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The cosmic ray radial and latitudinal gradients in the heliosphere near solar minima

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Abstract. Based on existing measurements of galactic and anomalous cosmic ray gradients obtained by the heliopsheric network spacecraft in the last three solar minima, we found that there is an approximately linear relationship between the magnitudes of the radial gradient and latitudinal gradient. Cosmic rays of a particular species/energy that exhibit a large latitudinal gradient tend to have a large radial gradient too and vice versus. This linear relationship is not affected by the sign of solar magnetic polarity. A similar linear relationship between the amplitude of 27-day recurrent variations and the magnitude of the latitudinal gradient was discovered earlier. These relationships mean that the 3-dimensional distributions of cosmic rays in the heliosphere have a scaling similarity among cosmic rays of different species/energies. Analytical approximations for the gradients and recurrent variation amplitude were derived using the stochastic process theory of cosmic ray modulation. The linear correlation exists because all the variations of cosmic ray at high energies are mainly determined by the adiabatic energy loss.

1. Introduction

Measurements of radial and latitudinal gradients of cosmic rays, G_r and G_λ, are important to our understanding of global flow patterns of cosmic ray particles in the heliosphere and to our understanding of the mechanism of cosmic ray modulation by the solar wind. In the last three decades, a heliospheric network of spacecraft, Pioneer 10/11, Voyager 1/2 and Ulysses, have made cosmic ray measurements covering large ranges of radial distance and heliographic latitude. These measurements, together with near-Earth spacecraft (such as IMP) measurements as baseline indicators of the global modulation level, have provide comprehensive measurements of the radial and latitudinal gradients of cosmic ray fluxes (McKibben 1989; Cummings et al. 1987; Cummings et al. 1995; McDonald et al. 1998). The cosmic ray intensity at two spacecraft α and β in the heliosphere, J_α and J_β, are given a relationship

$$J_\beta = J_\alpha \exp(G_r \Delta r + G_\lambda \Delta |\lambda|) \qquad (1)$$

where $\Delta r = r_\beta - r_\alpha$ and $\Delta|\lambda| = |\lambda_\beta| - |\lambda_\alpha|$ are the radial and latitudinal separation of the two spacecraft. By using simultaneous measurements from at least two different combinations of the spacecraft in the heliospheric network, we can determine the radial and latitudinal gradients in (1).

A picture that is qualitatively consistent with the predictions from the effects of particle gradient/curvature drifts in the heliospheric magnetic fields [Jokipii and Thomas, 1981] has emerged from the radial and latitudinal gradient measurements. The radial gradient is generally positive and small (about few percent per AU) and it decreases with radial distance from the sun [Cummings et al. 1995; Fujii and McDonald, 1997]. The sign of the radial gradient does not depend on the polarity of solar magnetic field, which is consistent with cosmic ray particle source being located outside the maximum distance of the spacecraft. The magnitude of the radial gradient is quite sensitive to the tilt of the heliospheric current sheet when the solar magnetic field polarity is negative ($qA < 0$), but it is not so when $qA > 0$. This is consistent with the fact that during the $qA < 0$ period cosmic ray nucleons come in mainly through drift in the current sheet; as the tilt angle of the current sheet gets larger, it becomes more difficult for the particles to transport inward, resulting larger a radial gradient [Cummings et al. 1987]. The sign of latitudinal gradient has been found to depend on the solar magnetic polarity in a way as predicted from the flow pattern of particle drift in the heliospheric magnetic field. It is positive (meaning that the polar regions have higher flux than the equatorial) when $qA > 0$, and it is opposite when $qA < 0$.

In this paper, we report a new finding that there is an approximately linear correlation between the magnitude of radial gradient and the magnitude of latitudinal gradient.

