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Space weather prediction by cosmic rays

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Abstract

Relativistic (galactic and solar) cosmic rays (CR) registered by neutron monitors can play a useful key-role in space weather storms forecasting and in the specification of magnetic properties of coronal mass ejections (CMEs), shocks and ground level enhancements (GLEs). In order to produce a real-time prediction of space weather phenomena, only real-time data from a neutron monitor network should be employed. Recently in Athens cosmic-ray station a real-time data collection and acquisition system has been created in collaboration with the cosmic ray group of *IZMIRAN*. This system collects data in real-time mode from about 15 real-time cosmic ray stations by using the internet. The main server in Athens station collects 5-min and hourly cosmic ray data. The measurements of all stations are being processed automatically while converted into a suitable form, so as to be serviceably for forecasting purposes. All programs have been written in an expandable form, in order to upgrade the network of real-time neutron monitors with the biggest possible number of stations, easily. Programs which make use of these data for forecasting studies are already running in experimental mode. The increased number of NM stations operating in real time provides a good basis for using Neutron Monitor network as a tool of forecasting the arrival of the interplanetary disturbances at the Earth.

Keywords: Cosmic rays; Neutron monitor network; Space weather; Ground level enhancements; Forbush decreases

1. Introduction

Space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space born and ground based technological systems and endanger human life and health. In our days internet becomes one of the most important tools for researchers working in solar-terrestrial physics. There is a tight relation and mutual penetration of space weather and internet. Information updated every minute or even more frequently is provided by many tens of instruments for studies of different solar, interplanetary and geophysical effects. Until 1997 cosmic-ray variations were not presented in the internet and therefore the picture of space weather was not complete. Cosmic rays, mostly the galactic cosmic rays, are a part of the interplanetary medium and the human environment and their variations reflect all large effects of the solar activity and solar wind disturbances. GOES satellites provide some information on solar cosmic-rays behavior in real time and possible magnetospheric effects. The worldwide network of ground based neutron-monitor stations can provide reliable and complete information on galactic cosmic ray variations for more than a 50-years time period. During the last six years the quality and the abilities of this network increased significantly since a new information system has been installed firstly in Moscow station (Mavromichalaki et al., 2001). Today a new real-time data collection system has been developed using the

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latest networking methods in order to achieve maximum data collection reliability through the best synchronization and expandability. The new IP-based network lays the foundation of a worldwide data collection system with the specification to join all neutron monitor stations in a common real-time network, capable of real-time data processing and forecasting.

2. Precursors in cosmic-ray real-time data

Disturbances of the solar wind, the magnetosphere and the cosmic rays are closely related, since they are generated by the same active processes at the Sun. The effect of the solar wind disturbances on cosmic rays may extend to large distances. Due to their relativistic velocity, cosmic rays bring information on these disturbances well in advance of their arrival at the Earth. Characteristic signatures in cosmic rays may be selected by special methods from neutron monitor network (NMN) data and input to space weather applications (Belov et al., 2003). Real-time data in combination with developed and tested methods should be used for successful prediction (Mavromichalaki et al., 2004).

2.1. Solar proton events

The early detection of an Earth-directed solar proton event by NMs gives a good chance of preventive prognosis of dangerous particle flux and can provide alert with a minimal probability of false alarm. The flux cannot be recorded on satellites with enough accuracy because of their small detecting area. However, it can be measured by ground-based neutron monitors with high statistical accuracy (in average, 0.5% for 5 min) as ground level enhancement. A feasible and statistically proven method, using total counts from several stations in real time, could be used on this direction, with the following basic steps:

1. Search for a significant increase in the total counts of the 1-, 2-, or 5-min data from several stations. If it is found, go to a state known as "Alert-1".
2. (i) Estimate the rigidity spectrum of the SEP event. (ii) Calculate spectra parameters best fitted to the data from at least three different stations (Dorman et al., 2004).
3. Evaluate the energy-dependent diffusion constant for energetic particle propagation in interplanetary space using the rigidity spectra calculated from the three preceding 1-min data.
4. Predict the near Earth spectrum for a time window of $\sim$1 h. Compare GOES on-line measurements for the last several minutes (if available) with previous predictions.
5. If the predicted flux at 100 MeV exceeds the predetermined threshold, issue an "Alert-2".
6. Repeat steps 2–5, until the total number of counts returns to the background level.

