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Cosmic ray hard sphere scattering in the solar wind and heliospheric modulation parameters: 1963-2013

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At high rigidities (≥ 10 GV) galactic cosmic ray (GCR) particle density gradients and mean free paths (λ) in a turbulent interplanetary magnetic field (B) can only be computed from the solar diurnal anisotropy (SDA) data. Long-term changes of SDA components recorded by the global network of neutron monitors (NMs) with a long track record are used to compute the annual mean values of the heliospheric modulation parameters for 1963-2013, using the concept of cosmic ray isotropic hard sphere scattering in the solar wind plasma. The computations of the coefficient α (= $\lambda_\perp/\lambda_\parallel$) at 1 AU were reported at the 40th COSPAR Scientific Assembly held in Moscow in 2014. In this paper we present the computed values of the mean free path parallel to mean B ($\lambda_\parallel$), the radial gradient (G_r) and the north-south asymmetric gradient ($G_{\theta a}$) with respect to the heliospheric current sheet (HCS) and discuss their dependence on GCR rigidity, positive and negative polarity intervals of B, sunspot activity, and solar wind parameters at 1 AU.

Keywords: Cosmic Rays, Scattering in Solar Wind, Modulation, Gradients.

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1. Introduction

Neutron monitor (NM) data, with median rigidity of response (Rm) >10 GV, are analyzed for 1963-2013 to compute the galactic cosmic ray (GCR) solar diurnal anisotropy (SDA) components to determine transport coefficients in the heliosphere. The cosmic ray isotropic hard sphere scattering concept, in solar wind plasma, is used to compute the mean free path ($\lambda_{\parallel}$) parallel to the mean interplanetary magnetic field (IMF) intensity (B) at 1 AU; the radial gradient (G_r) and the north-south asymmetric gradient ($G_{\theta a}$) are computed as well.

2. Data Analysis and Results

The coefficient α (= $\lambda_{\perp}/\lambda_{\parallel}$), ratio of perpendicular to parallel mean free path, was computed with data from 18 NM sites (see Table 1) with Rm in the range: 10 GV < R_m < 33 GV. The results were reported at the 40th COSPAR Scientific Assembly held in Moscow in 2014 (Modzelewska, et al., 2014). NMs are sub-divided into two groups based on geomagnetic threshold rigidity (R_0); for NM1 group R_0 < 4.5 GV and R_0 > 4.5 GV for NM2 group.

Table1. Groups NM1, NM2 used in the analysis for computing α.

NM1 Station	R0 (GV)	Rm (GV)	Latitude (+ N, - S)	Longitude (+ E, - W)	Altitude (m)	Data Span
Apatity	0.65	16	67.57	33.39	182	1969-2013
Calgary	1.08	10	51.08	-114.13	1128	1964-2008
Climax	2.97	11	39.37	-106.18	3400	1963-2006
Deep River	1.07	16	46.10	-77.50	145	1963-1995
Durham	1.58	16	43.10	-70.83	0	1963-1991
Jungfraujoch	4.49	15	46.55	7.98	3570	1963-2013
Kiel	2.32	17	54.30	10.12	54	1965-2013
Lomnicky Stit	3.84	15	49.20	20.22	2634	1982-2011
Moscow	2.39	17	55.47	37.32	200	1966-2013
Newark	2.00	17	39.68	-75.70	50	1965-2013
Oulu	1.10	16	65.05	25.47	15	1965-2013
NM2 Station	R0 (GV)	Rm (GV)	Latitude (+ N, - S)	Longitude (+ E, - W)	Altitude (m)	Data Span
Hermanus	4.51	20	-34.43	19.23	26	1963-2013
Haleakala	13.30	33	20.72	-156.28	3030	1991-2006
Huancayo	13.49	33	-12.03	-75.33	3400	1963-1992
Mt. Norikura	11.36	28	36.11	137.55	2770	1963-1992
Pochefstroom	6.94	21	-26.70	27.09	1351	1971-2013
Rome	6.32	23	41.86	12.47	60	1963-2010
Tseumeb	9.12	24	-19.12	17.58	1240	1976-2013

