Radial and Latitudinal Gradients of Anomalous Cosmic Rays in the Outer Heliosphere

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Abstract

We use recent data from the Voyager 1 and 2 and Pioneer 10 spacecraft to determine the radial and latitudinal gradients of anomalous cosmic rays (ACRs) in the outer heliosphere. The latitudinal gradient is small and positive, as opposed to the large and negative values observed during the last solar minimum in 1987. The radial gradient is small and steady. We compare our results with current theories of the acceleration and propagation of ACRs. We also suggest that the large increase in the intensity of ACR helium that we observe during 1992 is due primarily to a change in the ACR source flux as interplanetary conditions approach quasi-equilibrium. The continuing increases at lower energies in 1993 and 1994 are consistent with a decreasing level of modulation during a period of quasi-equilibrium.

1. Introduction

Anomalous cosmic rays (ACRs) are thought to be neutral atoms [1] which flow into the heliosphere from the local interstellar medium, become ionized in the interplanetary medium and carried to the outer heliosphere where they are accelerated at the solar wind termination shock [2]. There are seven known elements that comprise the ACR component: H, He, C, N, O, Ne, and Ar [3].

During solar minimum conditions, the heliospheric radial and latitudinal intensity gradients of ACRs should depend on the polarity of the solar magnetic field due to the effects of curvature and gradient drifts [4]. During the 1987 solar minimum period, the so-called $A < 0$ period, when the magnetic field was directed inward at the solar North pole, we observed a large negative latitudinal gradient and a positive radial gradient of ACR oxygen [5]. These gradients were correlated with the tilt of the heliospheric neutral sheet, as expected for positive particles which gain access to the inner heliosphere via rapid inward drift along the neutral sheet during such $A < 0$ periods. However, during $A > 0$ periods, appropriate to the current study, the latitudinal gradient should reverse sign because the particles then flow down to the heliographic equatorial plane from the polar regions [3]. Such sign reversals in 3 consecutive solar minimum periods have recently been noted from observations of ACR O and He at various locations in the heliosphere [6,7].

It is also known that the intensity of ACRs varies by a factor of >100 from solar minimum to solar maximum periods [8]. We shall examine the evolving energy spectra of helium at Voyager 1 and suggest the reasons for the variation.

2. Observations

Figure 1a shows 52-day average fluxes of helium observed on Voyager 1 and 2 (V1 and V2) and Pioneer 10 (P10) with energies ~10 - 22 MeV/nuc during 1992 - 1994. The fluxes at all 3 spacecraft increase by a factor of ~40 from the beginning of 1992 to the end of 1994. The P10 and V1 fluxes are in approximate agreement throughout the period. The flux at V2 is consistently lower than the flux at P10 and V1. From the shape of the energy spectra we believe the flux in this energy interval is dominated by ACRs throughout the period shown, although the first two periods in 1992 have substantial contributions from galactic cosmic rays (GCRs).

In Figure 1b we show the radial gradient of the intensities from V1 to V2:

$$G_r^{V1V2} = \ln(f_{V1}/f_{V2})/\Delta r \qquad (1)$$

where Δr is the difference in the radial distances of V1 and V2 and f_{V1} and f_{V2} are the intensities at V1 and V2, respectively. This gradient is clearly affected by transient disturbances but appears to show no systematic decrease or increase from 1992 through 1994. This near constancy of the local gradient implies that $C \cdot V/K$, where C is the Compton-Getting factor, V is the solar wind velocity, and K is the radial diffusion coefficient, is approximately unchanged while the fluxes are increasing by a factor of ~40.

