Multiscaling of galactic cosmic ray flux

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Abstract

Multiscaling analysis of differential flux dissipation rate of galactic cosmic rays (Carbon nuclei) is performed in the energy ranges: 56.3-73.4 MeV/nucleon and 183.1-198.7 MeV/nucleon, using the data collected by ACE/CRIS spacecraft instrument for 2000 year. The analysis reveals strong (turbulence-like) intermittency of the flux dissipation rate for the short-term intervals: 1-30 hours. It is also found that type of the intermittency can be different in different energy ranges.

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I. INTRODUCTION

Galactic cosmic rays (GCR) originate outside the solar system. They comprise protons (85%), alpha particles (14%) and heavy nuclei. Interaction with large-scale ordered magnetic field causes the gradient- and curvature-drift motion of GCR in the inner heliosphere, while the interaction with the irregular (stochastic) field component results in the pitch angle scattering of GCR. The scale sizes for the two effects, drifts which depend on variations in the mean field on the order of the heliocentric radial distance, and diffusion which depends on irregularities of sizes comparable to the particles gyro-radii, are quite distinct (see, for instance [1],[2] and references therein).

Until recently space instruments have lacked the combination of large geometrical factor and good mass resolution required to address the question of the variation on short time scales of individual nuclides other than H and He. In present Letter we report on an investigation of the flux fluctuations of GCR nuclei (Carbon - C: \(z = 6\)) based on the data obtained by instrumentation carried aboard the Advanced Composition Explorer (ACE) spacecraft for 2000 year. The intensities of these low energy particles have been continuously monitored by the Cosmic Ray Isotope Spectrometr (CRIS).

In order to get away from the effects of the Earth’s magnetic field, the ACE spacecraft orbits at the L1 libration point which is a point of Earth-Sun gravitational equilibrium about 1.5 million km from Earth and 148.5 million km from the Sun.

The large collecting power and high resolution of the CRIS instrument allow us to investigate modulation of GCR flux on short time scales (beginning from 1 hour) and in different energy ranges.

Current theories of parallel and perpendicular diffusion are fairly well accepted for high energy particles. However, there are important outstanding issues pertaining to diffusion and transport of charged particles at medium to low energies. The particles at low energies are believed interact directly with the steepened dissipation range that sets in near the ion inertial scale. Dynamical scattering theory suggests that these particles may be sensitive to (1) the dynamical decorrelation mechanism that operates at these scales; (2) the ”geometry” of the fluctuations in the dissipation range; and (3) the spectral distribution of power at the small scales [3].
Multiscaling properties of cosmic rays have been already discussed in the light of the data obtained by neutron monitors with cut-off rigidity 1.09 GeV (see, for instance, [4],[5] and references therein) as well as modulation of the cosmic rays by solar wind turbulence and magnetic field intermittency [6]-[13]. However, as far as we know, multiscaling analysis of the GCR heavy nuclei data obtained by satellite instruments is performed here for the first time. This analysis reveals a strong (turbulent-like) intermittency of the GCR dissipation rate and dependence of the intermittency type from the energy ranges (not to be confused with the HEP multiplicity intermittency [14],[15]).

II. DIFFERENTIAL FLUX DISSIPATION RATE

Differential flux of the GCR: $J$, as measured by CRIS, is proportional to the normal component of the velocity field of the GCR: $u$, and to their local concentarion: $n$,

$$J \sim un$$

(1)

Fluctuations of $J$ with time are then determined by corresponding fluctuations of $u$ and $n$.

Dissipation of passive admixture concentration in fluid turbulence is characterized by a "gradient" measure [16]-[18]:

$$\chi_r = \frac{\int_{v_r} (\nabla n)^2 dv}{v_r}$$

(2)

where $v_r$ is a subvolume with space-scale $r$ (for detail justification of this measure see handbook [16]: p. 381 and further). Scaling law of this measure moments,

$$\langle \chi_r^p \rangle \sim r^{-\mu_p}$$

(3)

is an important characteristic of the dissipation rate field just in inertial interval of turbulence (see, for instance, [16]-[18]). Analogous measure is used to characterize also dissipation rate of turbulent velocity (or kinetic energy) in the inertial interval of scales [16]-[18].

For turbulent flows the Taylor hypothesis is generally used to interpret the data [6],[13],[17]. This hypothesis states that the intrinsic time dependence of the wavefields ($u$ and $n$) can be ignored when the turbulence is convected past the probes at nearly constant speed. With this hypothesis, the temporal dynamics should reflect the spatial one, i.e. the fluctuating velocity (concentration) field measured by a given probe as a function of
time, \(u(t)\) is the same as the velocity \(u(x/\langle u \rangle)\) where \(\langle u \rangle\) is the mean velocity and \(x\) is the distance to a position "upstream" where the velocity is measured at \(t = 0\).