2.2. Geomagnetic storms

Real-time cosmic ray data can provide an important tool for the study of coronal transients, their structure and their propagation from the source to the Earth. The most significant near-earth manifestation of large disturbances is the shock arrival. Cosmic ray density and anisotropy vary significantly during these special times. Precursory increases may result from accelerated particles reflected by the approaching shock. This anomalous pitch-angle distribution has very specific features, such as: (a) a decrease of the CR intensity within a narrow range of pitch-angles close to the interplanetary magnetic field direction and (b) a large, sometimes >1%, difference between the CR intensity from these and from other directions. A pitch-angle distribution which cannot be fitted by the sum of only the first two spherical harmonics can be used as an early indicator of an approaching disturbance and as a predictor of a magnetic storm (Belov et al., 1999, 2001, 2003). During a large heliospheric storm indicated by different space weather parameters, significant variations in CR density and in the first harmonic of the CR anisotropy derived from ground level observations occur simultaneously with dramatic changes in the interplanetary and geomagnetic parameters (Leerungnavarat et al., 2003).

3. NM network as a unique multidirectional detector

The era when a single or a few NMs were used to analyze solar-terrestrial phenomena has come to the end. The NM network should now be considered as a unique multidirectional spectrograph. The development of special programs (global survey method-GSM, ring station method-RSM) allows the derivation of the CR density, anisotropy and pitch-angle distribution at any moment, by using as many neutron monitor stations as possible. The use of all stations as a unified multidirectional detector makes the accuracy substantially higher (<0.1% for hourly data). Several recent results on the use of the prognostic properties of ground level CR observations indicate the need of providing continuous data in real time. Starting in July 1997, the Moscow NM64 was the first in the world to present data on the internet in real time. After Moscow, several other stations became involved in this process, and now 23 stations present their data in real time and many others are going to involve (Mavromichalaki et al., 2004).

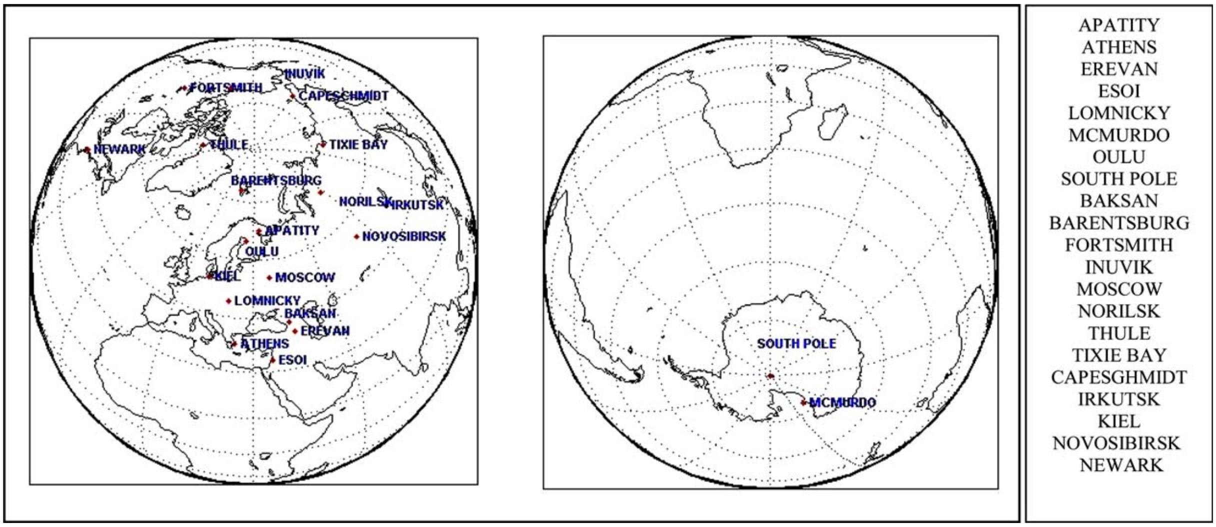

Fig. 1. Distribution of the neutron monitor stations on the Earth presented data in real time in the Athens Center.

