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 819–822

ID 255

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Analysis of Cosmic Ray Data from Regular Balloon Experiments and Voyager – 1, 2 Spacecraft

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Abstract: The analysis of experimental data on cosmic ray fluxes measured in the Earth's stratosphere at 1 a.u. and at the different distances from the Earth on Voyager – 1, 2 spacecraft was made. On the base of these sets of long-term data on cosmic ray fluxes the values of radial G_r and latitudinal G_λ gradients were calculated for the period from 1978 till 2007. Analysis of step-like changes of cosmic ray fluxes observed in balloon experiments at 1 a.u. and at Voyager – 1, 2 spacecraft in the outer heliosphere suggets that at the distances r = (105 - 115) a. u. cosmic ray modulation will disappear.

Introduction

Many papers devoted to the analysis of the radial gradient of cosmic ray (CR) flux in the heliosphere have been published. Here we continue this subject using three homogeneous sets of experimental data: CR fluxes at the top of the Earth's atmosphere (energy E > 170 MeV) and fluxes measured by Voyager – 1, 2 (V1, V2) spacecraft (particles with energy $E > 70$ MeV) at the different distances from the Earth. The CR fluxes $J(> 70$ MeV) were taken from INTERNET [1]. These data cover the period from September 1977 till March 2007 and correspond to the distances from 1 a.u. to ~ 102 a.u. The data on primary CR fluxes $J(> 170$ MeV) impinging on the atmosphere have been obtained from the measurements of charged particles in the northern polar atmosphere at the station with the low geomagnetic cutoff rigidity $R_c = 0.6$ GV [2]. The radiosondes with the standard detectors (gas-discharged counters) have been used in these experiments. To ensure the same efficiency of detectors during a long-term experiment the special calibration had been made for each detector. Below we have used the values of cosmic ray fluxes averaged per month. The difference in particle threshold energies for balloon and V1, V2 data is not essential because in this energy range the differential spectrum of primary particles goes down steeply with the energy decrease. As a consequence the integral fluxes of CRs $J(> 70$ MeV) and $J(> 170$ MeV) differ one from another less then 3%. Because of this, below we will write $J(> 0.1$ GeV) instead of $J(> 70$ MeV) and $J(> 170$ MeV).

Experimental Data

In Figure 1 the time dependences of CR fluxes obtained from stratospheric measurements and measurements made by V1, V2 at the distances from 1 a.u. to ~ 100 a.u. are shown.

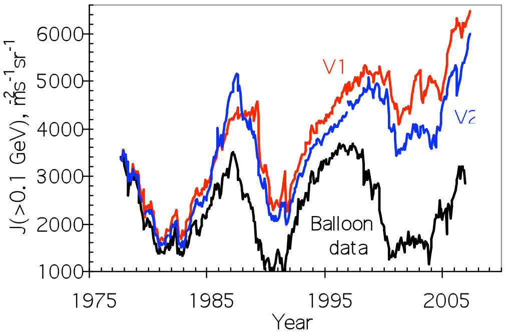

Figure 1: Time dependences of CR fluxes $J(> 0.1$ GeV) averaged per month: V1 data - red curve, V2 data – blue curve, balloon data – black curve.

The V1, V2 data were normalized to balloon data for the period of September – November 1997 when spacecraft were at the distances less then 1.5 a.u. from the Earth. To get the CR flux J(> 0.1 GeV) in the units of m^{-2} s^{-1} sr^{-1} from the V1, V2 data one has to multiply these data by the normalization coefficients 5659.8 and 5202.3, correspondingly.

Comparison of Cosmic Ray Time Dependences

As one can see from Figure 1, all the three curves are similar: time variations of CR ray fluxes observed at 1 a.u. take place at V1 and V2 with some delay time Δt. The wide disagreement between V1 and V2 data was observed during the period of July, 1986-April, 1988. In this period V1 was at the heliolatitude ~ 28° N and V2 was almost in the equatorial plane. Close to this period during March, 1986 – May, 1987 a large north-south positive asymmetry in sunspot group areas was observed.

