Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 1 (SH), pages 571–574

30TH INTERNATIONAL COSMIC RAY CONFERENCE

The radial gradient of galactic cosmic rays: Ulysses KET and ACE CRIS Measurements

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Abstract: The radial gradient of galactic cosmic rays in the inner heliosphere is studied, using the 125 to ~200 MeV/n Helium channel from the Kiel Electron Telescope aboard Ulysses and the 147 - 198 MeV/n carbon channel from the Cosmic Ray Isotope Spectrometer aboard ACE. The time period from 1997 to 2006 covers the solar minima in the A>0-solar magnetic epoch, the solar magnetic reversal to an A<0-magnetic epoch at solar maximum and the declining phase of solar cycle 23. We determined the radial gradient between Ulysses and Earth by assuming that the radial gradient is the same during 1998 and 2004, when Ulysses was at a radial distance of about 5 AU. The analyses for the time period from 1997 to 2006, when the spacecraft was below 30° S, resulted in a radial gradient of $G_r = 4.5 \pm 0.6$%/AU, which is consistent with previous measurements.

Introduction

Galactic cosmic rays consist of 87% protons, 12% helium nuclei, 1% heavier ions with similar energy spectra if displayed as a function of energy per nucleon [1]. At energies below a few GeV per nucleon the modulation of the galactic cosmic ray energy spectra based on interactions within the heliosphere becomes more significant. This modulation is caused by a number of physical processes, including spatial diffusion in the turbulent heliospheric magnetic field, convection and adiabatic deceleration in the expanding solar wind, gradient and curvature drift in the large scale magnetic fields. The strength and relative importance of these processes varies with the location in the heliosphere and with the 22-year solar cycle.

Since its launch in October 1990, Ulysses reached high southern heliographic latitudes three times, around 1994 close to solar minimum, around 2000 close to solar maximum, and again in 2007 during the declining phase of the solar cycle. The global modulation picture changed significantly when the first high latitude results were obtained by Ulysses during the last solar minimum in an A>0 solar magnetic epoch [2, 3, and references there in]. During the fast latitude scan at solar maximum the polarity of the heliospheric magnetic field changed direction from an A>0 to an A<0 solar magnetic epoch [4]. From 2003 to 2007 Ulysses was heading towards high southern heliographic latitudes and reached 80.2° S on 07.02.2007. From Feb. 2007 to Jan. 2008 it will move from 80.2° S to 80.2° N, giving a "snapshot" of the latitudinal distribution of cosmic rays at solar minimum. In contrast to the previous solar minimum scan in 1994/1995, the polarity of the heliospheric magnetic field will be opposite. Since Ulysses is not only moving in latitude but also in radial distance, cosmic ray observations have to be corrected not only for temporal variation but also for the radial intensity gradient in order to determine a latitudinal gradient.

The temporal variation of galactic cosmic rays at Earth is given by a combination of carbon energy channels from the Cosmic Ray Isotope Spectrometer (CRIS) aboard the Advanced Composition Explorer (ACE). That spacecraft was launched August 25, 1997 [5], carrying six high resolution spectrometers that measure the elemental, isotopic, and ionic charge state composition of nuclei from

H to Ni ($1 \leq Z \leq 28$) from solar wind energies ($\sim$ 1 keV/n) to galactic cosmic ray energies ($\sim$ 500 MeV/n). It orbits the L1 libration point which is a point of Earth-Sun gravitational equilibrium at a distance of approximately 1 AU from the Sun and 1/100 AU from the Earth.

Data analysis

In order to calculate the galactic cosmic ray intensity distribution in the inner heliosphere, we need to find energy channels on widely seperated s/c with the same temporal variation. Following Webber et al. [6], we used the 125 to ∼200 MeV/n helium channel from the Kiel Electron Telescope [7] aboard Ulysses and a combination of carbon channels from CRIS. Figure 1 displays from top to bottom Ulysses radial distance and heliographic latitude, the sunspot number, Ulysses 27 day averaged count rates $C_{ULS}(t)$ of 125 to ∼200 MeV/n helium and 27 day averaged intensities $C_{ACE}(t)$ of 147 to 199 MeV/n carbon. In contrast to the carbon channel, short term intensity increases are found in the Ulysses helium data, which can be attributed to large solar energetic particle events. In order to minimize their impact on the data analysis, we include a second helium channel, which measures helium in the energy range from 38-125 MeV/n, in our analysis. The counting rate of this channel, not shown here, is much more sensitive to solar energetic particle events. Thus marking active time periods in the lower-energy helium rate and ommiting these periods from the higher-energy helium counting rate is an efficient way to determine quiet time count rates. In Figure 1 the quiet time intensity time profile is given by the red curve in the fourth panel.