In Figure 1c we show the radial gradient of the intensities using the 3-spacecraft method. In this method, we assume a constant radial and latitudinal gradient in each 52-day period and solve for each from the two measured intensity ratios f_{P10}/f_{V2} and f_{V1}/f_{V2} (see [9] for more explanation). The radial gradient in Figure 1c shows no systematic trend and the weighted mean of the 20 points is 3.91 ± 0.12 %/AU. The latitudinal gradients in Figure 1d

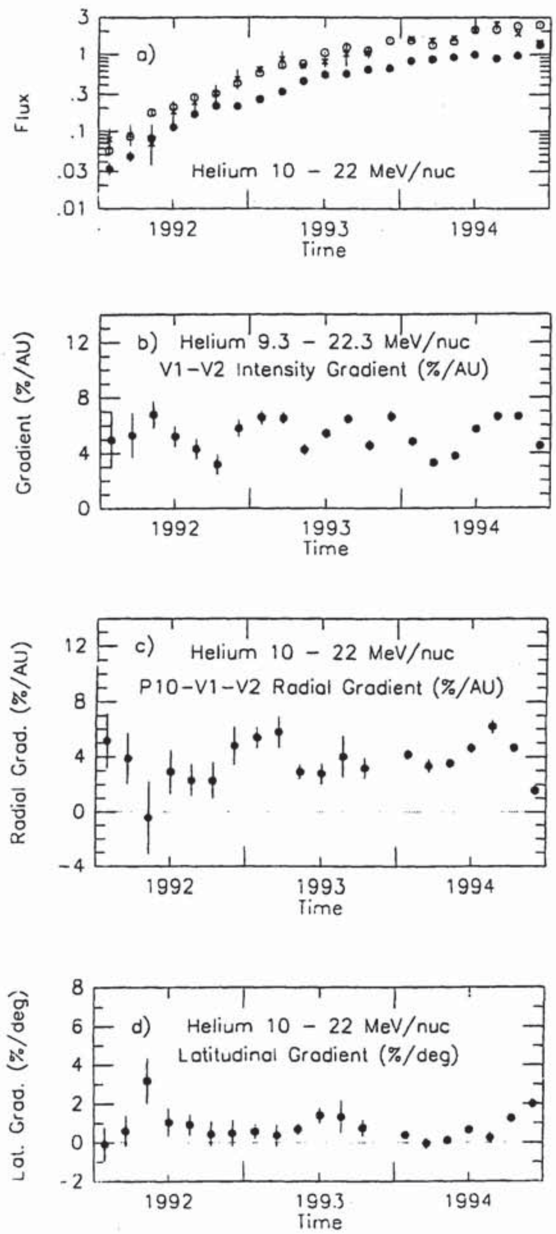

Figure 1. a) Flux of He at V1 (open circles), V2 (solid circles), and P10 (crosses) with energy 10 - 22 MeV/nuc versus time. b) Intensity gradient between V1 and V2 for He with 9.3 - 22.3 MeV/nuc versus time. c) Radial gradient of He with 10 - 22 MeV/nuc versus time. d) Latitudinal gradient of He with 10 - 22 MeV/nuc versus time.

also show no systematic trend and the weighted mean is 0.77 ± 0.07 %/deg.

In Figure 2 we show the tilt of the neutral sheet [10] shifted to the midway position between V2 and P10. The tilt is in a rapid, steady decline until approximately the beginning of 1993, at which time it levels off at ~35°. The rapidly changing tilt in 1992 implies that the magnetic field topology in the heliosphere is evolving in a complex way, since the Sun's magnetic field is embedded in the solar wind and carried with it into the outer heliosphere. This changing magnetic field topology will affect the drift motion of the particles as well as affecting the drift acceleration of the ACR particles at the solar wind termination shock. In addition, we might expect the GMIR [11] that evolved from the 1991 solar activity [12] to cause other complex changes in the magnetic field topology and in the acceleration conditions at the shock. An interaction of this structure with the heliopause is thought to be responsible for the low-frequency radio emissions observed in 1992 and 1993 by the plasma wave experiment on the Voyager spacecraft [13].