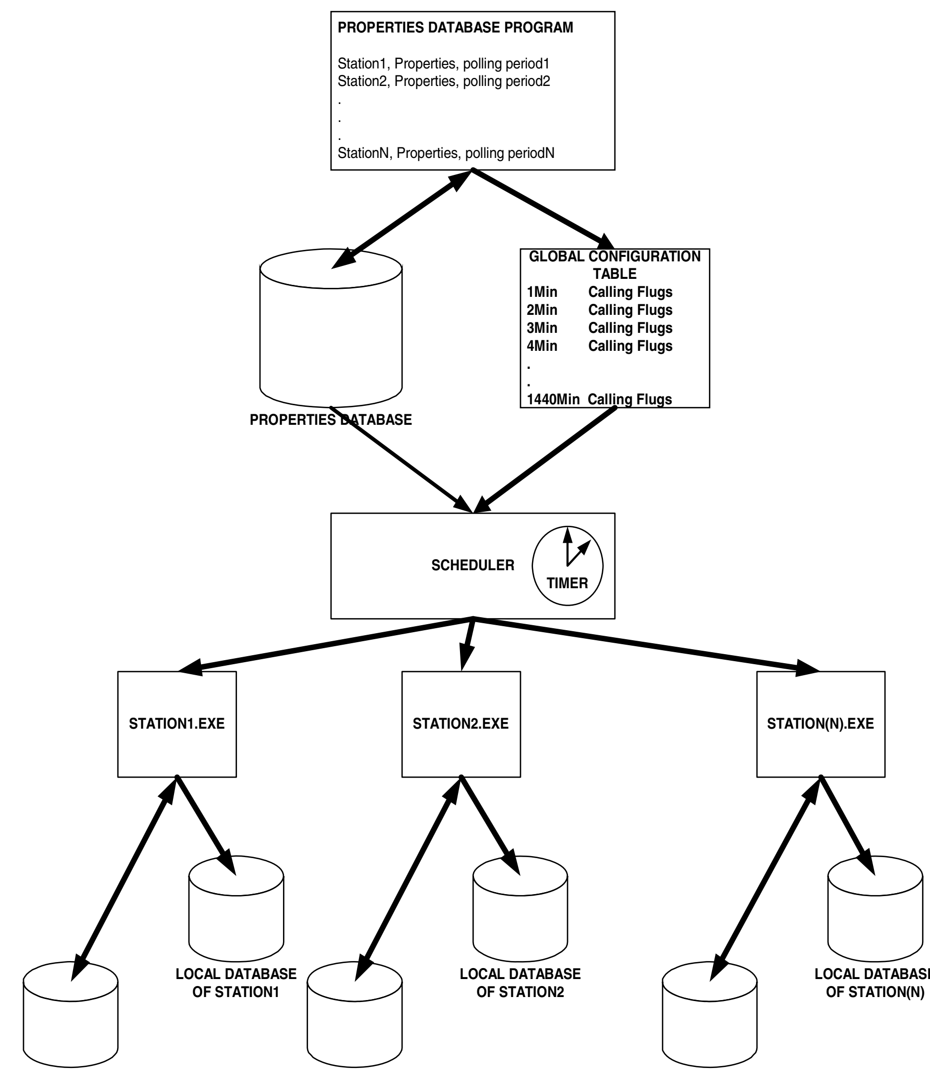

Fig. 2. Schematic diagram of the data collection procedure.

Our main task now is to make it possible to get all these data in real time in close sequence from all servers in order to achieve a real time monitoring of space weather conditions.

4. Real-time neutron monitor network in Athens

In Athens cosmic ray station a data collection system capable of collecting data from remote cosmic ray stations that can present their data in internet via FTP or HTTP servers has been developed. The data collection system has been designed with the capability to support a very large number of stations. It can access simultaneously all the supported stations in order to reduce data collection synchronization problems. The reliability of data collection process is based on the issue that independent programs collect simultaneously data from different stations and by different ways. Till today the data collection system collects data from 21 stations, as it is appeared in Fig. 1.

The overall process of the data collection is described in Fig. 2. The properties of each station are concentrated in one database program, the "Properties Database". In the same database the initialization parameters for the data collection poling of every station are deposit.

A "Scheduler" program reads the properties of each station and gets the decision if it is the exact minute to make a data collection call to the station. For every station there is a data collection program that brings the data from the remote station to the local database.

