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ON THE LONG-TERM VARIATIONS OF THE MEDIUM ENERGY GALACTIC COSMIC RAY INTENSITY ACCORDING TO THE BALLOON AND NEUTRON MONITOR DATA COLLECTED IN THE KOLA PENINSULA AND IN MOSCOW REGION

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Abstract. The balloon and neutron monitor data collected the Kola peninsula and in Moscow region for the last 50 years are discussed as a means to get and improve the time series for the galactic cosmic ray intensity in the unique (so called "medium"- T= 100-500 MeV/n) energy range. The perspectives of using the spacecraft cosmic ray data to improve the stratospheric proxies for the medium energy galactic cosmic ray intensity are considered.

1. Introduction

The long-term behavior of the galactic cosmic ray (GCR) intensity of the medium energy (ME) nuclei (100-500 MeV/n) is of special interest as only for these particles: 1) the intensity and hence the statistical accuracy of the data are the highest; 2) the solar modulation is significant during all phases of the solar cycle and everywhere in the heliosphere; 3) the contribution of the anomalous cosmic rays to the intensity is small; and 4) there are long-term experiments that have provided data on the GCR intensity in this range in the inner, intermediate and outer heliosphere. Unfortunately, the detailed direct monitoring of the ME GCR intensity near the Earth had been carried out only from the end of 1969s till October 2001.

It was shown earlier (see [1]) that one of the effective indirect methods to study the medium energy GCR intensity at 1 AU is the investigation of the difference between the atmospheric ionizing particle fluxes measured at high altitudes above the Kola peninsula (the cutoff rigidity R_c = 0.6 GV, corresponding to $T_c^p \approx 180$ MeV for protons and $T_c^{He} \approx 50$ MeV/n for α-particles) and the Moscow region (R_c=2.3 GV, $T_c^p \approx 1500$ MeV for protons and $T_c^{He} \approx 600$ MeV/n for α-particles) in the course of the regular balloon monitoring of cosmic rays, carried out by the Lebedev Physical Institute since 1957. This method allows the investigation of the medium energy GCRs from 1957 up to now.

We found it interesting also 1) to estimate to what extent one can approach the GCR medium energy range using the neutron monitor data (both from the global survey method and from the difference in the count rates of the individual high and middle latitude neutron monitors); 2) to use the neutron monitor data of high statistics to try to improve the stratospheric data sets related to the ME GCR intensity; and 3) to formulate the perspectives of adding the analysis of the spacecraft data to fulfil the latter task.

2. The balloon and neutron monitor data as proxies for the ME GCR intensity

In Figure 1 the relative (with respect to the February 1997 level) monthly averaged count rates of some neutron monitor, balloon and spacecraft cosmic ray detectors are shown since 1957. The lowest and lightest (green) line shows the difference between the count rates of the omnidirectional Geiger counter at the transition (or Pfoetzer) maximum in stratosphere measured in the Kola peninsula (Loparskaya, Olenya and, since 2002, Apatity; below we refer to these locations as "Murmansk" after the region's name) and Dolgoprudny (the Moscow region). It coincides within few percents with those for ME GCR intensities measured onboard IMP8 (the darker black curve; [1]). The intermediate (magenta) line shows the normalized GCR intensity for R=5 GV particles obtained from the global survey method as the lowest energy particle intensity that could be reliably estimated from the neutron monitor data (see its discussion in [2]). Finally, the upper (brown and orange) lines show, respectively, the Apatity and Troitsk neutron monitor uncorrected (except 1.4 factor for Apatity to normalize for different collecting time) relative count rates.

