°)$, and 10 above the poles. This quenches drift and diffusive transport at high heliolatitudes by the same inverse amounts. Without this modification the $qA > 0$ and $qA < 0$ intensities at Earth are typically separated more, and the $qA > 0$ inner gradients fall to $\lesssim 0.5\%$. Moreover, that unsatisfactory state can only be achieved at the cost of reducing $K_\parallel$ by a factor of at least 20. This leads to the unrealistic case of very strong, almost isotropic ( $K_\parallel \approx K_\perp$ ) scattering.

**5. Conclusion.** The natural way in which the global intensity distributions, as well as the $qA < 0$ observations in the outer heliosphere can be explained, strongly supports the wavy neutral sheet/drift modulation hypothesis. The problems for a detailed matching of observations, especially in the inner heliosphere, almost certainly indicate that other effects, such as temporal variations, may play a role. However, given the large influence of polar field modification in this first and primitive attempt, a more detailed understanding of latitudinal transport may be even more important.

**6. Acknowledgements.** I gratefully acknowledge the computational and technical assistance of K. R. Lim, as well as the stimulating discussions with A.C. Cummings and E.C. Stone. This work was supported in part by NASA under contract NAS-7-918 and grant NGR-05-002-160.

**7. References.** Burger, R.A., and M.S. Potgieter, *Ap. J.*, **339**, 501,1989.
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Evenson, P., M.G.-Munoz, P.Meyer, K.R.Pyle, J.A.Simpson, *Proc. 18th ICRC*, **3**, 27, 1983.
Jokipii, J.R., and J. Kota, *Geophys. Res. Lett.*, **16**, 1, 1989.
Moraal, H., *Proc. 21st. ICRC*, Paper SH6.4-12, 1990.
Webber, W.R., M.S. Potgieter, and R.A. Burger, *Ap. J.*, in press, 1989.