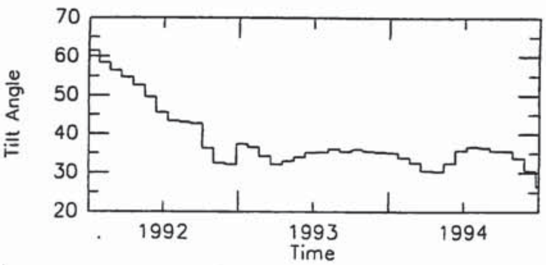

Figure 2. Tilt angle of the heliospheric current sheet shifted to the mid-point of V2 and P10 using a solar wind velocity of 500 km/s. The data are 3-point moving averages, where a point is a 26-day average value.

In Figure 3 we show the energy spectrum of He at V1 for seven 52-day periods beginning with 1992/105-157 and ending with 1994/313-365. For the two 1992 spectra, the entire energy spectrum is growing in intensity uniformly over the full energy range shown (~3 to 60 MeV/nuc). This is consistent with a non-equilibrium period caused by effects on the drift of the particles from the changing magnetic field topology (Figure 2) and effects of the 1991 GMIR on the strength of the termination shock [12].

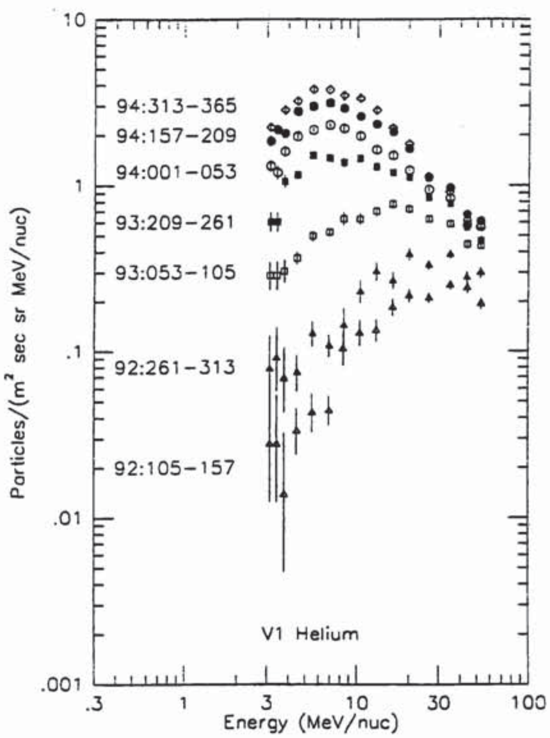

Figure 3. Energy spectra of He at V1 for 7 time periods.

Beginning in 1993 the high-energy end of the spectrum changes intensity only slowly, whereas the lower-energy end continues to rise rapidly. This is consistent with the onset of a quasi-equilibrium period with a stable magnetic field topology (see Figure 2) giving rise to stable conditions for acceleration and propagation. The continued increase in fluxes at low energies could be due to either an energy-dependent mean free path that is increasing with time or a decreasing distance between the shock and V1. The increase is smaller at high energies where the modulation between the shock and the spacecraft is small. We note that the energy of the peak intensity of ACR He is ~6 MeV/nuc in late 1994, lower than previously observed and consistent with a lower level of modulation than at any time in the past.

3. Discussion

The small positive latitudinal gradient reported here contrasts with the much larger negative value (-4.3 %/deg) reported for ACR He in the last solar minimum period in 1987 [5]. In 1976, however, when the Sun's magnetic polarity was the same as now, a small positive latitudinal gradient of ACR helium, ~2 %/deg, was observed based on P11 observations at 16° N [15]. In addition, a small positive radial gradient of ACR O at 10 MeV/nuc during the current $A > 0$ period has also been reported [6 and 7]. In agreement with these earlier reports we have strong evidence that the latitudinal gradient reverses sign in three consecutive solar magnetic field epochs, giving strong support to the role of gradient and curvature drifts in the large-scale magnetic field [15].

The V1 and P10 spacecraft are near 60 AU at the end of 1994 and moving outward. The expectation is that the modulation level should continue to decrease for several years. We expect the peak energy of the ACR He spectra to continue to evolve to lower values as the power law dependence extends to lower energies. At the end of 1994 we believe we may be observing the unmodulated shock spectrum of ACR He at energies $\geq$50 MeV/nuc.

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