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An explanation for the unusual cosmic ray diurnal variation in 1954

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During the 1954 solar minimum the cosmic ray diurnal variation underwent a dramatic swing in its direction of maximum intensity, from the normal value of 16:00 to 18:00 to as early as 08:00. This swing can be explained as due to a negative radial density gradient of cosmic rays in the inner heliosphere, and that this negative gradient is caused by large latitudinal diffusion mean-free-paths that bring in particles from high latitudes.

1. Introduction

The ionization chamber [4, 12, 13, 14] and neutron monitor data in Figure 1 reveal that the phase of the cosmic ray diurnal variation exhibited a 22-year period, being several hours earlier at the sunspot minima of 1933, 1954 and 1976 than at the 1944, 1965 and 1987 minima. The 1954 minimum was particularly early, at about 10:00 hr, which means that the cosmic ray flow was approximately aligned with the outward direction of the heliospheric magnetic field (HMF). Recently, McCracken *et al.* [7] reported that the ^{10}Be concentration (responding to ≈ 2 GeV/n cosmic rays), and balloon measurements [11], indicate that there was an unusually high cosmic ray influx to Earth in 1954. They speculated that this influx and the early diurnal maximum were both due to enhanced cosmic ray transport from high heliolatitudes, noting that the sunspot number was one of the lowest on record. Moraal *et al.* [10] recently explained this phenomenon as due to negative radial gradients in the inner heliosphere. This paper is a summary of those results.

2. The Cosmic Ray Transport Model and Anisotropy Expressions

Cosmic ray transport processes are described by the transport equation

$$\frac{\partial f}{\partial t} + \nabla \cdot \mathbf{S} + \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 < \dot{p} > f) = 0, \quad \text{where} \quad \mathbf{S} = 4\pi p^2 (C\mathbf{V}f - \mathsf{K}\cdot\nabla f), \tag{1}$$

for the distribution function, f, where $\mathbf{S}$ is the particle flux, $< \dot{p} >= (p/3)\mathbf{V}\cdot\nabla f/f$ the adiabatic loss rate of momentum, p, $\mathbf{V}$ is the solar wind velocity, and $\mathsf{K}(\mathbf{r}, P, t)$ the diffusion tensor. $C = -(1/3)\partial \ln f/\partial \ln p$ is the Compton-Getting coefficient. K contains elements $\kappa_{\|}(\mathbf{r}, P, t)$ and $\kappa_{\perp}(\mathbf{r}, P, t)$ for scattering along and perpendicular to the HMF, $\mathbf{B}$, together with an antisymmetric $\kappa_T = \beta P/(3B)$ which describes gradient, curvature and neutral sheet drift effects [5, 9]. The HMF is described by the Parker spiral $\mathbf{B} = B_e(r_e/r)^2(\mathbf{e}_r - \tan\psi\mathbf{e}_\phi)$, with $\tan\psi = \Omega(r - r_0)\sin\theta/V$. At Earth B_e is 5 to 10 nT. $\Omega/V = 1$ AU^{-1} if V = 400 km/s and Ω = one rotation per 27.27 days. $\mathbf{S}$ in (1) can be written in terms of an anisotropy vector $\xi = 3\mathbf{S}/(4\pi p^2 v f)$, diffusion mean free paths $\lambda_i = 3\kappa_i/v$ and gyroradius $\rho = 3\kappa_T/v = P/Bc$, as $\xi = -\lambda.\mathbf{g} + 3C\mathbf{V}/v = -\lambda_{\|}\mathbf{g}_{\|} - \lambda_{\perp}\mathbf{g}_{\perp} - \rho\mathbf{e}_B\times\mathbf{g} + 3C\mathbf{V}/v$ where $\mathbf{e}_B = \mathbf{B}/B$ and $\mathbf{g} = \nabla f/f$ is the density gradient. When the intensity is azimuthally symmetric, this vector has radial, latitudinal and azimuthal components

$$\xi_r = 3CV/v - \lambda_{rr}g_r \pm \rho\sin\psi\, g_\theta, \quad \xi_\theta = \mp\rho\sin\psi\, g_r - \lambda_{\theta\theta}g_\theta, \quad \xi_\phi = -\lambda_{\phi r}\, g_r \pm \rho\cos\psi\, g_\theta, \tag{2}$$

where $\lambda_{rr} = \lambda_{\|} \cos^2\psi + \lambda_{\perp} \sin^2\psi$, $\lambda_{\theta\theta} = \lambda_{\perp}$, $\lambda_{\phi r} = (\lambda_{\perp} - \lambda_{\|}) \sin\psi \cos\psi = (\lambda_{\theta\theta} - \lambda_{rr}) \tan\psi$, and where the top and bottom signs hold for the qA>0 and qA<0 heliomagnetic cycles. The radial and azimuthal components of this anisotropy constitute the diurnal variation, with magnitude and time of maximum

$$\xi^2 = \xi_r^2 + \xi_\phi^2, \quad \chi = [180^\circ + \tan^{-1}(\xi_\phi/\xi_r)]/15 \text{ hr}, \tag{3}$$