The scheduler can call many data collection programs in the same minute. These programs can run simultaneously in a parallel mode. Every data collection program has the ability to bring the latest data in a periodic scheme, to bring data automatically or manually for a certain time period. These data are processed by a special program to obtain key parameters that plan to be used for space weather tasks. A typical example for the period from 7 to 11 November 2004 is presented in Fig. 3, where the behavior of the cosmic ray density and anisotropy derived from the real-time collected data

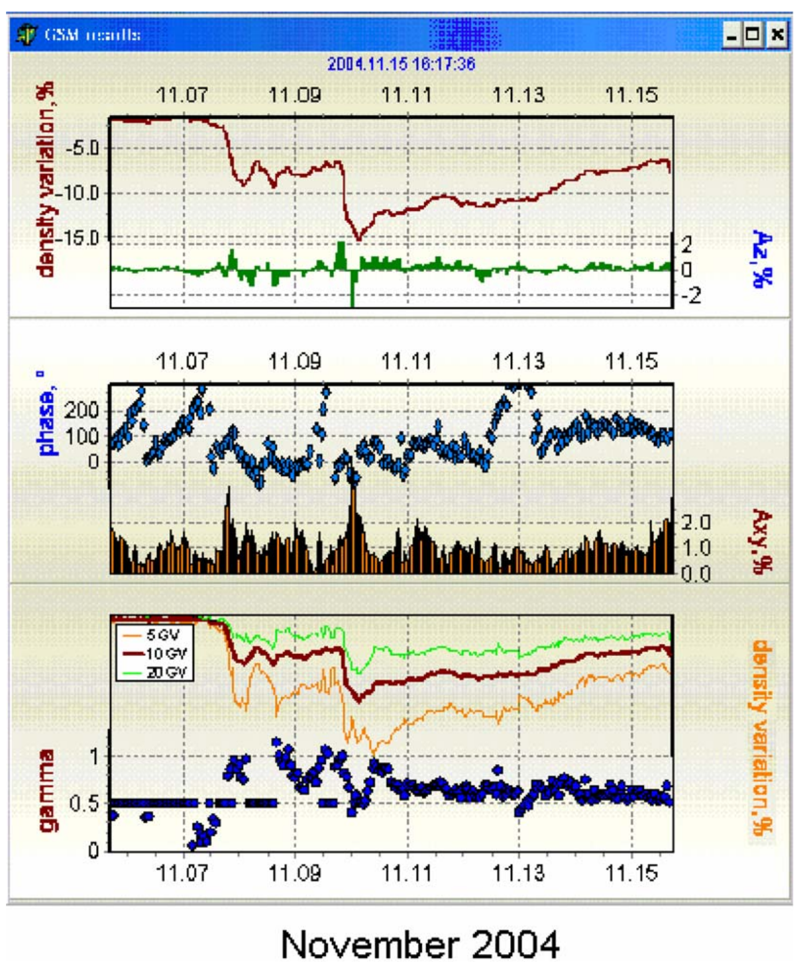

Fig. 3. Cosmic ray parameters calculated in real-time by the data of neutron monitor network for the disturbed period of November 2004.

allows to be carried out the analysis of space weather conditions.

5. Results and discussion

5.1. Ground level enhancement 'Alert'

Cosmic-ray real-time data may be used in programs that produce a preliminary alert for an incoming GLE. The method is described by Dorman et al. (2004) and it is shown schematically for the case of October 2003 in Fig. 4.

(1) Data from at least three NM stations at Earth (two high latitudinal and one/two low latitudinal ones) and two independent satellite channels, for example X-ray on GOES10 and GOES12 and protons with energy >100 MeV, are processed to search for the start of a ground level enhancement (GLE). If it is traced, the computer sends a signal to collect data from all stations which take part to the neutron monitor network and to calculate spectra and other parameters in order to estimate the expected CR profiles for lower energies at different altitudes and for several hours ahead.

(2) The obtained by such a way 'Alert' signal is used for sending out the forecasting by e-mail, and, mainly, to run a system of minute data collection from the whole NM network. In such case it is very important data on the network stations to be updated not rarer than every 5 min. The number of necessary stations should be about 10–20.