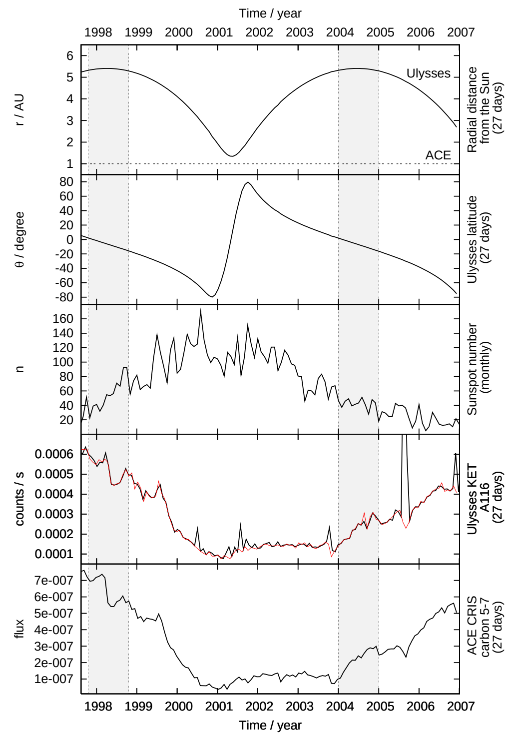

Figure 1: From top to bottom: Ulysses radial distance and heliographic latitude, the sunspot number, Ulysses daily averaged count rates of 125 to ∼200 MeV/n helium and 27 day averaged intensities of 147 to 199 MeV/n carbon. The red curve in panel four reflects quiet time helium intensities. Marked by shading are two time periods in 1998 and 2004 when Ulysses was at about 5 AU from the Sun.

Temporal variations

The first step in order to determine spatial gradients is to find the ACE carbon channel which shows the same temporal variation as the Ulysses quiet time helium channel. Since ACE orbits the Sun at a constant distance of 1 AU, the time history reflects the temporal variation. The time history of the Ulysses measurements, as shown in Fig. 1, however, varies also due to the spatial variation of the spacecraft. In the time intervals from 1998 to 1999 and from 2004 to 2005, the Ulysses space probe is at about 5 AU from the Sun, its most distant position. The time intervals are chosen at Ulysses aphelium so that the radial distance and the heliographic latitudes are nearly constant and the same. It is important to note that Ulysses was below 20° heliographic latitude so that the latitudinal gradient is not altering our analysis [3, 8]. If we assume that the radial gradient is the same in both periods, the difference in both periods should reflect the temporal variation only. Thus it is the ACE channel or combination of channels, which reflects the temporal variation of 1.2 GV helium best, which has the same intensity ratios as the Ulysses helium chan-

Channel (MeV/n)	Counts/s resp. Flux 1998	2004	R eq. 1
Ulysses			
125 - ∼200	5.01E-04	2.30E-04	-
ACE			
56.3 - 73.4	4.46E-07	1.67E-07	1.22
75.0 - 102.0	5.34E-07	2.12E-07	1.16
103.3 - 125.6	6.23E-07	2.58E-07	1.07
126.6 - 146.2	6.63E-07	2.84E-07	1.07
147.1 - 164.9	6.87E-07	3.10E-07	1.02
165.8 - 182.3	6.91E-07	3.25E-07	0.98
183.1 - 198.7	7.10E-07	3.35E-07	0.97
147.1 - 198.7	6.95E-07	3.23E-07	0.99

Table 1: Ulysses KET helium and ACE CRIS carbon accumulated data and ratios $R_{A,B}$ for time-intervals 1998-1999 (A) and 2004-2005 (B) as given by eq. 1.

nel. Thus the best agreement is achieved when

$$R = \frac{C_{ACE}(1998) \cdot C_{ULS}(2004)}{C_{ACE}(2004) \cdot C_{ULS}(1998)} \stackrel{!}{=} 1 \quad (1)$$

Table 1 summarizes the mean counting rates of Ulysses KET and the carbon channels during the time periods in 1998 and 2004, and the ratio according to eq. 1.