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This correlation is similar to the correlation found between the amplitude of 27-day recurrent variations and the amplitude of latitudinal gradient (Zhang, 1997). Based on the correlation we suggest that there is a common, dominant modulation mechanism controlling cosmic ray distribution in the 3-dimensional heliosphere. Using the stochastic process theory of cosmic ray modulation, we argue that adiabatic energy loss caused by the solar wind on the cosmic rays has most important modulation effects for particles of high rigidities.

2. Observations

The cosmic ray gradient data used in this paper are mainly from previous publications derived from Pioneer 10/11, Voyager 1/2 and IMP-8 [McKibben, 1989; Cummings et al. 1987; McDonald et al. 1998]. Readers may find detailed information about the spacecraft, instruments and data analyses that led to the determination of the radial and latitudinal gradients. We will use the data for both galactic and anomalous cosmic ray components, since the anomalous cosmic rays, which are interstellar neutrals singly ionized in the heliosphere and subsequently accelerated to cosmic ray energies by the termination shock, are modulated in the same way in the heliosphere as galactic cosmic rays. In many other publications, there are measurements of the gradient, but we are unable to use them because our study requires simultaneous measurements of both the radial and latitudinal gradients in several particle/energy channels.

Table 1 lists the values of radial and latitudinal gradients for four different time periods in the last three solar minima. In Figure 1 we display correlation plots between the radial and latitudinal gradients. As one can see, although the sign of the latitudinal gradient changes with the solar magnetic field polarity and the magnitudes of the gradients may change from time to time, there is always an approximately linear correlation between the radial and latitudinal gradients. A few data points are scattered quite away from the lines in some cases. This could be due to uncertainties that have not been quantified. For example, the data point for the 8-18 MeV/n anomalous oxygen in Figure 1(C) may have been overestimated. But even with the large scatter the approximate correlation still exists. The relationship means that those particles that experience a large radial gradient tend to have a large latitudinal gradient too.

3. Discussions

A similar linear correlation between the magnitude of latitudinal gradient and the amplitude of 27-day recurrent variations was previously reported (Zhang, 1997). If we assume that the recurrent structure due to the solar rotation is in a steady state viewed in the frame rotating with the sun, the recurrent variation of cosmic rays reflects the longitudinal distribution of cosmic ray intensity. The correlation among the radial, latitudinal and longitudinal variations indicates that cosmic ray intensity distributions in the 3-dimensional heliosphere are roughly similar independent of particle species or energies.

At a glance, the existence of the correlation seems very puzzling, since the mechanisms that affect the distribution of cosmic rays in the 3 dimensions are so different. The radial gradient is affected by diffusion and drift in the radial direction as well as the convection with the solar wind. In

Table 1. Radial and Latitudinal Gradients in the Heliosphere

Time	1975-1976		1985-1986		1987		1996	
Reference	McKibben, 1989		Cummings et al. 1987		McDonald et al. 1998		McDonald et al. 1998	
	Radius	Latitude	Radius	Latitude	Radius	Latitude	Radius	Latitude
P-10	7-13 AU	8°N	36.9 AU	3.8°N	42.3 AU	3°N	64.5 AU	3°N
P-11	4 AU	9-16°N						
V-1			24.9 AU	26.5°N	31.3 AU	31.5°N	62.7 AU	34.1°N
V-2			18.4 AU	0.2°N	23.6 AU	4°S	48.5 AU	19.2°S
IMP-8	1 AU	7°S-7°N						
	1975-1976 (A)		1985-1986 (B)		1987 (C)		1996 (D)	
	G_r %/AU	G_λ %/°	G_r %/AU	G_λ %/°	G_r %/AU	G_λ %/°	G_r %/AU	G_λ %/°
7-11 MeV/n O^+			5.0±.8	-2.9±.4				
11-17 MeV/n O^+			5.7±.7	-3.0±.3				
8-18 MeV/n O^+					2.3±.3	$-5.1^{\dagger}\pm.6$	1.9±.6	.2±.6
17-31 MeV/n O^+			9.1±.8	-3.7±.6				
6-10 MeV/n He^+					4.2±.3	-3.5±.4	3.7±.3	1.9±.3
10-20 MeV/n He^+	14.8±.4	1.5±.2	5.3±.6	-2.2±.7	6.4±.1	-4.5±.2	3.3±.3	1.6±.3
30-60 MeV/n He^+	9.1±.3	1.2±.1	5.0±.4	-1.6±.3	2.3±.2	-3.1±.1	1.65±.25	1.1±.2
140-380 MeV/n He			2.1±.1	-.8±.1	0.9±.4	-1.1±.1	0.4±.2	.02±.15
130-225 MeV H			3.3±.1	-0.9±0.1	2.0±.2	-1.8±.2	1.0±.2	0.14±.2
>70 MeV H	1.9	.01±.04	0.95±.12	-.34±.08				
30-60 MeV H	7.8±.3	0.2±.1			5.7±.7	-2.5±.7	3.0±.2	0.6±.2