With the Taylor hypothesis \(dJ/dx\) is replaced by \(dJ/\langle u \rangle dt\) and one can define GCR flux dissipation rate as:

\[
\chi_\tau \sim \int_0^\tau \left(\frac{dJ}{dt}\right)^2 dt
\]

where \(\tau \simeq r/\langle u \rangle\) and corresponding scaling of the dissipation rate moments as \([18]\):

\[
\langle \chi_\tau^p \rangle \sim \tau^{-\mu_p}
\]

Substituting (1) into (4) one can estimate the GCR flux dissipation rate through characteristics of \(u\) and \(n\). We can consider two asymptotic regimes. For sufficiently small GCR energies the flux dissipation rate has been dominated by the concentration dissipation:

\[
\langle \chi_\tau^p \rangle \sim \langle \left[\frac{1}{\tau} \int_0^\tau \left(\frac{dn}{dt}\right)^2 dt\right]^p \rangle \sim \tau^{-\mu_p}
\]

while for sufficiently large GCR energies the flux dissipation rate has been dominated by the energy (velocity) dissipation:

\[
\langle \chi_\tau^p \rangle \sim \langle \left[\frac{1}{\tau} \int_0^\tau \left(\frac{du}{dt}\right)^2 dt\right]^p \rangle \sim \tau^{-\mu_p}
\]

III. THE DATA

As it was mentioned in Introduction we will use the data collected by ACE/CRIS instrument during 2000 year (the year of maximum solar activity). We will consider carbon nuclei \(C\ (z = 6)\), due to carbon is the lightest abundant nuclei (after \(H\) and \(He\)) in the ACE/CRIS collection. As we shall see this fact allow us consider the both asymptotes mentioned in previous Section.

Figure 1a shows scaling of the GCR flux dissipation rate moments \(\langle \chi_\tau^p \rangle\) \(4\)-(5) for the C-nuclei with energies from energy range: 56.3-73.4 Mev/nucleon (the lowest energy range in the ACE/CRIS collection for carbon).

Figure 1b shows the scaling exponents \(\mu_p\) (circles) extracted from figure 1a (as slopes of the straight lines, cf (5)). The solid curve in figure 1b corresponds to the intermittency exponents \(\mu_p\) obtained for the inertial-convective region of a passive admixture concentration in a laboratory turbulent air flow \([18]\). To support the striking correspondence between
the two data sets multiscaling let us calculate also the Extended Self-Similarity (ESS [19]) exponents, $\beta_p$, extracted from equation:

$$\langle \chi^p \rangle \sim \langle \chi^3 \rangle^{\beta_p}$$  \hspace{1cm} (8)

The ESS of type (8) usually has clearer scaling form than ordinary scaling (5) and covers a wider range of scales (see [19] for a review of ESS and for examples). Figure 2a shows the ESS of the GCR flux dissipation rate moments $\langle \chi^p \rangle$ (8) using log-log scales. The straight lines (the best fit) are drawn to indicate the ESS (8). Figure 2b shows the ESS exponents $\beta_p$ (circles) extracted from figure 2a (as slopes of the straight lines, cf (8)). The solid curve in figure 2b corresponds to the intermittency exponents $\beta_p$ obtained for the inertial-convective region of passive admixture concentration in different laboratory turbulent flows [18].

Now let us turn to the data corresponding to energy range with the highest for the carbon nuclei energies observed by ACE/CRIS. Figure 3a shows scaling of the GCR flux dissipation rate moments $\langle \chi^p \rangle$ (4)-(5) for the C-nuclei with energies from energy range: 183.1-198.7 MeV/nucleon.

Figure 3b shows the scaling exponents $\mu_p$ (circles) extracted from figure 3a (as slopes of the straight lines, cf (5)). The solid curve in figure 3b corresponds to the intermittency exponents $\mu_p$ calculated using the She-Leveque model [20], which is in very good agreement with the data for velocity (kinetic energy dissipation) field intermittency obtained in inertial interval for isotropic fluid turbulence. Figures 4a and 4b shows corresponding Extended Self-Similarity (ESS) properties

$$\langle \chi^p \rangle \sim \langle \chi^4 \rangle^{\beta_p}$$  \hspace{1cm} (9)

observed for the data. Again, as in figure 3b, correspondence to the fluid turbulence (energy dissipation rate - the solid curve in figure 4b) is very good.

