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Radial diffusion coefficients of 1-30 MeV protons in the outer heliosphere

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Abstract: Radial and latitude gradients of low-energy protons are estimated using Voyager and Ulysses data during solar activity minima. From the radial gradient the radial diffusion coefficient is calculated and compared with a two dimensional, full drift model below for <500 MV protons..

The spatial variations of quiet-time fluxes of ~1-30 MeV protons are examined at distances of 2-85 AU using Voyager 1-2 (LECP, CRS) and Ulysses (LET) data. Attention is focused on the solar cycle minima of 1986-87 and 1996-98. The comparison of V1 and V2 proton fluxes in 1986-87 shows some differences in the temporal behavior of intensity (Fig. 1). During the negative phase

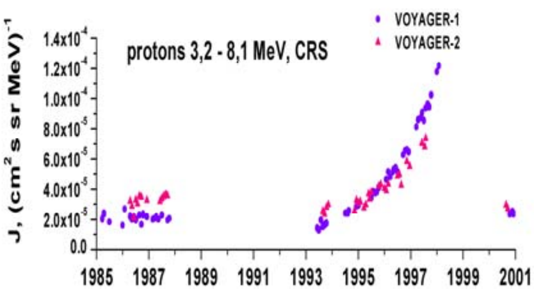

Figure 1: Time profiles of 26-day average 3-8 MeV proton intensities during two subsequent solar minima.

minimum in 1986-87 of the heliomagnetic cycle (qA < 0) the ~6 MeV proton intensity on V1 was significantly smaller than on V2. At that time V2 was near the ecliptic at latitude 3-7N whereas the V1 was at 29-32N. The different flux behavior observed can be explained by drift effects in the heliosphere. When qA < 0 galactic and/or anomalous protons arrive inside predominantly along the heliospheric current sheet and from the poles when qA > 0. Then the higher proton intensity at V2 can be explained by an expected negative proton latitude gradient in 1985-87. During the recovery phase in 1995-1997 the intensity increase was more gradual on V2 than on V1. This effect can arise during qA > 0 phase due to the difference in the s/c distances from the Sun and partly may indicate a north-south asymmetry (lat V1: 34-34.3N, lat V2: 15-21.5S).

The spatial gradients G_r and G_λ were estimated by comparing V1 and V2 fluxes obtained at quiet time periods at both minima using the equation

$$\ln(J(V1)/J(V2)) = G_r\Delta R + G_\lambda\Delta\lambda, \qquad (1)$$

where ΔR and $\Delta\lambda$ are the radial and latitude separation, respectively, between V1 and V2. Here we used multiple regression fitting of values ln(J(V1)/J(V2)) setting differences in radial distance and latitude as variables assuming spherical symmetry. In order to exclude the temporal flux variations, the time delay between the two s/c was taken into account by shifting the data with the convection time between V2 and V1 assuming a mean solar wind speed 400 km/s. The gradient values obtained from the best fits of (1) are presented in the Table 1. The radial gradient values show an increase and a change of sign between 30 and 80 AU during the recovery phases indicating the increase of galactic and anomalous particle contribution to the proton population in the distant heliosphere.

The latitude variation of 2-4 MeV proton fluxes at ~5 AU based on Ulysses LET data suggest an intensity decrease towards higher latitudes in

1995-96 indicating a negative latitude gradient G_λ

	R [MV]	G_r [%/AU]	G_λ [%/deg]
1985-87	45	-13.3 ± 1.5	3.7 ± 1.2
	110	-8 ± 1.5	-0.9 ± 1.8
	140	-0.04 ± 4.3	-6.5 ± 2.6
1996-98	45	14.9 ± 3.4	-2.5 ± 1.2
	65	10.4 ± 6.6	-2.9 ± 2.3
	110	15.1 ± 3.7	2.1 ± 1.2
	140	11 ± 3.8	3.5 ± 1.9
	220	7.2 ± 4.1	1.8 ± 1.3
	240	6 ± 2.3	

Table 1: Values of spatial gradients of 1-30 MeV protons in the outer heliosphere during solar minima of 21 and 22 SC.

on both hemispheres, however, streamer belt low-flux data from Ulysses are very scarce due to contamination from solar events during the fast latitude scans. Our estimations of G_λ based on V1 and V2 data show different signs for protons <10 MeV and ≥10 MeV at both solar minima suggesting different pattern of drift of these protons in the inner and outer heliosphere. Meanwhile G_λ values are positive for rigidity >100 MV in accordance with the transport model suggesting galactic and anomalous proton drift from poles to ecliptic during the qA > 0 phase. Then the negative G_λ assumes predominant solar origin of particles at high latitudes.

The radial diffusion coefficients κ_{rr} were estimated using the obtained gradients G_r where $\kappa_{rr} = CV/G_r$, $C=1/3(2-2\gamma)$, γ is the spectral index, and V = 400 km/s is the average solar wind velocity. The Compton–Getting factor C was derived from the observed energy spectra using a one-dimensional modulation model. The energy spectral change with heliocentric distance is the following. For 1-8 MeV protons the characteristic negative slope with exponent –2 to –3 gradually decreases outwards and the spectra become nearly flat at 50 AU. Figure 2 shows the values of κ_{rr}/β (where $\beta = v/c$, v – proton velocity and c – speed of light) in dependence on rigidity. Also presented here are values of κ_{rr}/β of higher energy anomalous and galactic protons for the solar minimum period 1998/1-1999/182 taken from [1] and for the 2001 SC maximum from [2]. The solid lines in Fig. 2 are from a two dimensional, full drift model fit to the V1 - V2 energy spectra

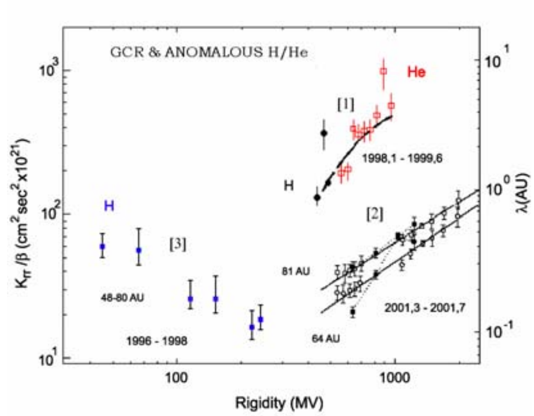

Figure 2. Values of κ_{rr}/β for <500 MV protons) – blue squares (present work) - as a function of rigidity R compared with galactic and anomalous protons and helium [1, 2].

[1]. The value of the mean free path is estimated from the gradients and suggests a tendency to decrease with rigidity increase for 1-30 MeV protons during solar activity minimum 1996-98. The comparison of radial diffusion coefficients of 1-30 MeV protons obtained here in the outer heliosphere with those for higher energies shows a possible minimum in the 200-300 MV range. Meanwhile the four highest rigidity points obtained here seem to conform to the extension of the fitting line of the set κ_{rr}/β of anomalous protons and He during solar minimum from [1].

Acknowledgements

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