As mentioned above, at Earth the ratio $R(P)$ reflects the modulation of galactic cosmic rays and is therefore only dependent on the particle rigidity P. This ratio increases continuously with decreasing particle rigidity. A difference of less than 1% is found when using the carbon channel in the energy range from 147 MeV/n to 198 MeV/n.

Determination of the radial gradient

With the known galactic cosmic ray intensities measured by Ulysses ($C_{ULS}(t)$) and at 1 AU ($C_{ACE}(t)$) and the radial distance of Ulysses and ACE from the Sun (Δr), we can determine the radial gradient of the galactic cosmic rays (G_r) and the normalization factor f between both channels, by fitting

$$\ln \frac{C_{ULS}(t)}{C_{ACE}(t)} = f + G_r \cdot \Delta r \quad (2)$$

to the data until 2005, when Ulysses was still below 20°S. In order to get a meaningful radial gradient from this fit, we make the assumption that the latitudinal gradient is zero from 1998 to 2005. This is reasonable because the analysis by Heber et al. [9] clearly showed that latitudinal gradients only became important during the last solar minimum, when Ulysses entered the region of the heliosphere dominated by the fast solar wind. With an exception of a short period in 1999 Heber et al. [10] and McKibben et al. [11] found that the latitudinal gradient is zero in the rising and maximum phase of solar cycle 23. Although the Sun has reversed its magnetic polarity during solar maximum, we assume that for the current A<0-solar magnetic epoch the latitudinal gradient will only become important when Ulysses is again embedded in the fast solar wind from the coronal holes. As reported by McComas et al. [12], Ulysses was embedded in the southern polar coronal hole from mid 2006 on. Thus the period from 1998 to 2005 is ideally suited to determine a mean radial gradient.

The left-hand side of equation 2 is plotted in Fig. 2: The natural logarithm of the ratio of the galactic cosmic ray intensity for Ulysses with that one at 1 AU against the radial distance of Ulysses from ACE. The line gives the best fit to these ratios leading to a radial gradient of

$$G_r = 4.5\%/\text{AU}.$$

The fit also gives the corresponding uncertainty with a $\Delta G_r = 0.6\%$/AU. These values are in agreement with previous observations and will be used in a following publication to determine the latitudinal gradient measured during the fast latitude scan in 2007.

Conclusion and Summary

Based on measurements by the Kiel Electron Telescope aboard Ulysses and the Cosmic Ray Isotope Spectrometer aboard the Advanced Composition Explorer, we have examined the radial intensity gradient. In order to determine a baseline for the 125 to ∼200 MeV/n helium channel, we calculated the ratio of the count rates measured in 1998 and 2004. During these periods Ulysses was at a distance of about 5 AU from the Sun and close to

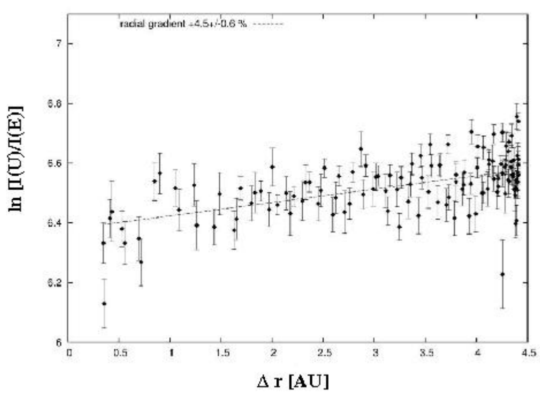

Figure 2: The radial gradient of the galactic cosmic ray intensity for alpha particles with energies from 125 to ~200 MeV/n in the inner heliosphere. Also plotted is the line of best fit from which we get the radial gradient ($G_r \approx 4.5 \pm 0.6\%/$AU).

the ecliptic plane. Under the assumption that the radial gradient is constant, we found that the helium 125 to ~200 MeV/n and the carbon 147 to 199 MeV/n show the same rate of increase during these periods. Thus analyzing the Ulysses to ACE ratio from 1998 to 2005 as a function of radial distance, we determined a radial gradient of $G_r = 4.5 \pm 0.6\%$/AU, which is consistent with previous measurements.

Acknowledgements

The ULYSSES/KET project is supported under grant No. 50 OC 0105 by the German Bundesminister für Wirtschaft through the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The work at Caltech was supported by NASA grant NAG5-12929.

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