The values of Δt were found from the correlation analysis of cosmic ray fluxes observed at 1 a.u. and at the locations of V1. The whole period of observation was divided in several time intervals. The duration of each interval was about 2 years. During this time the spacecraft passed ~ 7 a.u. For each interval the correlation coefficients were calculated as a function of Δt. The delay time Δt between the CR fluxes at 1 a.u. and that at V1 location was evaluated from the value of maximum correlation coefficient. The Figure 2 shows the Δt values vs. radial distance r to the spacecraft.

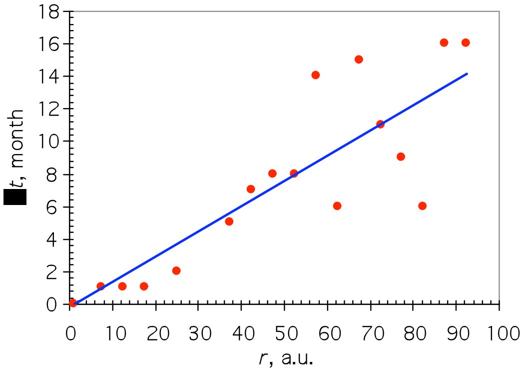

Figure 2: Time difference Δt between CR flux changes observed in balloon experiments (at 1 a.u.) and by V1 at the distance r (red points).

The values of Δt calculated by least-square method (blue line) are expressed as $\Delta t = 0.155\ r - 0.155$ where Δt is given in months and r is in a.u. The correlation coefficient between experimental data and straight line equals to 0.85.

It is worth to note that all values of Δt are positive irrespective of the 11-year solar cycle phase. It means that near the Earth the decrease or recovery of cosmic ray flux occur before than it is happened at the distances $r > 1$ a.u.

The Gradient of Cosmic Ray Flux during Solar Activity Minimum Periods

As it follows from Figure 1 during solar activity minimum periods the maximum values of J(> 0.1 GeV) at 1 a.u. are almost the same. The values of J(> 0.1 GeV) determined from balloon experiments in 1965, 1976, 1987, and 1997 were equal to 3621 ± 30, 3594 ± 11, 3499 ± 12, 3647 ± 19 m^{-2} s^{-1} sr^{-1}, correspondingly. In these periods we have minimal cosmic ray modulation and CR fluxes in the heliosphere depend on the radial distance only. We have used this fact to get the radial dependence of J(> 0.1 GeV), which is shown in Figure 3.

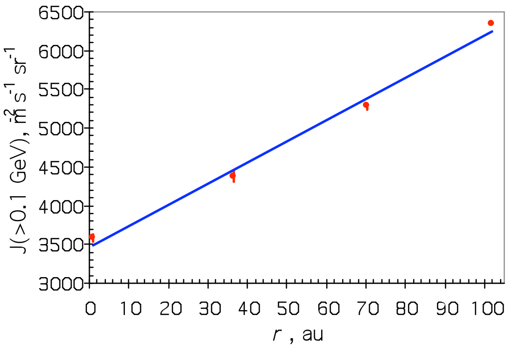

Figure 3: Radial dependence of CR flux in the periods of solar activity minimum according to V1 and balloon data. Blue straight line was calculated by a least-square method.

This dependence can be expressed as $J(>0.1\ \text{GeV}) = 27.27 \cdot r + 3467.5$ and it gives the CR radial gradient $G_r = (1/J)\cdot(\mathrm{d}J/\mathrm{d}r) \approx 0.8$ %/a.u.

In May 2007 the flux of CRs near the Earth did not reach its maximum whereas the CR flux at the distances ≥ 100 a.u., where the V1 is on its way, is almost constant (from May, 2006 till now the value of J(> 0.1 GeV) increased less than 4% [1]).