The energy range may be slightly different from those listed in the references.

$^+$Singly charged anomalous cosmic rays. †The number may be overestimated.

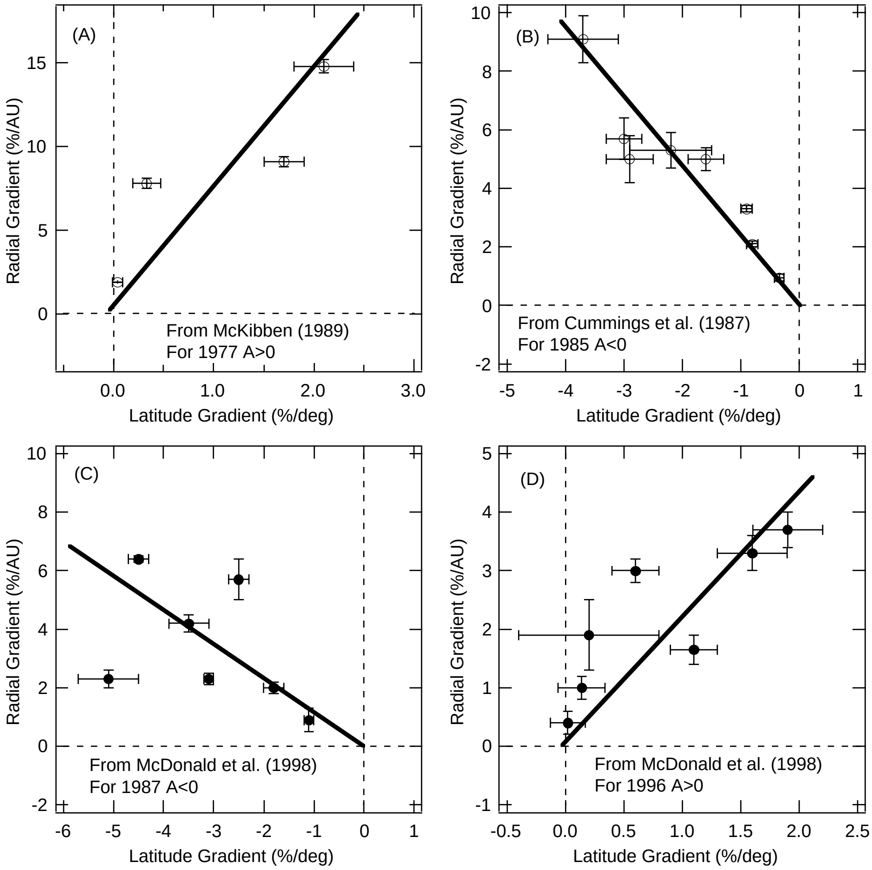

Fig. 1 — Correlation between the radial and latitudinal gradients of galactic and anomalous cosmic rays for four different time periods in the last three solar minima. Each data point is for a particle species at certain energy.

the latitudinal direction, drift is the most important. However, for the current variation, corotating interaction regions (CIRs) are the most dominant modulation agent (Zhang, 1995), but the effects of current sheet drift may also play some role in determining the longitudinal variation (Kota and Jokipii, 1983).