For a power law spectrum $P^{-2.5}$ ($f \propto P^{-4.5}$), $C = 1.5$, so that for $V = 400$ km/s and for relativistic particles, the convective part of the radial anisotropy is $\xi_c = 3CV/v = 0.6\%$. When there are no drifts and $\lambda_{\perp} << \lambda_{\|}$ so that $\xi_r = 0$, it follows from (2) that $g_r = 3CV/(v\lambda_{\|}\cos^2\psi)$. This leads to $\xi = \xi_\phi = 3CV\tan\psi/v = (3CV/v)\Omega(r - r_0) = 0.6\%$ at r = 1 AU, and χ = 18:00 hr. Letting $\alpha = \lambda_{\perp}/\lambda_{\|}$ and $\Omega(r - r_0)\sin\theta = 400$ km/s (at Earth), it follows that $\tan\psi = 1/W$, where $W = V$(km/s)/400 is the dimensionless solar wind speed. Then the radial and azimuthal components in (2) can be written as

$$\xi_r = 0.004CW/\beta - \xi_d(\alpha + W^2)/(1 + W^2) \pm \xi_{dr} \quad \xi_\phi = \xi_d(1 - \alpha)W/(1 + W^2) \pm \xi_{dr} \tag{4}$$

where $\xi_d = \lambda_{\|}\, g_r$, and $\xi_{dr} = \rho\, g_\theta W/(W^2 + 1)^{1/2}$. From the measurement of ξ_r and ξ_ϕ, and assuming $\xi_c = 0.6\%$ as above, Bieber and Chen [1] calculated ξ_d and ξ_{dr} over several cycles from 1933 to 1990. The result was that ξ_d in the qA>0 cycles is considerably smaller than for qA<0, while ξ_{dr} alternates in sign between these two cycles, due to the well-known switch in g_θ. Lemmer and Moraal [6] pointed out that the ξ_{dr} drift terms are not the primary cause of the 11-year periodicity in amplitude and 22-year periodicity in phase, because they are too small ($\approx 5\%$ of the convective term), and they are always in the same direction, regardless of the drift state of the heliosphere and the side of the wavy neutral sheet. This does not mean that drifts are not important for changes in the diurnal variation. Below we show that these drifts rearrange the cosmic ray spatial distribution in the heliosphere, thereby altering the gradients. Therefore, drifts are indirectly important to determine the anisotropy through the gradient-driven diffusive term. Thus, given that C is fairly fixed at 1.5 above 1 GeV, the diurnal variation is a function of just three parameters. They are the diffusive parameter, $\xi_d = \lambda_{\|} g_r$, the ratio $\alpha = \lambda_{\perp}/\lambda_{\|}$, and the solar wind speed $W = V/400$. This is explored in the next section.

3. Origin of the Amplitude and Phase Swings

The primary reason for the 11- and 22-year variations in the amplitude and phase of the diurnal variation is the change in the radial gradient, g_r, from qA>0 to qA<0 cycles, while the very early time of maximum in 1954 is due to this radial gradient becoming negative. This is demonstrated with numerical solutions of the transport equation (1). Details are given in [3] and [10]. Figure 2 shows the calculated 10 GeV intensity as a function of radial distance. The four panels are for (a) an effective one-dimensional case in which both the drift and latitudinal (perpendicular) diffusion are switched off, (b) the previous case but with latitudinal diffusion switched on, (c) the addition of drift in the qA>0, and (d) in the qA<0 cases. The one-dimensional intensities are lower in the ecliptic plane (full lines) than above the poles because the modulation parameter Vr/κ_{rr} is 1.5 times larger in the ecliptic than at the pole. The latitudinal gradient is much smaller in (b) because of the latitudinal diffusive transport. The same is observed in the qA>0 solution of (c), but in the qA<0 case (d) there is a small negative latitudinal gradient. This is well understood as due to the switch in drift direction, which is equatorward in the qA>0, and poleward in the qA<0 cycles. The central argument for our interpretation of the diurnal variation is that in the ecliptic plane of the inner heliosphere ($r < 10$ AU), the radial gradient in the no-drift and qA>0 cases (b) and (c) is negative, but positive in the qA<0 case (d). This is due to $g_\theta = f^{-1}\partial f/(r\partial\theta) = f^{-1}\partial f/\partial s$ becoming large as $r \rightarrow r_0$. Consequently, the latitudinal transport term $(\partial/\partial s)[\sin\theta\kappa_{\theta\theta}\,\partial f/\partial s]$ becomes increasingly important with decreasing r, "short-circuiting" the latitudinal gradient in the inner heliosphere. In the qA<0 case the radial gradient remains positive because this effect is