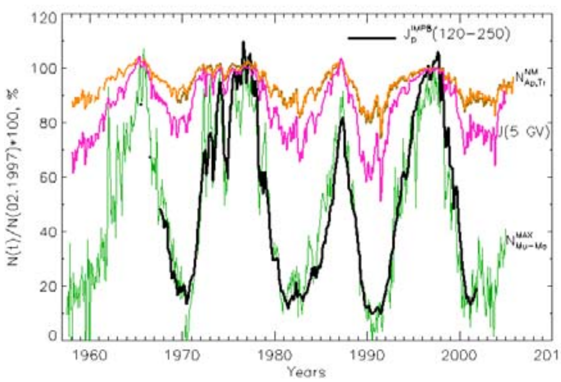

Figure 1. The time behavior of the relative count rates obtained from the balloon and neutron monitoring of cosmic rays as compared with that for the ME GCR intensity.

One can see that the GCR intensity for R=5 GV particles is modulated about twice as great as the count rates of the Apatity and Troitsk neutron monitors separately. In overall, this intensity is modulated in the way similar (or somewhat greater) to the difference between the count rates of the above neutron monitors (not shown in Figure 1).

It is easily seen from Figure 1 that the amplitude of the modulation in the intensity of the lowest energy cosmic rays which can be studied reliably using the ground level detectors is by a factor of 2-2.5 too small in comparison with the ME GCR intensity and with the difference between the count rates measured at high and middle latitudes near the top of the atmosphere. So because of the atmosphere absorbing the low and medium energy cosmic rays, the ground level neutron monitor data are not as useful as the high altitude (stratospheric) data to get the proxy for the ME GCR intensity.

3. The Neutron Monitor Data as a Means for Improving the Balloon ME time series

However, we hope that taking into account the neutron monitor data with high statistical accuracy, one can significantly improve the quality of balloon time series related to the medium energy GCR intensity. An important point is that the differential data (such as the difference between the atmospheric particle fluxes measured at high and middle latitudes) may strongly depend on some factors, which only insignificantly influence the fluxes measured at these latitudes separately.

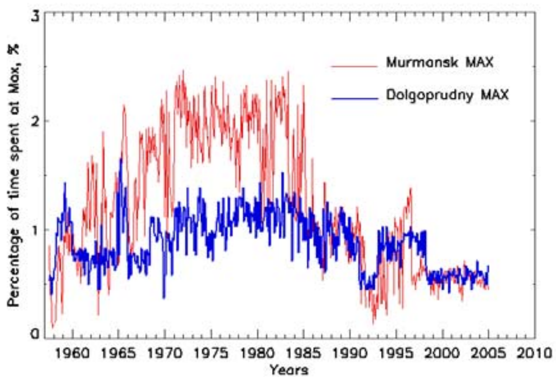

Figure 2. The percentage of time when the count rate at the Pfoetzer maximum was obtained above the Kola Peninsula and Dolgoprudny for each month in 1957-2004.

Below, we, using the results of the simultaneous balloon and neutron monitoring of cosmic rays at approximately the same locations (Murmansk/Apatity in the Kola peninsula and Dolgoprudny/Troitsk in Moscow region), are discussing the influence of one such factor: how the small duration of each balloon flight and small (and variable) number of flights per month could influence the monthly means, calculated as the average of the values obtained in the individual flights. By analogy with the solar flare monitoring we call the sought-for correction for the stratospheric monthly means the "patrol" correction.

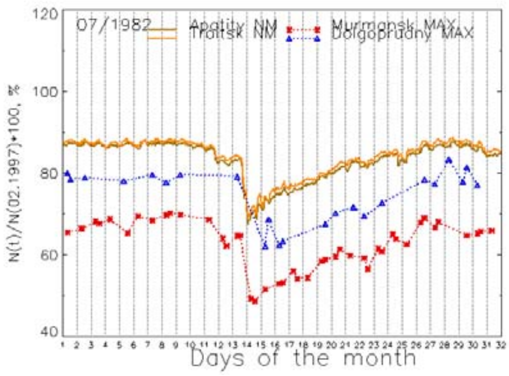

Figure 3. The count rates at the Pfoetzer maximum above the Kola Peninsula and Dolgoprudny for each flight in 07.1982 as compared with the hourly count rates of the Apatity and Troitsk neutron monitors.

