30TH INTERNATIONAL COSMIC RAY CONFERENCE

Analysis of Cosmic Ray Data from Regular Balloon Experiments and Voyager - 1 Spacecraft

YURI STOZHKOV, VLADIMIR MAKHMUTOV, NIKOLAY SVIRZHEVSKY
Lebedev Physical Institute of Russian Academy of Sciences
stozhkov@fian.fiandns.mipt.ru

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 spacecraft was made. On the base of two sets of long-term data on cosmic ray fluxes the value of radial gradient G(r) was calculated for the period from 1978 till 2007.

Introduction

Many papers have been published on the analysis on radial gradient of cosmic ray flux in the heliosphere. Here we continue this subject using two homogeneous sets of experimental data: cosmic ray fluxes at the top of the Earth's atmosphere (energy E > 170 MeV) and fluxes measured by Voyager - 1 spacecraft (particles with energy *E* > 70 MeV) at the different distances from the Earth. The cosmic ray fluxes *J*(>70 MeV) were taken from INTERNET [1]. These data cover the period from September, 1977 till March, 2007 and distances from 1 a.u. to 102 a.u.

The data on primary cosmic ray fluxes *J*(>170 MeV) impinging on the atmosphere have been obtained from the measurements of absorption curves of charged particles in the northern polar atmosphere with the low geomagnetic cutoff 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. Here we have used the values of cosmic ray fluxes averaged per month.

The difference in particle energies for balloon and Voyager – 1 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 cosmic rays *J*(> 70 MeV) and *J*(> 170 MeV) will be the same with the accuracy better than several %. 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 cosmic ray fluxes obtained from stratospheric measurements and measurements made by Voyager-1 at the distances from 1 a.u. to ~ 100 a.u. are shown.

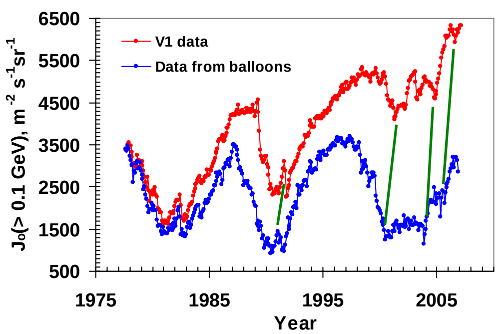

Figure 1. Time dependence of cosmic ray fluxes *J*(> 0.1 GeV) averaged per month. The Voyager – 1 data are shown by red curve and data from balloons are depicted by blue curve. Green straight lines show the same features in *J*(> 0.1 GeV) observed in balloon experiments at 1 a.u. and in Voyager – 1 data at larger distances.

The Voyager – 1 data were normalized to balloon data for the period of September – November 1997 when spacecraft was at the distance less then 1.5 a.u. from the Earth. To get the cosmic ray flux *J*(> 0.1 GeV) in the units of $m^{-2}\ s^{-1}\ sr^{-1}$ from the Voyager – 1 data it is to multiply these data by the normalization coefficient 5659.845.

Comparison of Cosmic Ray Time Dependences

As one can see from Figure 1, the both curves (red and blue) are similar: decreases (increases) of cosmic ray flux observed at 1 a.u. take place at Voyager – 1 with some delay time Δt. The green straight lines allow to see the same features observed in both curves.

The values of Δt were found from the comparison of cosmic ray fluxes observed at 1 a.u. and at the locations of Voyager – 1. The whole period of observation was divided in separate time intervals. The duration of one interval was about 2 years during which the spacecraft passed ~ 7 a.u. For each interval the correlation coefficients were calculated as a function of Δt. The delay time between the cosmic ray fluxes at 1 a.u. and Voyager – 1 location was evaluated when the values of correlation coefficients had maximum. The Figure 2 shows the Δt values vs. radial distance *d* to the spacecraft.

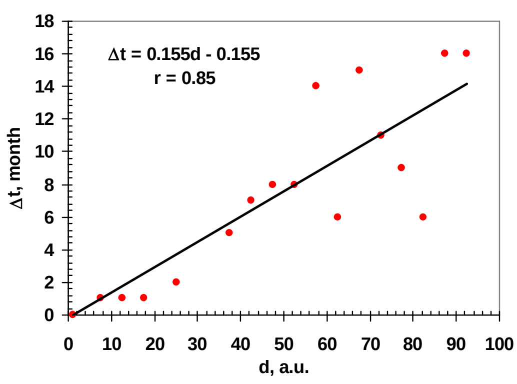

Figure 2. Delay time Δt between cosmic ray fluxes observed in balloon experiments (at 1 a.u.) and by Voyager – 1 at the distance ***d*.** The relationship between Δt and *d* is also given.

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 recovery of cosmic ray flux at 1 a.u. earlier than it occurs at larger distances could mean that cosmic ray modulation takes place in the bounded region of the heliosphere near the solar equatorial plane. These cosmic ray particles could penetrate to the Earth from high heliolatitudes where they were not experienced the solar modulation.

Gradient of Cosmic Ray Flux during Solar Activity Minima

From Figure 1 it follows that during solar activity minimum periods the maximum values of *J*(> 0.1 GeV) at 1 a.u. are almost the same. From balloon experiments the values of *J*(> 0.1 GeV) in 1965, 1976, 1987, and 1997 were equal to 3621 ± 30, 3594 ± 11, 3499 ± 12, 3647 ± 19 $m^{-2}\ s^{-1}\ sr^{-1}$, correspondingly. Let us consider the quiet heliomagnetosphere with minimal cosmic ray modulation as during solar activity minima periods. In this case one can expect that cosmic ray fluxes in the heliomagnetosphere are a function of radial distance only. We have used this fact to get the radial dependence of *J*(> 0.1 GeV), which is shown in Figure 3.