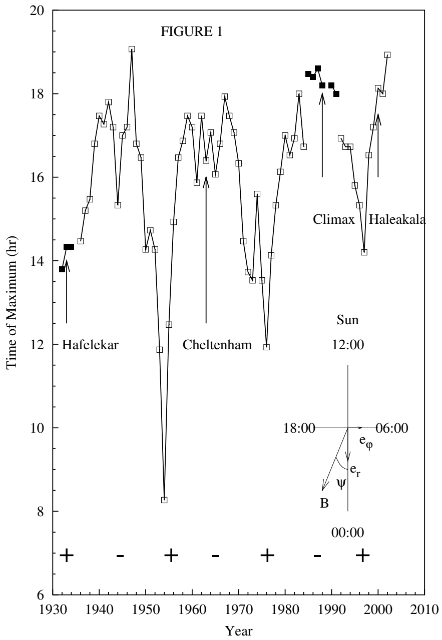
FIGURE 1
Time of Maximum (hr)
Year
Hafelekar
Cheltenham
Climax
Haleakala
Sun
12:00
18:00
06:00
00:00
B
+ - + - + - +

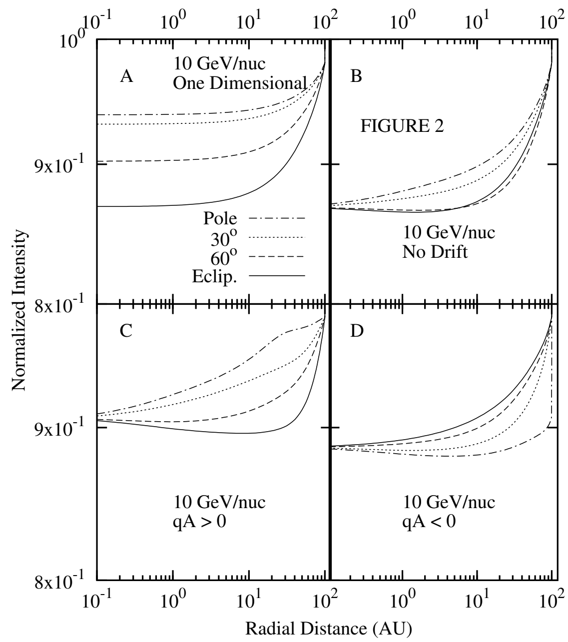
FIGURE 2
A
10 GeV/nuc
One Dimensional
B
10 GeV/nuc
No Drift
C
10 GeV/nuc
qA > 0
D
10 GeV/nuc
qA < 0
Pole
30°
60°
Eclip.
Normalized Intensity
Radial Distance (AU)

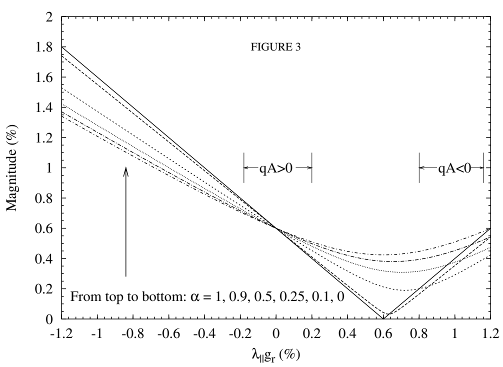
FIGURE 3
Magnitude (%)
qA>0
qA<0
From top to bottom: α = 1, 0.9, 0.5, 0.25, 0.1, 0

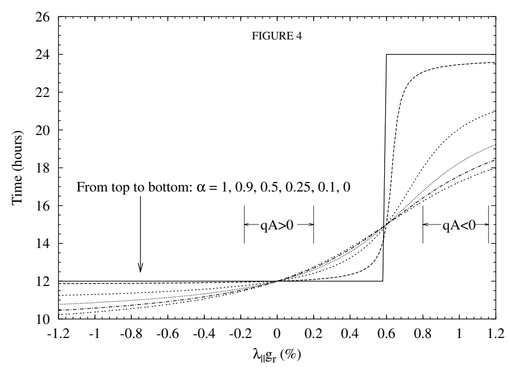
FIGURE 4
Time (hours)
From top to bottom: α = 1, 0.9, 0.5, 0.25, 0.1, 0
qA>0
qA<0