To understand the correlation, we use the stochastic process theory for cosmic ray modulation (Zhang, 1999). The exact solution to the transport equation:

$$\frac{\partial f}{\partial t} = \nabla \cdot \boldsymbol{\kappa} \cdot \nabla f - (\boldsymbol{V} + \boldsymbol{V}_d) \cdot \nabla f + \frac{1}{3}(\nabla \cdot \boldsymbol{V}) p \frac{\partial f}{\partial p} \qquad (2)$$

with boundary conditions $f_b = f_{ism}(p)$ (the interstellar spectrum) at an outer boundary and $f_b = 0$ at the inner boundary (solar surface) is given by:

$$f(x,p,t) = \langle f_b(p_e) \rangle \qquad (3)$$

where $\langle\ \rangle$ denotes the expectation value and p_e is the first exit momentum of time-backward stochastic processes

$$\begin{aligned} d\boldsymbol{X}(s) &= (\nabla \cdot \boldsymbol{\kappa} - \boldsymbol{V} - \boldsymbol{V}_d)\, ds + \sum_{i=1}^{3} \sqrt{2\kappa_i}\, dw_i(s),\ \boldsymbol{X}(t) = \boldsymbol{x} \\ dP(s) &= \frac{1}{3}(\nabla \cdot \boldsymbol{V}_{sw}) P\, ds,\ P(t) = p \end{aligned} \qquad (4)$$

when they reach either of the boundaries for the first time (see Zhang, 1999). For cosmic rays with relatively high rigidities like those listed in Table 1, detailed simulation (Zhang, 1999) found that the probability for the time-backward stochastic process (4) to get into the sun is very small because the drift and diffusion dominate the convection in most conditions. Thus the modulated cosmic ray distribution function is essentially

$$f(x,p,t) = \langle f_{ism}(p_e) \rangle \qquad (5)$$

the average value of interstellar spectrum at momenta before the particles get into the heliosphere. Equation (5) clearly states what solar modulation really means for high-rigidity cosmic rays: The particles we observed at any location in the heliosphere are actually of higher energies in the interstellar medium because of the adiabatic cooling by the solar wind. Suppose that the particle loses Δp in the transition through the heliosphere, then the modulated

$$f(x,p,t) \approx f_{ism}(p) + \frac{\partial f_{ism}(p)}{\partial p} \langle \Delta p \rangle \qquad (6)$$

Since the interstellar distribution function of cosmic rays decreases sharply with p, cosmic rays get modulated because of the momentum loss term in (6).

The radial gradient of cosmic ray intensity is the result of extra momentum loss when the particles have to travel extra distance to different radii. The average extra momentum loss between the two location separated by radial distance Δr can be estimated through the stochastic trajectories described by (4)

$$\Delta \langle \Delta p \rangle = \frac{2 V_{sw} p}{3r(2\kappa_r / r + \partial \kappa_r / \partial r - V_{dr} - V_{sw})} \Delta r \qquad (7)$$

where κ_r is the radial diffusion coefficient, V_{sw} the solar wind speed, V_{dr} the radial drift speed. Then

$$G_r = \frac{\Delta f}{f\Delta r} \approx -\frac{\partial f_{ism}}{f\partial p}\frac{2V_{sw}p}{3r(2\kappa_r / r + \partial\kappa_r / \partial r - V_{dr} - V_{sw})} \quad (8)$$

Equation (8) becomes a force field approximation when the terms $\partial\kappa_r / \partial r - V_{dr} - V_{sw}$ is much smaller than $2\kappa_r / r$, which is assumed for high-energy particles by Gleeson and Axford, (1968). Similarly, we can work out an approximation for the latitudinal gradient due to extra momentum loss in the latitudinal transport:

$$\mp G_\lambda = G_\theta \approx -\frac{\partial f_{ism}}{f\partial p}\frac{2V_{sw}p/3}{\kappa_\theta \cot\theta / r + \partial\kappa_\theta / r\partial\theta - V_{d\theta}} \quad (9)$$