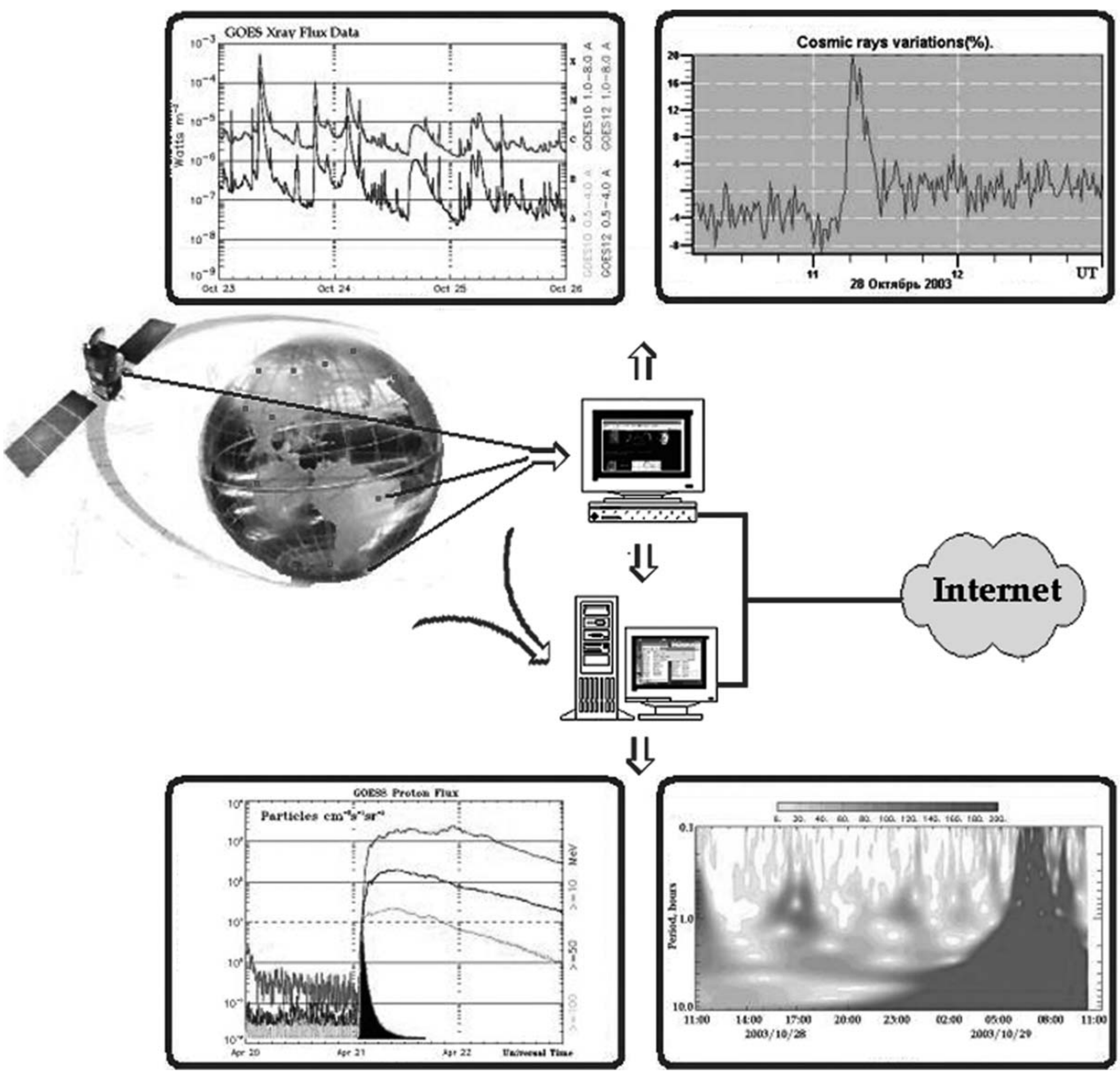

Fig. 4. Preliminary GLE ALERT.