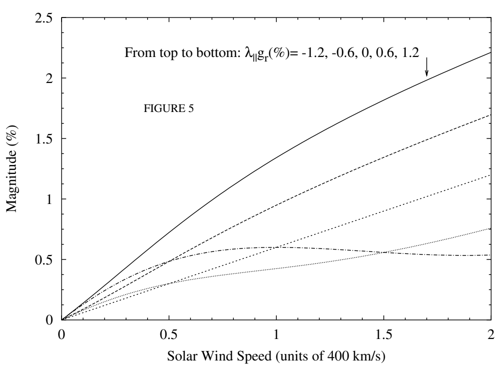
FIGURE 5
From top to bottom: $\lambda_{||}g_r$(%)= -1.2, -0.6, 0, 0.6, 1.2
Magnitude (%)
Solar Wind Speed (units of 400 km/s)

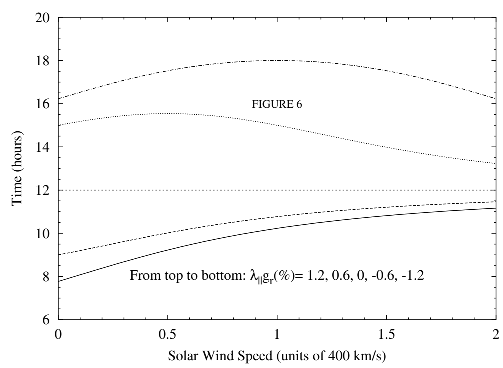
FIGURE 6
Time (hours)
From top to bottom: $\lambda_{||}g_r$(%)= 1.2, 0.6, 0, -0.6, -1.2
Solar Wind Speed (units of 400 km/s)

counteracted by poleward drift, which is $\propto r^2$ in the inner heliosphere [2]. Also note that the intensity in the ecliptic goes through a broad extreme value, leading to values of g_θ that are of the same order as g_r.

Based on this insight, it is a simple matter to parameterize the magnitude and time of maximum of the diurnal variation in (3) with the values given by (2), with $\xi_{dr} = 0$. The results are shown in Figures 3 and 4, with the independent variable being $\xi_d = \lambda_{\|} g_r$, and for six values of $\alpha = \lambda_{\perp}/\lambda_{\|}$, and $W = 1$ ($V = 400$ km/s). Figure 3 shows that the magnitude goes through a minimum value at $\xi_d \approx 0.6\%$, which corresponds to a time of maximum of 15:00 hr. Figure 4 shows, however, that the time of maximum is a monotonically increasing function of ξ_d, limited between 09:00 hr [if $-\xi_d >> \xi_c$ in (3) and (4)], and 24:00 hr if $\xi_d >> \xi_c$ (or if α = 1). Based on the numerical solutions above, we demarcate two regions for reasonable values of ξ_d for the qA>0 and qA<0 cycles. They show that the magnitude in the two cycles is of the same order, but that the time of maximum is much earlier in the qA>0 cycle than in the qA<0 one. These two figures favor the smaller values of α for two reasons. First, observations indicate that the time of maximum is near 18:00 hr in the qA<0 cycle, which is progressively violated for larger values of α and, second, the smaller the value of α, the earlier the time of maximum in the qA>0 cycle. Figure 4 shows that such an early time of maximum can only be reached in the limiting case for small α and large negative $\xi_d = \lambda_{\|} g_r$. We note, however, that V will also affect the phase through its influence on the spiral angle. In Figures 5 and 6 we calculate (4) for other values of V, with $\alpha = 0$. Figure 5 shows that the magnitude in the qA>0 cycle (ξ_d = -1.2 and -0.6) is a strong function of V, while in the qA<0 cycle (ξ_d = 1.2 and 0.6) it is weakly V-dependent. The time of maximum in Figure 6 depends only moderately on V, with the strongest dependence in the qA>0 cycle (ξ_d = -1.2 and -0.6) for low solar wind speeds. This is precisely the region of interest for the anomalously early time of maximum observed in 1954 and it suggests that the solar wind speed may have decreased below 400 km/s.

Thus, our interpretation for the early times of maximum observed in 1954 is a scenario with a strong negative radial gradient and low solar wind speed. Measurements of the solar wind speed do not exist for this epoch, but the speeds measured at Earth since about 1964 have always been in the region of 400 km/s or higher, and only weakly dependent on solar cycle [1]. On the basis of the modeling reported herein, it is possible that the diurnal variation provides a direct means to investigate the solar wind speed in the past. To this end, it will be important that the effects of muon decay must be removed from the data as accurately as possible.

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