Eqn (1) shows the relationship between α and SDA components, V is the solar wind speed at 1 AU, C the Compton-getting factor (≈1.6), v the GCR speed (≈ c), and ψ the angle between IMF and the sun-earth line. The negative and positive superscripts on radial (A_r) and azimuthal component (A_φ) indicates: away (+, A > 0)/ toward (-, A <0) IMF polarities.

$$\alpha = \frac{\left(\frac{A_r^+ + A_r^-}{2} - \frac{3}{v}CV\right)\sin\psi\cos\psi + \left(\frac{A_\varphi^+ + A_\varphi^-}{2}\right)\cos^2\psi}{\left(\frac{A_r^+ + A_r^-}{2} - \frac{3}{v}CV\right)\sin\psi\cos\psi - \left(\frac{A_\varphi^+ + A_\varphi^-}{2}\right)\sin^2\psi} \tag{1}$$

The relation between α and the parallel mean free path ($\lambda_{||}$) is shown in eqn (2), r_L is GCR Lamor radius. The mean free paths parallel ($\lambda_{||}$) and perpendicular ($\lambda_{\perp}$) to B arise from isotropic hard sphere scattering in solar wind plasma.

$$\alpha = \frac{\lambda_{\perp}}{\lambda_{||}} = \frac{1}{1+\left(\lambda_{||}/r_L\right)^2} \tag{2}$$

Yearly values of $\lambda_{||}$ are computed (with error bars) from eqn (2) and plotted in Figure 1, along with the yearly smooth sunspot number (SSN) cycle and solar magnetic polarity intervals. We

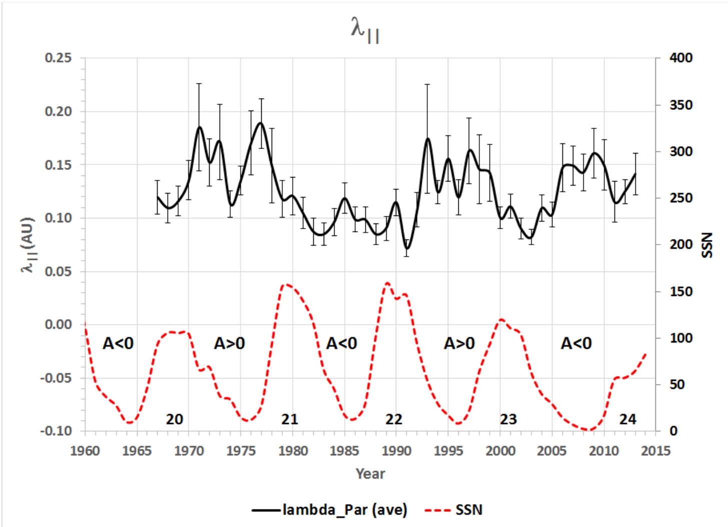

Figure 1. Mean free path ($\lambda_{||}$) parallel to B.

note the following characteristics of $\lambda_{||}$ for 1967-2013:

1. The diffusion parallel to B shows no rigidity dependence, i.e. the values calculated for NM1 and NM2 are the same within the errors. Future calculations for a broader rigidity range need to be made before we make any conclusive statements on the rigidity dependence of $\lambda_{||}$.
2. $\lambda_{||}$ is large during SSN minimum and small during SSN maximum, hence 11 year cycle.
3. The largest value for $\lambda_{||}$ appears to occur during the positive polarity period (A>0) near SSN minimum, hence dependence on solar magnetic polarity. This is opposite to result reported by Munakata et al (2014) and Chen & Bieber (1993).

The equation for the coupled parameter $\lambda_{||}G_r$ in terms of the coefficient α and SDA components is shown in eqn (3). Ygbuhay (2015) derived this relationship in order to compute the radial gradient G_r.

$$\lambda_{||}G_r = \frac{A_{\varphi}^{+} + A_{\varphi}^{-}}{2}\frac{1}{(1-\alpha)\sin\psi\cos\psi} \tag{3}$$

Figure 2 shows the yearly computed values of $\lambda_{||}G_r$ (with error bars) as well as the yearly smooth SSN and the magnetic polarity intervals. We note the following:

