Investigation of angular distribution of solar energetic particles

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Abstract. Rotation is often used to stabilize the orientation of satellites in outer space. A method for recording of the angular distribution of energetic particles aboard a spacecraft oriented to the Sun is proposed. This is an example is shown of how to study the angular distribution of energetic solar particles using the own rotation of a spacecraft.

1. Introduction

To ensure that the orientation of a certain axis of the satellite is unchanged, an orientation system that uses the gyroscopic properties of rotating bodies is often used. Rotation orientation was used on the TIROS, ATS-B, ATS-C, some Explorer, Prognoz, and other satellites.

Currently small spacecraft are widely used more and more in both scientific and applied research (Nervold 2016). For the last decade a problem of space weather develops intensively. In this problem the account of interactions between solar influences and particularly terrestrial processes is important. Studying of dynamics of the energetic charged particle fluxes in the nearby-Earth environmental space and interplanetary environment can give helpful information on this problem (Miroshnichenko 2008, Reames 2017). Investigations aboard small space vehicles can make a big contribution into solution of this problem. For these satellites, the devices of small sizes and weight and at the same time with good functional features are necessary.

Distribution of the charged particle fluxes in the solar wind is controlled by its magnetic field consisting of regular and irregular components.

In the range of small energies 1 - 15 MeV, particles of only solar origin, propagated in the interplanetary magnetic field or captured by it, are registered. The problem on free propagation of particles or their capture plays an important role in the physics of interplanetary environment.

For example, the captured particles at expansion of the interplanetary environment can "be cooled" quickly, whereas the "freely" propagated particles do not undergo such cooling.

There may also be quasi-stationary traps of particles in this energy range which rotate together with the Sun and do not lead to "cooling" of particles, and, probably, on the contrary, accelerate them. To classify cases of observation of the charged particle fluxes into specified types of their propagation, it is necessary to measure an anisotropy of particle fluxes. The main goal of our paper is to show the method of measuring the angular distribution of charged particles, which best suits the conditions of a scientific experiment, with a hard limit on weight, size, power consumption and also with high requirements on the flexibility of logic, reliability of operation and preliminary onboard processing of information.
2. Features of registration of low-energy component of charged particle fluxes

Such measurements almost in the same range were conducted aboard the spacecraft (SC) "Prognoz" and IMP-8 (Miroshnichenko, 2008, Reames 2017). As a result of these measurements the anisotropy components only in the plane of solar equator were determined.

To study the angular characteristics of investigated low-energetic flows aboard the IMP-8 "Prognoz" satellites a scientific equipment including sensors located at angles of 0°, 45°, 90°, 135°, to the axis of orientation was used.

Each detector registers the integral flow of particles only from a solid angle that "falls on the aperture of detector during the rotation of satellite around its axis. It is difficult to determine the anisotropy components in the plane perpendicular to the direction of the Sun using this technique. The measurement of these components provides the additional valuable information.

The mentioned anisotropy can be divided into the equilibrium and nonequilibrium components. The first one is caused by the movement of cosmic rays with the magnetic field and substance of the solar wind. This anisotropy is connected with a transport velocity of particles. It can be directed radially. In this case, the particles are transferred by the radial solar wind and the magnitude of anisotropy accounts for ≈ 20 %.

Let's estimate anisotropy amplitude. Anisotropy caused by the movement of cosmic ray gas in the magnetic field with the velocity U is equal to: \( A = \frac{(\gamma+2)U}{c\beta} \). Here \( \gamma \) is an indicator of differential spectrum of pulses, C is the velocity of light, \( \beta \) is the relative velocity of the particles equal to \( \sqrt{\frac{2T}{E_0}} \), where \( E_0 \) is a rest energy, \( T \) is the kinetic energy. For particles 1-15 MeV \( \gamma =5 \), \( \beta = 0.05 \). The solar wind velocity \( U = 400 \) km/s. The rotational velocity of the Sun related to the Earth's orbit is 400 km/s too. Hence \( A = 20 \) %.

The nonequilibrium anisotropy can be connected with its own movement of particles along the field lines and direction along the magnetic field and its value must be > 20 %.

In a case of sudden changes of the radial or azimuthal particle density gradients there should appear a nonequilibrium anisotropy in the south-north direction proportional to the value of gradient.