For the modulation by the CIRs, the extra energy loss is due to the slow transport within the CIR high magnetic fields, which can be written as

$$\Delta\langle\Delta p\rangle \approx \frac{V_{sw}p}{3}\left(\frac{1}{\kappa_{cir}} - \frac{1}{\kappa_r}\right)\Delta l \quad (10)$$

where we have assumed the CIR is spherical with a thickness of Δl and the diffusion coefficients are weakly spatial dependent within the CIR as assumed for the force field approximation. Then the amplitude of cosmic ray recurrent variations is (in percentage)

$$A = \frac{\Delta f}{f} \approx \frac{\partial f_{ism}}{f\partial p}\frac{V_{sw}p}{3}\left(\frac{1}{\kappa_{cir}} - \frac{1}{\kappa_r}\right)\Delta l \quad (11)$$

From Equations, (8) (9) and (11), a few points immediately become clear about the observations of radial gradient, latitudinal gradient and recurrent modulations by CIRs:

(1) The formulae for the radial gradient, latitudinal gradient and amplitude of 27-day variation all contain the effects of adiabatic momentum loss, that is, the common factor $V_{sw}p\partial f_{ism} / \partial p / f$, which is proportional to the Compton-Getting anisotropy.

(2) For cosmic rays with high rigidities, where the radial drift and diffusion dominate the convection, the radial gradient is always positive.

(3) The radial gradient decreases with increase of radial distance from the sun because radial diffusion coefficient and drift speed become larger at large radii.

(4) The latitudinal gradient may not always agree with the pattern of particle drift. This happens when the diffusion in the latitudinal direction dominates the latitudinal drift. However, when the drift dominates, the sign of cosmic ray latitudinal gradient varies with the drift pattern, which depends on the solar magnetic field polarity.

(5) The latitudinal gradient (in % per degree) becomes insensitive to r at large distance from the sun, because there κ_θ / r, $\partial\kappa_\theta / r\partial\theta$, and $V_{d\theta}$ (see its formula in e.g. Jokipii and Kopriva, 1979) approach constant if we assume κ_θ is inversely proportional to the magnetic field strength.

(6) The relation between changes in the cosmic ray intensity and the magnetic field strength (so called CR-B relation by Burlaga et al. 1985) can also be explained by (11) with a propagating interaction region passing by a spacecraft.

(7) We have observed the approximate linear correlation between the radial and latitudinal gradients

$$\frac{G_r}{G_\theta} = \frac{(\kappa_\theta \cot\theta / r + \partial\kappa_\theta / r\partial\theta - V_{d\theta})}{r(2\kappa_r / r + \partial\kappa_r / \partial r - V_{dr} - V_{sw})} \quad (12)$$

because the dependence of the ratio (12) on the particle rigidity or energy is much smaller than the gradients themselves. For example, when the diffusion coefficients are proportional to vR, where v is the particle speed and R the particle rigidity, the ratio is essentially independent of the characteristics of the particles. The approximate linear correlation between the latitudinal gradient and the amplitude of recurrent variations arises from a similar theoretical ground.

4. Summary

We have presented an observation of a correlation between the radial and latitudinal gradients. This correlation is similar to the one between the latitudinal gradient and the amplitude of 27-day recurrent variations. The correlation means that the 3-dimensional distributions of cosmic rays in the heliosphere have a similarity independent of particle energies or species. The observation suggests that there is a common dominant mechanism that controls the cosmic ray modulation.

Using the stochastic process theory of cosmic ray modulation, we found that adiabatic energy loss is the most important mechanism for modulation of cosmic rays at high rigidities. We have derived several analytical approximations for the radial and latitudinal gradients and the modulation by solar wind interaction regions to explain the observational results.

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