So, from the data presented in Figure 1 we can suggest that the unmodulated flux of CRs equals to $J_o(> 0.1\ \text{GeV}) \approx 6300\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$.

From balloon experiments we obtain the long-term data on CR fluxes in energy interval of (0.1 - 1.5) GeV, $J(0.1\div1.5\ \text{GeV})$. The modulation of this flux has to be stronger than the modulation of integral flux $J(> 0.1\ \text{GeV})$. Owing to that the radial gradient of particles $J(0.1\div1.5\ \text{GeV})$ has to be larger than the value of $G(r)$ for particles with $E > 0.1$ GeV. Let us take that in our case the values of $G(r)$ are the same for integral and differential fluxes of CR particles. Then the value of $J(0.1\div1.5\ \text{GeV})$ can be expressed as $J(0.1\div1.5\ \text{GeV}) = (1774 \pm 65)\cdot \exp[0.0057(r\text{-}1)]\ \text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$ and at the distance $r = 100$ a.u. $J_o(0.1\div1.5\ \text{GeV}) \approx 3140\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$. The difference in fluxes of $J_o(> 0.1\ \text{GeV})$ and $J_o(0.1\div1.5\ \text{GeV})$ gives us the flux of energetic particles $J_o(> 1.5\ \text{GeV}) \approx 3160\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$. From balloon measurements at 1 a.u. $J(>1.5\ \text{GeV}) \approx 1800\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$ and then the radial gradient of these particles is $G(r) < 0.5$ % / a.u.

Average Radial and Latitudinal Gradient

Using data sets obtained at V1, V2 and in regular balloon observations at 1 a.u. we can find the radial dependence of the average radial gradient G_r in the range from 7 to 102 a.e. (see Figure 4). We do not consider the value of G_r at $r < 7$ a.u. because of fluctuations observed in experimental data.

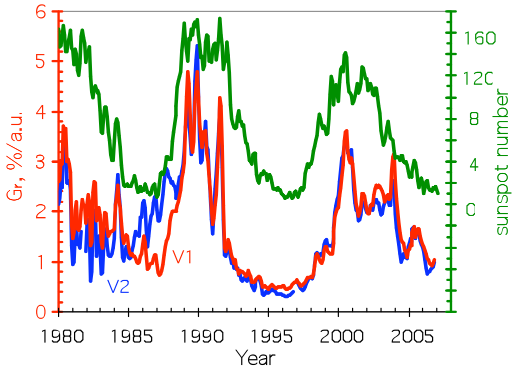

Figure 4: The average radial gradient G_r calculated from balloon and V1 data (red curve) and balloon and V2 data (blue curve). Green curve represents sunspot number. All the data were smoothed with the period of 3 months.

The gradient was calculated as $G_r = 100\square[J(r) - J(1\text{a.u.})]/[J(1\text{a.u.})\square(r - 1)]$, %/a.u. where $J(r)$ was the CR flux recorded by spacecraft at the distance r from the Earth and $J(1\text{a.u.})$ is the CR flux measured in balloon experiments at 1 a.u. [1, 2].

There is a good coincidence between these two curves especially when spacecraft were at the distances more then 20 a.u.

The value of G_r changes in response to the changing of solar activity level. In periods of solar activity maximum G_r increased and during low solar activity periods its value was small. It needs to call attention to the period from the end of 1992 till the start of 1998. During almost 6 years the values of G_r were very small (≤ 0.5 %/a.u.). From the data presented in Figures 1, 2, 3 we can get the value of average latitudinal gradient G_λ as a function of time, if we convert the data of V2 obtained at the distance r_{V2} to the distance of V1, r_{V1}. It can be done with the use of radial gradients shown in Figure 3. The result is given in Figure 5.