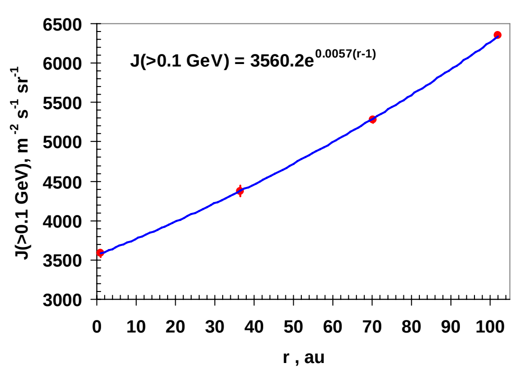

Figure 3. Radial dependence of cosmic ray flux in the periods of solar activity minimum.

From Figure 3 is seen that the radial gradient G(r) equals to 0.57 %/a.u.

Now (May, 2007) the flux of cosmic rays near the Earth did not reach its maximum whereas the cosmic ray flux at the distances ≥ 100 a.u., where the Voyager-1 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 cosmic rays equals $J_o(> 0.1\ \text{GeV}) \approx 6300\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$.

From balloon experiments we have the long-term data on cosmic ray fluxes in energy interval of $0.1<E<1.5$ GeV $J(0.1 < E < 1.5\ \text{GeV})$. It is clear that modulation of this flux has to be more than the modulation of integral flux *J*(> 0.1 GeV). The radial gradient of particles $J(0.1 < E < 1.5\ \text{GeV})$ 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 cosmic ray particles. Then the value of differential flux can be expressed as $J(0.1 < E < 1.5\ \text{GeV}) = (1774 \pm 65) \exp[0.0057(r-1)]\ \text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$ and at the distance $r = 100$ a.u. $J_o(0.1 < E < 1.5\ \text{GeV}) \approx 3140\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$. The difference in fluxes $J_o(> 0.1\ \text{GeV})$ and $J_o(0.1 < E < 1.5\ \text{GeV})$ 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 radial gradient of these particles is G(r) < 0.5 % / a.u.

Average Radial Gradient

Using data sets obtained at Voyager-1 and in daily balloon observations at 1 a.u. we can find the radial dependence of the average radial gradient G(r) in the range from 6 to 102 a.e. (see Figure 4). We do not consider the value of G(r) at r < 5 a.u. because the standard deviations in balloons data of *J*(> 0.1 GeV) do not allow to find it.

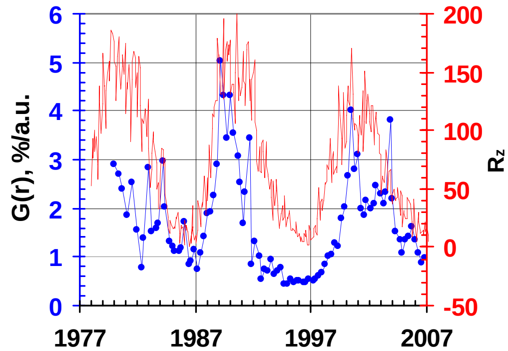

Figure 4. The average radial gradient G(r) (blue curve) and sunspot number R_z (red curve).

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

The value of G(r) changes in response to the changing of the solar activity level. In periods of solar activity maximum average radial gradient is increased and during low solar activity periods its value is small.

It needs to call attention to the period from the end of 1992 till the start of 1998. During almost 5 years the value of G(r) was rather small (about 0.5 %/a.u.).

We calculated the values of G(r) using the data from Voyager-2 spacecraft and our data from balloons [1, 2]. The values of G_{V1} and G_{V2} are shown in Figure 5.

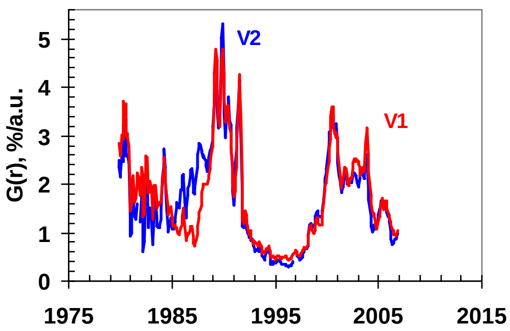

Figure 5. The average radial gradient G(r) calculated from balloon and Voyager-1 data (red curve) and from balloon and Voyager-2 data (blue curve).

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

Conclusions

The radial gradient G(r) was obtained from the two sets of data on cosmic ray flux (particles with E > 0.07 GeV): data from Voyager-1 spacecraft at the distances from 6 a.u. to ~ 100 a.u. and data from regular balloon flights ((particles with E > 0.17 GeV) at 1 a.u.

The gradients calculated from the balloon data and Voyager-1 and 2 spacecraft are in a good agreement with each other (especially for distances more than 20 a.u.).

It is probably that galactic cosmic ray modulation is over at the distance ~ 100 a.u. This conclusion will be verified in the nearest future.

Acknowledgements

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

References

[1] http://voycrs.gsfc.nasa. gov/heliopause/ heliopause /data.html.
[2] Y.I. Stozhkov, N.S. Svirzhevsky, G.A. Bazilevskaya, A.K. Svirzhevskaya, A.N. Kvashnin, M.B. Krainev, and V.S. Makhmutov, and T.I. Klochkova. Data on galactic cosmic ray fluxes according to the measurements in the atmosphere (1957 – 2007). Preprint of Lebedev Physical Institute, Russian Academy of Sciences. Moscow, Russia, 2007.