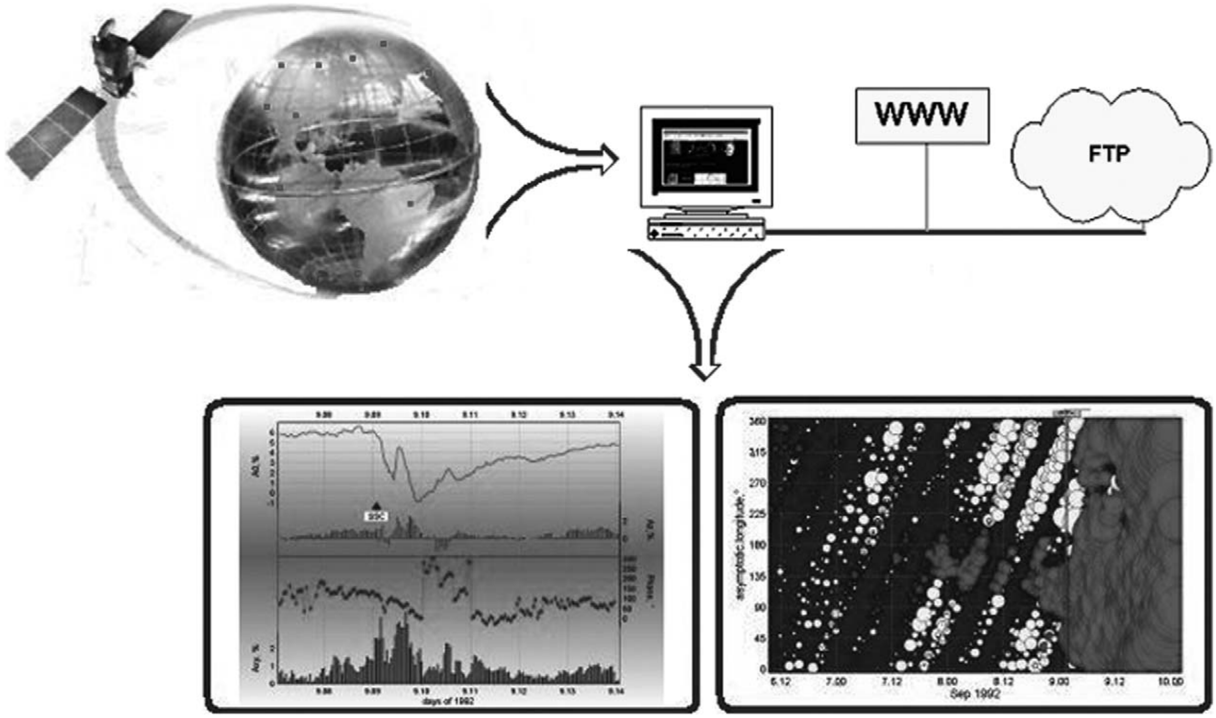

Fig. 5. Cosmic ray anisotropy and other parameters calculated via CR variation measurements from the NM network.

(3) While the minute data are collected, the program of the proton enhancement analysis is running. The proton spectrum will be derived with more and more accuracy along the accumulation new and new data.
(4) Solar relativistic particles registered at Earth have an essential property to bring information on solar and interplanetary conditions much earlier than low and mid energy solar particles. Due to their big diffusion coefficient high energy particles come from the Sun in 8–20 min after acceleration and escaping into solar wind, whereas the main part of lower energy particles, which cause dangerous situation for electronics and hazard radiation, usually come later in more than 30–60 min. Proton events registered at Earth (GLEs) have a complete profile well before the enhancement evolving in the lower energies. This fact can be used for the calculations of spectra and fluxes of lower energies at different levels in 20–30 min after the onset while these results will be continuously improved along the time. In a whole it allows prognosis of the time behavior of non-relativistic solar protons up to 10–15 h.

5.2. Interplanetary shock arrival

Another aspect of the real-time ground level monitoring cosmic rays is the use of the obtained galactic CR characteristics for diagnosing situations in the heliosphere caused dangerous events in Earth's vicinity like the magnetic storms (Fig. 5).

(1) System of hourly data collection in real time from neutron monitor network has been created and supports unlimited number of stations. In this listing high latitudinal stations should be included and mid and low latitudinal as well.
(2) After collection data for a current hour from at least 15 stations (optimum 30) the program of analysis by the global survey method (GSM) runs out. As a result the CR density, spectral parameters of density and three components of CR anisotropy vector are derived at this current hour. In The results of such a program applied to the retrospective data for the period in September 1992 are presented in Fig. 5. On the right fraction of this figure a longitudinal distribution of CR variations for every moment is plotted. One can see that the anomaly in this distribution is revealed several hours prior to the shock arrival.
(3) Amplitude of isotropic variations and characteristics of the CR anisotropy (first harmonic) are set at web sites in real-time mode. Those are the initial experimental data for analysis of the current heliospheric situation. To carry out a more reliable analysis it would be desirable to use these results together with other data on solar and solar wind measurements.

6. Conclusions

The Worldwide Network of neutron monitor stations provided reliable information on cosmic rays usually one year after the observations itself and needed at least two years for the collection of data and the calculation of differential density and anisotropy. The use of these data in so much delayed form is impossible for the direct follow-up of space weather. The installation of a modern system of collecting and processing current data since 1997 allowed the variations of cosmic rays to be analyzed in "Real Time" that constituted the initial step for the integration of CR in the space weather studies. The use of real-time data is perfectly different from the filed data and more efficient. The creation of the Center of collecting and processing data from Neutron Monitors in real time in Athens University, lets a unique opportunity for the forecast of dangerous flows of particles or geomagnetic storms and the ability of creating a warning signal with appreciable precision in each interested institution.

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