1. $\lambda_{||}G_r$ shows no apparent rigidity dependence throughout the period from 1967 to 2013.
2. We see a solar cycle variation with $0.64\% < \lambda_{||}G_r < 1.27\%$ with error of $\pm$ 0.02%.
3. Relative minimum values occur during SSN minimum for positive polarity (A>0) intervals. At the beginning of A>0 (1968, 1991) the value for the coupled parameter starts a descent to a local minimum. The local minima for $\lambda_{||}G_r$ are at SSN minima.
4. The 11-year dependence for $\lambda_{||}G_r$ is weak but the 22-year dependence is pronounced.
5. Chen & Bieber (1993) show results for the period from 1961 to 1988. The lower and upper bounds of their results are very similar to this analysis.
6. Ahluwalia (1993) reported mean $\lambda_{||}G_r$ = (1.085 ± 0.015) % for 1968-1970 for four GCR detectors (16 GV < R_m < 299 GV), similar to value of 1.188% for this analysis.

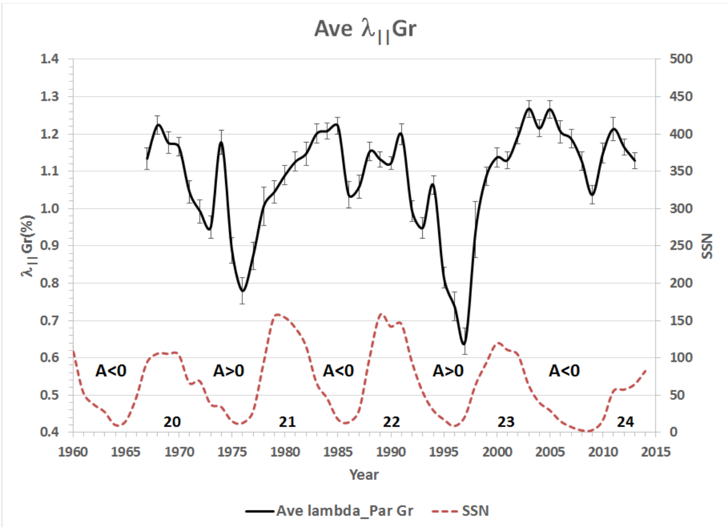

Figure 2. $\lambda_{||}G_r$ plot for 1967-2013.

With the results for calculations for $\lambda_{||}$ and for $\lambda_{||}G_r$ we can now compute G_r as shown in eqn 4.

$$G_r = \frac{\lambda_{||}G_r}{\lambda_{||}} \tag{4}$$

Figure 3 shows the calculated average results for NM1, NM2; within observational errors there appears to be no rigidity dependence for G_r. The results show that G_r ranges from 3.9 to 16.7 %/AU with an error of ±0.43 %/AU. This is in stark contrast to other published results that report different values for G_r depending on the rigidity. Compared to G_r values in this analysis the published results give much smaller values as discussed below.

1. Hashim and Bercovitch (1972) reported G_r ~ 1.9 %/AU and 0.1 %/AU for Rm values of 16 GV and 134 GV respectively for 1967-1968. Webber and Lockwood (1991) estimated G_r ~3 %/AU for > 60 Mev/n GCRs for 1972-1980.

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2. Munakata et al (2014) and Chen & Bieber (1993) found that G_r correlates with SSNs. Though their solar cycle correlation agrees with our results, G_r values are an order of magnitude higher than ours; the difference comes from their ad hoc assumption of low value of $\alpha = 0.01$.
3. For SSN minimum it appears that for positive polarity (A>0) periods G_r values are lower than for negative polarity periods (A<0). This comes about from the higher relative value for $\lambda_{\parallel}$ and lower value for $\lambda_{\parallel}G_r$ during the period of positive polarity.

Our results are in apparent conflict with other studies, so further investigation is called for.

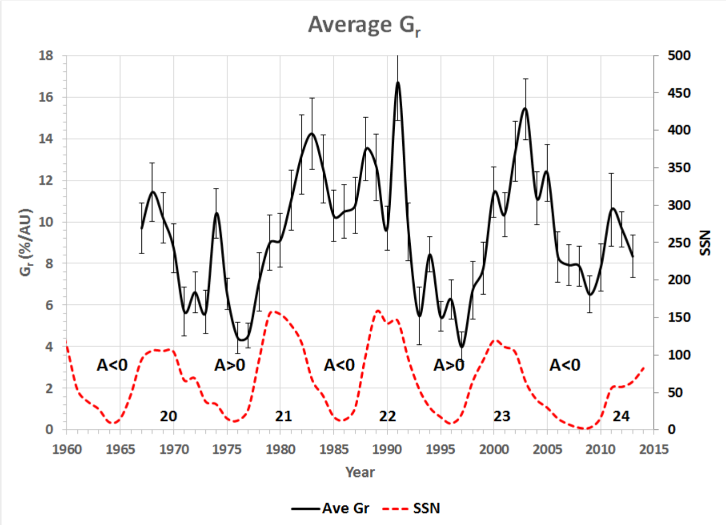

Figure 3. Integral radial gradient.