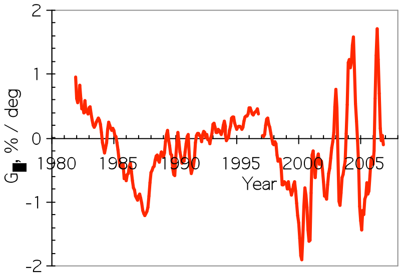

Figure 5: The average latitudinal gradient of CRs G_λ between V1 and V2 spacecraft: $G_\lambda = 100\ (J_{V1} - J_{V2})\ /\ [J_{V1}\square(|\lambda_{V1}| - |\lambda_{V2}|]$ where J_{V1} and J_{V2} are CR fluxes measured with V1 and V2 correspondingly, λ_{V1} and λ_{V2} are spacecraft heliolatitudes. The values of G_λ were smoothed with 3 points.

In the period of (1990 – 1998) during positive phase of solar magnetic cycle the values G_λ were small [3, 4] and in the period of (1998 – 2007) in the outer heliosphere large fluctuations of G_λ have been observed.

Step-like changes of cosmic ray flux

From Figure 1 step-like structure of CR flux variations in 2001-2006 are seen both at 1 a.u. and in the outer heliosphere. In this period two sharp changes in CR flux occurred. In Table the following information on these phenomena is given: start time and end of CR flux sharp changes, interval of distances where the measurements of V1 and V2 were made, average distance (in brackets), and amplitude of CR flux changes.

Table. Two step-like changes of CR fluxes observed at 1 a.u. and in the outer heliosphere.

No. of step	1	2
Start and end of changes at 1 a.u. (balloons). Amplitude, %	11.2003 – 10.2004 113	05.2005 – 06.2007 79
Start and end of changes at V1. Distance (a.u.) Amplitude, %	02.2004 – 06.2006 93.7 – 99.4 (96.5) 36	08.2006 – 09.2007 100 – 104 (102) 9
Start and end of changes at V2. Distance (a.u.) Amplitude, %	06.2004 – 02.2006 73.6 – 78.8 (76.2) 32	04.2006 – 05.2007 81 – 82.7 (81.8) 27.5

As one can see from the Table the amplitudes *A* of step-like changes decreases vs. increase of distance *r*. Figure 6 shows the dependence of *A* on distance *r*. We suggest that CR modulation will be stopped at $r \approx (105 - 115)$ a.u. and at larger distances CR flux will be constant.

Conclusions

Analysis of primary cosmic ray fluxes obtained in balloon experiments at 1 a.u. and in the heliosphere at the distances up to ~ 100 a.u. obtained on board the Voyager – 1 and 2 spacecraft shows:

- Time changes of cosmic ray fluxes at $r = 1$ a.u. and $r = (1 - 100)$ a.u. are mainly similar.
- Radial gradients G_r calculated from balloon and Voyager – 1 and 2 data are in a good agreement with each other (especially for r > 20 a.u.) except for the period of 04.1985 – 07.1988.
- There is a relation between changes of radial gradient and solar activity.
- The amplitudes of step-like changes of cosmic ray flux decrease with the increase of distance from the Sun. At $r = (105 - 115)$ a.u. galactic cosmic ray modulation could be over. This conclusion will be verified in the nearest future.

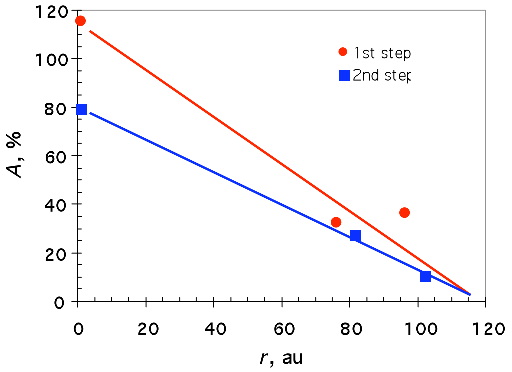

Figure 6: The amplitudes *A* of two step-like changes of CR flux vs. distance *r*. The straight line was drawn by hand.

Acknowledgements

This work was partially supported by the Russian Fond of Fundamental Research grants 05-02-16185, 07-02-01019, and 07-02-10018.

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