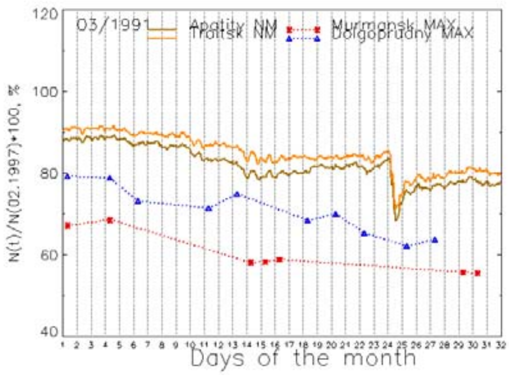

Figure 4. The same as in Figure 3 for 03.1991.

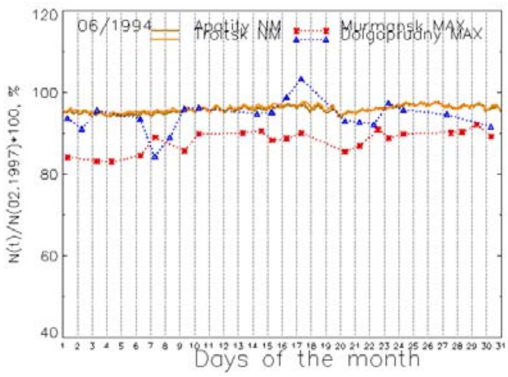

Figure 5. The same as in Figure 3 for 06.1994.

In Figure 2 the percentage of time when the count rates of the omnidirectional Geiger counter at the Pfoetzer maximum at stratosphere have been estimated is shown for each month in 1957-2004 for the Kola Peninsula locations (the lighter (red) line) and Dolgoprudny (the darker (blue) line). One can see that even in the "best" times (1970-1985, Murmansk) this percentage never exceeded 2.5 percents (flights twice a day) and it is only ≈ 0.5 % since 1998 (less than 20 minutes for each of 14-15 flights a month for each location). Is it enough to estimate the time behavior of the GCR intensity? Strange though it may seem, provided one's task is to estimate the behavior of the monthly average (and not the daily, 27-day or Forbush decrease changes), the answer would be positive if the balloon monitoring results had the same accuracy and the same ratio of the within-the-month to monthly changes as the neutron monitor data.

In Figs. 3-5 the hourly averaged relative count rates of the Apatity and Troitsk neutron monitors are shown for three months by the smooth (brown and orange) curves, respectively. The relative count rate of the omnidirectional Geiger counter at the transition maximum for each flight (when we could estimate it) are shown by the crosses (red) for the Kola Peninsula locations and by the triangles (blue) for Dolgoprudny (the symbols are connected by the dotted lines just for the eye's convenience). One can see that sometimes the stratospheric data follow the within-the-month intensity variations rather satisfactory (Fig. 3), while in other cases the Forbush decreases are missed (Fig. 4), or even the general behavior is wrong (Fig. 5). However, if we calculate the neutron monitor "monthly" count rate using only moments when the stratospheric data were taken, usually the results will not differ from the actual monthly means by more than 0.5 %.

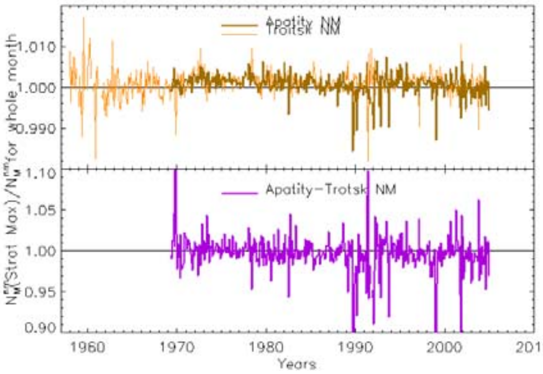

Figure 6. The ratios of the "monthly" (see text) to the actual monthly means for the Apatity and Troitsk neutron monitors (the upper panel) and for the difference of the count rates of these monitors (the lower panel).