The study of anisotropy in the plane perpendicular to the direction of the Sun, gives an opportunity to investigate the nonequilibrium anisotropy connected with the deviation of direction of the interplanetary field from the plane of solar equator. The high-energy particles are most often observed in the form of the short-term increases following the fronts of shock waves, or after the solar flashes. The increases of flows of particles with energies of 0.5 - 15 MeV have a much larger time scale. In these cases the sequences of increases in 27 days like recurrent events can be observed.

In a number of works (Reames D.V. 2017, Gallagher, Simpson 1966, K.G. McCracken, U.R. Rao 1967) these sequences are interpreted as a repeated passage of spacecraft through the solar wind sector filled by energetic charged particles. The existence of such stationary structures in the solar wind, filled with low-energetic charged particles, constitute a new phenomenon, significantly different from the discrete flashes of cosmic rays. The nature of this phenomenon is not yet established.

One can assume two possible scenarios. One of them explains the existence of constant sectors filled with cosmic rays by means of continuous emission of particles by areas in the solar atmosphere. According to another one, the particles are considered as if captured in a "bag" that rotates together with the Sun. Such "bag", basically, can be formed by crowding of magnetic field lines at some distance from the Sun appearing as a result of collision of fast and slow streams of the solar wind. The area between this crowding and the Sun is a magnetic "bottle", which is stationary in a rotated system of reading.

Both of these development scenarios predict a quite different anisotropy of charged particle fluxes of the solar origin.

In the first scenario, the particles propagate mainly along the field lines outwards (Figure.1). And in the second one, the particles take part in the rotation of the Sun and their anisotropy has a direction of maximum from the east.
The separation of these scenarios by types of anisotropy maybe implemented using the following experiment.

*Figure. 1.* Scheme explaining to anisotropy lying in a plane perpendicular to a direction towards the Sun. The dashed lines show the sector filled with low-energetic cosmic rays; 0 is the object, E - S is the Earth-Sun line, H, A is the direction of vector of the magnetic field and anisotropy, A is the cross-section component of anisotropy vector.

We propose to measure the angular distribution of cosmic ray intensity in the plane perpendicular to the Sun’s direction. These measurements make it possible to determine a component of anisotropy of charged particle flows lying in this plane.

And the first scenario predicts anisotropies for this plane, one of them is directed to the east, and the second one – to the west.

Such measurements are conveniently carried out with a rotated spacecraft with a rotation axis towards the Sun using the technique of scanning.

When the scanning accuracy is not worse than \(\approx 1\%\), the important information can be also obtained for solving the following scientific problems:

1. Detection and confident identification of small flows (a few tens % from the galactic flows) of charged particles of solar origin against the background of the galactic ones. The methodical side of this problem is based on the fact that the galactic cosmic rays form a current directed from east to west, whereas a solar particle flow has a component directed opposite, from west to east.

2. Estimation of the distribution of the "diffusion resistance" along the distribution channel, representing, roughly speaking, the number of scatterings of particles towards the observer.

The matter is that in the first case when scatterings occur, mainly, on the last section of the way, temporal characteristics of registered radiation differ a little. At the same time these two extreme cases are essentially various on the anisotropy amplitude. Thus, comparing the anisotropy with a temporal change of intensity, it is possible to judge a distribution of sources of particle scattering along a solar radius.
3. Anisotropy of charged particles of solar origin could give information about the fine structure of interplanetary medium. The anisotropy undergoes oscillations in directions with the orientation change of the field tubes of the interplanetary magnetic field. The frequency spectrum of anisotropy oscillations must be, in some degree, adequate to the spectrum of inhomogeneities.

The value of measurements of the low-energetic components increases, if aboard the same spacecraft, which conducts the scanning, the solar wind parameters such as the wind velocity and magnetic field intensity will be measured.

The experiment can be carried out aboard the spacecraft when it is outside of the magnetosphere in the undisturbed solar wind by it.

It is supposed to use a spectrometer consisting of semiconductor detectors for registration of the radiation, whose detectors are placed in a protective collimator (Timofeev et al. 2017, Brilkov 2014, Tsoulfanidis 2015). The effective space angle from an entrance window accounts for 0.5 ster.