We compute the north-south asymmetric gradient ($G_{\theta a}$) shown in eqn 5 from the difference between the away/toward values of A_r and A_ϕ as given by Ahluwalia and Dorman (1997) .

$$G_{\theta a} = \frac{A_r^+ - A_r^-}{2r_L \sin\psi}$$
$$G_{\theta a} = \frac{A_\phi^+ - A_\phi^-}{2r_L \cos\psi} \quad (5)$$

We calculate $G_{\theta a}$ from both equations and take the average of two values to get the gradient for NM1, NM2; we find that $G_{\theta a}$ is rigidity independent. The mean value is plotted in Figure 4. Note the following characteristics for $G_{\theta a}$ during the period from 1967 to 2013:

1. Ahluwalia and Dorman (1997) analyzed data obtained with NMs and muon detectors of the global network (10 GV < R_m < 299 GV) from 1965 to 1993. Their results show a south pointing gradient from 1965 to 1968 and a northward gradient from 1969 to 1973. The results from this analysis show positive values for $G_{\theta a}$ for 1965-1968 (0.6386 %/AU average value), it is consistent with a southward gradient. From 1969 to 1973 we get an average negative value (-0.1383 %/AU) for $G_{\theta a}$, it is consistent with a northward gradient, in a heliospherical coordinate system centered at the sun.
2. $G_{\theta a}$ values computed by Ahluwalia and Dorman for the Deep River NM (Rm = 16 GV) have large errors ($1\sigma = \pm$ 0.8 %/AU). Their values are higher than those plotted in Figure 4. but the trends in the results appear to be comparable.

3. When we plot $G_{\theta a}$ versus the smooth SSNs and compute the correlation coefficient we find that its value is very small indicating no correlation at all.

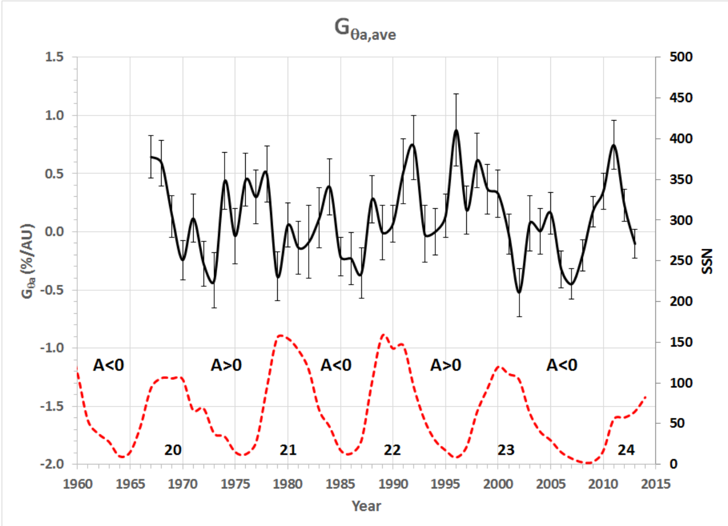

Figure 4. North-south asymmetric gradient ($G_{\theta a}$) plot.

3. Summary

We started with the values of the coefficient α, derived from the neutron monitor data from global network, reported at the 40th COSPAR Scientific Assembly held in Moscow in 2014; the values are orders of magnitude higher than ad hoc value of α (0.01) used by some colleagues, without rigorous justification. From α values we computed other modulation parameters like the parallel mean free path ($\lambda_{||}$), the radial (G_r) and the north-south asymmetric gradient ($G_{\theta a}$), using the model of isotropic hard sphere scattering in solar wind plasma. Our values for G_r are in apparent conflict with other published results, they are an order of magnitude higher. The research is ongoing, future results will be reported elsewhere.

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