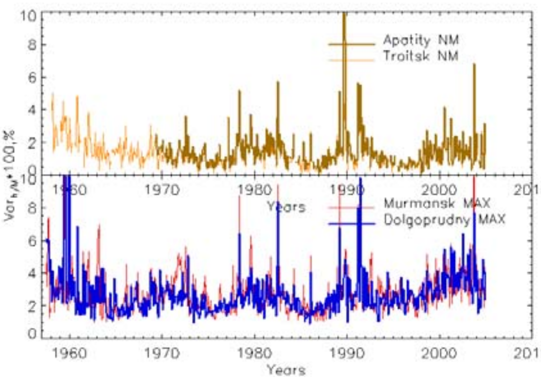

Figure 7. The relative mean square root of the hourly with respect to monthly data for the neutron monitor (the upper panel) and of the stratospheric data in the individual flights with respect to the monthly means (the lower panel).

It is easily seen from the upper panel of Figure 6 where the ratios of the "monthly" to the actual monthly means are shown for the Apatity (the darker (brown) curve; the "monthly" data are calculated using the moments of the balloon monitoring in the Kola peninsula) and Troitsk (the lighter (orange) curve; the balloon monitoring in Dolgoprudny) neutron monitors. However, if we calculate the same ratio for the difference between the count rate of the Apatity and Troitsk neutron monitors (the lower panel), it will be much greater (≤3%).

Of course, the small influence of the period of estimation on the value of the average is due to small amplitude of the within-the-month variations (diurnal and 27-day) with respect to the longer-term ones. This is by no means true for the transient events (Forbush decreases and solar flares) which manifest themselves as the great excursions on both panels of Figure 6. In the upper panel of Figure 7 the time behavior of the relative mean square root of the hourly with respect to monthly data ($Var^{nm}_{h/M}$) is shown for the neutron monitor data. The solar cycle dependence is easily seen with the Gnevyshev Gap in the maximum phases. Generally, $Var^{nm}_{h/M}$ is in the range 0.5-3 %. However, for the stratospheric data the corresponding quantity (the relative root mean square of the data in the individual flights with respect to monthly, $Var^{\max}_{j/M}$, the lower panel) is 2-3 times greater. So we expect the greater patrol correction for the balloon than for the neutrol monitor data.

A corrected for patrol monthly stratospheric count rate $N^{\max}_{M}$ can be estimated as a weighted mean:

$$N^{\max}_{M} = \sum_{j=1}^{K} N^{\max}_{j} \cdot W^{\max}_{j} / \sum_{j=1}^{K} W^{\max}_{j}, \qquad (1)$$

where K is the number of flights per month when we could estimate the count rate at the transition maximum and $N^{\max}_{j}$ is this count rate in the j-th flight. The weight $W^{\max}_{j}$ can be estimated as

$$W^{\max}_{j} = \frac{N^{\max}_{M}}{N^{\max}_{j}} \approx \frac{N^{nm}_{M}}{N^{nm}_{j}} \cdot \frac{Var^{\max}_{j/M}}{Var^{nm}_{h/M}}, \qquad (2)$$

where N^{nm}_{j} and N^{nm}_{M} are the neutron monitor count rate taken at the same moment as $N^{\max}_{j}$ and monthly mean, respectively.

4. Discussion and perspectives

Instead of calculating $N^{\max}_{M}$ according to (1-2) for Murmansk and Dolgoprudny and then forming the difference between these corrected values we prefer here to discuss the validity of the assumptions implied in (2).