The scanning facility of the device synchronized by impulses from the transducer of angular velocities of object divides each turn around its own axis, irrespective of its duration, into N of equal sectors and the special device connects the transducer sequentially to N memory channels. Thus, the information accumulated in these channels will reflect the anisotropy of radiation registered by the transducer.

The device should automatically monitor the time of turn of the object and be adjusted anew as it changes. To estimate the total number of registered particles necessary for definition of one point of anisotropy with the given accuracy we will make the following calculations.

The anisotropy can be defined as Fourier-components of the angular distribution of cosmic rays. In this case, its value is calculated by the formula:

\[ A = \sum_{i=1}^{N} k_i I_i; \quad (1) \]

Where \( I_i \) are intensities in each of \( i \)-channels expressed in relative units, and \( k \) are harmonic coefficients.

The specified formula is the approximate expression of the following integral ratio:

\[ A = \frac{\int_{0}^{2\pi} \sin(\theta) d\theta}{\int_{0}^{2\pi} \sin^2(\theta) d\theta}; \quad (2) \]

From a comparison of these two expressions at \( N \gg 1 \) it is seen that

\[ K_i = \left( \frac{2}{N} \right) \sin I_i \theta_i; \quad (3) \]

Let's assume that the relative error in each of channels is equal to \( \sigma \). Then the error of anisotropy component \( A \) equals:

\[ \sigma_A = \sqrt{\sum_{i=1}^{N} k_i^2 \sigma^2} = \sigma \sqrt{\sum_{i=1}^{N} k_i^2} = \sigma \sqrt{N} \quad (4) \]

Considering that, \( \sin^2 \theta = \frac{1}{2} \), we obtain from (3) and (4)

\[ \sigma_A = \sigma \frac{2}{N} \sqrt{\frac{1}{2} \sqrt{N}} = \sigma \sqrt{\frac{2}{N}} \quad (5) \]

If we designate the total number of particles registered by all channels together through \( n_0 \), then the number of particles registered by each channel, will be approximately equal to \( \frac{n_0}{N} \), and a relative error of each channel is

\[ \sigma = \sqrt{\frac{N}{n_0}} \quad (6) \]
Thus, from (5) and (6) we obtain: $\sigma_A = \sqrt{\frac{2}{n_0}}$  \hspace{1cm} (7)

In order to reliably measure the anisotropy of 20% value with a triple reserve of error, it is required:

$\sigma_A \approx 0.07$

Hence, it seen that, it is necessary $n_0 = \frac{2}{\sigma_A^2} \approx 400$, i.e. to achieve the required precision for each point of the anisotropy, the sensor must register $\approx 400$ particles.

Based upon these numbers and assumed geometrical factors of sensors, we will estimate the required time of exposure for each point of anisotropy.

In the chosen energy ranges the geometrical factor of each detector is $G = 0.5 \text{ cm}^2 \text{ ster}$. The intensity of such particles by measurements (Miroshnichenko, 2008, Reames 2017, Longair) during quiet time accounts for 1 particle / $\text{cm}^2 \text{ s sr}$.

Hence, the required time is: $t = \frac{n_0}{G \cdot \Gamma \cdot I} \approx 10$ - 15 min.

It is seen that measurements of anisotropy can be conducted with a rather good temporal resolution.

In order for this resolution to be achieved in practice, the rotation velocity of the object should be not less than 1 rotation/min. The specified method of measurement of the anisotropy will give additional errors in the case of fast increase or decrease in the radiation intensity. The greater is the rotation velocity of the object, the smaller are these errors.

A rough estimation of this error can be obtained by the formula:

$\Delta A = \frac{dI}{dt} \ast T$

Where $T$ is a period of rotation of the object.

This error can be reduced by a subsequent analysis in each particular event.

3. Conclusion

A specific example shows how to study the angular distribution of the charged particle fluxes. For this purpose the own rotation of small spacecraft is used. As an example it is shown how to measure the angular distribution of charged particle fluxes in the interplanetary space. This method can be used to study the angular distribution inside the Earth's magnetosphere and also in the investigation of the radiation belts.

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Acknowledgments
The work was financially supported by the Russian Fund for Basic Research (the project № 01-02-17278, the project № 01-02-96206, the project №09-02-98507, the project №18-42-140006)