The interval of time scales under consideration is 1-30 hours. It seems to be useful to compare the observed properties of GCR flux dissipation rate with relevant properties of the local interplanetary magnetic field. Figure 5 shows energy spectrum of 3D magnetic field measured by ACE/MAG magnetometer in the same time intervals as the ACE/CRIS data. The slope -5/3 indicates Kolmogorov-like scaling (cf [11]). Let us recall that the turbulent fluid dissipation rates used for comparison in figures 1-4 were obtained just for inertial (inertial-convection) interval of scales where the Kolmogorov-like scaling should to be expected [18],[20].
IV. DISCUSSION

The results of previous Section seems to be in agreement with the qualitative estimates made in Section 2: for relatively small energies the flux dissipation rate behaves as one dominated by the GCR particles concentration dissipation rate, whereas for relatively large energies the GCR flux dissipation rate seems to be dominated by velocity (kinetic energy) dissipation.

Since CRIS instrument measures the differential flux \( J \) only, but not the velocity of GCR \( u \) and their concentration \( n \) separately (cf (1)) we have no idea about magnitudes of the fluctuations of \( u \) and \( n \) themselves. Therefore existence of the two asymptotes (6) and (7) is still a pure phenomenology (for the intermediate energies the scaling is deformed by competition between the two different mechanisms of the flux dissipation). The same reason (unknown \( u \) and \( n \) for the GCR) makes it impossible to perform any theoretical estimates for the scales of the GCR flux dissipation rate multiscaling.

Although correspondence between the motions in MHD and hydro cases has been reported earlier (see, for instance, very recent paper [21] and references therein) it is much more difficult to understand such detail correspondence between cosmic rays and fluid turbulence. Indeed, as it follows from previous two sections the observed GCR particles dissipation rate exhibits intermittent properties of a passive admixture convected by turbulent motion of a classic (isotropic, incompressible) non-magnetic fluid. While the solar wind (including the interplanetary magnetic field - IMF) is certainly very different from such a fluid. Moreover, interaction of the electrically charged GCR particles with the solar wind and the magnetic field is expected to have strong resonance features (see, for instance, [7]-[9],[21] and references therein). Therefore, even the fact that many characteristics of solar wind and IMF turbulence are known to be similar to those of turbulence of classic non-magnetic fluids (see [6]-[13] and references therein) the presumably resonance-like interactions of GCR particles with solar wind and IMF seems to be non-consistent with the observed here picture, that request reconsideration of our approach to stochastic short-term convection of the low-energy GCR particles (heavy nuclei) in the heliosphere and their short-term interactions with solar wind and IMF. This reconsideration represents a serious challenge for a wide scientific community: both for astrophysicists and for plasma experts.
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Figure Captions

Figure 1a. The GCR flux dissipation rate moments $\langle \chi^p \rangle$ against $\tau$ for the C-nuclei with energies from energy range: 56.3-73.4 Mev/nucleon. The time interval $\tau$ is measured in hours, whereas the GCR differential flux $J$ is measured in $10^{-7.5}$ particles/m$^2$ s sr Mev. Log-log scales are chosen in the figure for comparison with scaling equation (5). The straight lines (the best fit) are drawn to indicate the scaling. The upper data sets correspond to larger $p = 2, 3, 4, 5$.

Figure 1b. The scaling exponents $\mu_p$ (circles) extracted from figure 1a. The solid curve corresponds to the intermittency exponents $\mu_p$ obtained for the inertial-convective region of a passive admixture concentration dissipation rate in a laboratory turbulent air flow [18].

Figure 2a. The ESS of the GCR flux dissipation rate moments $\langle \chi^p \rangle$ against $\langle \chi^3 \rangle$ in log-log scales (8) for energy range: 56.3-73.4 Mev/nucleon. The straight lines (the best fit) are drawn to indicate the ESS (8). The upper data sets correspond to larger $p = 2, 3, 4, 5$.

Figure 2b. The ESS exponents $\beta_p$ (circles) extracted from figure 2a. The solid curve corresponds to the intermittency exponents $\beta_p$ obtained for the inertial-convective region of passive admixture concentration dissipation rate in different fluid turbulent flows [18].

Figure 3a. The GCR flux dissipation rate moments $\langle \chi^p \rangle$ (4)-(5) against $\tau$ for the C-nuclei with energies from energy range: 183.1-198.7 MeV/nucleon.

Figure 3b. The scaling exponents $\mu_p$ (circles) extracted from figure 3a. The solid curve in figure 3b corresponds to the intermittency exponents $\mu_p$ calculated using the She-Leveque model for isotropic fluid turbulence [20].

Figure 4a. The ESS of the GCR flux dissipation rate moments $\langle \chi^p \rangle$ against $\langle \chi^3 \rangle$ in log-log scales (9) for energy range: 183.1-198.7 MeV/nucleon. The straight lines (the best fit) are drawn to indicate the ESS (9).

Figure 4b. The ESS exponents $\beta_p$ (circles) extracted from figure 4a. The solid curve...
corresponds to the intermittency exponents $\beta_p$ calculated using the She-Leveque model.

Figure 5. Energy spectrum of 3D magnetic field measured by ACE/MAG magnetometer in the discussed range of the time-scales.