First, for the neutron monitor data the calculated variation $Var^{nm}_{h/M}$ actually combines different variations (diurnal, 27-day, transients) with, probably, different energy dependences. So the subindex *j* should also be added to it to account for the different type of variation determining the data in the j-th moment. Second, for the balloon monitoring the meaning of the calculated variation $Var^{\max}_{j/M}$ is not clear: it very poorly accounts for the diurnal wave and usually poorly takes into account the transients. So to use (2) effectively one should 1) isolate the main type of variation setting the neutron monitor data at the time when the stratospheric data for the individual flight was obtained; and 2) extrapolate the energy dependence of the above type of variation beyond the energy range specific for the neutron monitors in order to estimate the characteristics of this type of variation for the high altitude cosmic ray fluxes. We believe that it would be indispensable to use the spacecraft GCR daily or even hourly data (of the ME range or somewhat higher energies, e. g., T>70 Mev/n) for the latter purpose as it allows to use interpolation instead of extrapolation. Besides, the use of the monthly spacecraft data would make much more reliable the correction of the high altitude balloon data for the long-term trends in the efficiency by the model method (see [2]).

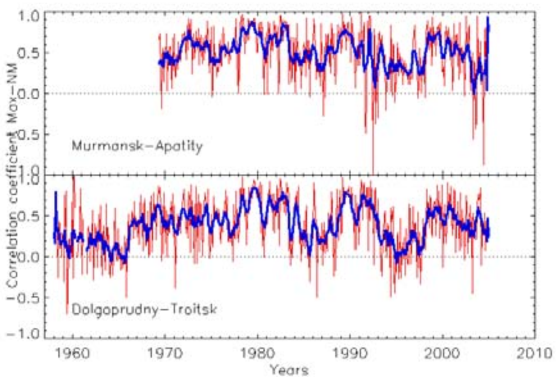

Figure 8. The time behavior of the correlation coefficient between the count rates at the Pfoetzer maximum for each flight of the month and the neutron monitor hourly count rates measured at the same time.

The last and very important point is that the expression (2) implies that the recorded stratospheric count rate $N^{\max}_j$ for the individual flights is correlated with the neutron monitor count rate N^{nm}_j measured at the same time. As easily seen from Figures 3-5 it is not true in many cases. To illustrate the real situation we show in Figure 8 the behavior of the correlation coefficient between the above quantities for each month for the Murmansk (upper panel) amd Moscow (lower panel) regions. The lighter (red) curves show the correlation coefficient r_c between $N^{\max}_j$ and N^{nm}_j for each month while the darker (blue) lines is for the 0.5-year smoothed r_c. One can see that the initial correlation coefficient varies in the wide limits, sometimes being even negative. However, the smoothed r_c is positive and it also demonstrates the solar cycle dependence, especially for the data obtained in Moscow region in 1977-2004 (the solar cycle 21-23), the correlation coefficient being 0.6-0.9 during solar cycle maximum phase and 0-0.3 during periods of low solar activity. Of course, this variation is due to the greater role of the 27-day variations and Forbush decreases in the maxima of solar cycles. Besides, it demonstrates that the relative uncertainty in the determination of $N^{\max}_j$ is significantly greater than its relative variation within the month for the low activity periods. In its turn it means that the accuracy of the method of estimating the count rate in the transition maximum in stratosphere is too low now for using the expression (2) to make the patrol correction for monthly averages during the periods of the low solar activity and we should try to modify it.

5. Conclusions

1. In contrast to the results of the high altitude (stratospheric) cosmic ray monitoring, the results of the cosmic ray measurements by the ground level neutron monitors cannot directly give a useful proxy for the medium energy galactic cosmic ray intensity.

2. The comparison of the balloon high altitude data for the individual flights with the high accuracy hourly and daily neutron monitor data can help in improving the balloon time series related to medium energy GCR intensity, although some methodical efforts with both the neutron monitor and stratospheric data are needed.

3. The inclusion in the analysis, beside the stratospheric and neutron monitor data, of the lower energy spacecraft data of the medium and higher energies of both small and longer time scales would be very useful in improving the balloon time series related to the medium energy GCR intensity.

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