Spectrum of Ultra-High Energy Cosmic Rays from Cluster Accretion Shocks

V.S. Ptuskin, S.I. Rogovaya, and V.N. Zirakashvili

***Abstract*— The acceleration of protons and nuclei by large-scale accretion shocks surrounding clusters of galaxies is considered. The contribution of these sources to the observed cosmic ray intensity at 10^{17} – 10^{20} eV is calculated. Account is taken for the generation of MHD turbulence by streaming instability in a shock precursor, the mass distribution of galaxy clusters, and the energy losses of particles interacting with the CMB and the IR background radiation.**

1. Introduction

THE origin of cosmic rays with energies $E > 10^{17}$ eV is still a matter of debate. The observed severe suppression of cosmic ray flux at energies above approximately 5×10^{19} eV [1,2] testifies that the highest energy cosmic rays experience interactions with photons of background radiation in the Universe for more than $\sim 3\times10^{9}$ years that proves their extragalactic origin. The protons lose their energy for the electron-positron and pion creation in the process (the Greisen – Zatsepin – Kuzmin effect) while nuclei undergo the photodisintegration in addition. Cosmic rays with energies below 10^{17} eV are of Galactic origin; they are accelerated in supernova remnants. The debating point is the characteristic energy E_c, 10^{17} eV < E_c < 10^{19} eV, where the Galactic component gives way to extragalactic component in the cosmic ray flux observed at the Earth, see [3]. The list of potential extragalactic sources contains active galactic nuclei (AGN), gamma ray bursts (GRB), interacting galaxies, large-scale structures including galaxy accretion shocks, and some other astronomical objects, see [4]. The recent analysis of data collected by Pierre Auger Observatory showed that events with energies $E > 6\times10^{19}$ eV are coming from the directions towards relatively nearby AGN [5]. A conservative conclusion reached in [5] is that AGN or other candidate sources with similar spatial distribution are sources of ultra-high energy cosmic rays. In the context of the present work, the cluster-AGN spatial correlation, see e.g. [6], should be noted.

Particle acceleration by accreting shocks in galaxy clusters was considered as a possible source of ultra-high energy cosmic rays in a number of papers [7 – 12]. A shock with typical velocity of the order of 10^3 km/s is driven by the gravitational attraction and is formed at the interface between the virialized gas and the diffuse gas. The energy processed by strong accretion shocks ~ 10^{41} erg/(s Mpc^3) is higher by about an order of magnitude than the supernova energy output and is higher or comparable with the AGN energy output. It makes the galaxy accretion shocks an appealing site for efficient particle acceleration.

Features of the present work are the use of results [13] for consideration of diffusive shock acceleration, the averaging of cosmic ray source spectrum on cluster mass distribution, and the further development of approach [14] for calculations of transport of ultra-high energy protons and nuclei through the background radiation in the expanding Universe.

2. Acceleration of Cosmic Rays by Accretion Shock

According to self-similar solution [15], the quasi-stationary flow with a shock located at the radial distance from the centre of the cluster $R_{sh} = 2.12 M_{15}^{1/3} h^{-2/3}$ Mpc is formed in the process of accretion to the spherical galaxy cluster with a total mass $M = M_{15}\times10^{15} M_{\rm e}$, where $M_{\rm e}$ is the solar mass, h = 0.71 is the Habble constant in units 100 km/(s Mpc). The shock velocity is equal to $u_{sh} = 1.75\times10^3 M_{15}^{1/3} h^{1/3}$ km/s. The galaxy clusters mainly site at the intersections of large-scale filaments where the gas density, temperature and magnetic field just upstream of the shock are estimated as $n = 3\times10^{-5}$ cm^{-3}, $T = 5\times10^5$ K and $B = 10^{-8}$ G respectively. Essential for our consideration is the cluster mass function which according to [16] is of the form

$$n_{cl}(>M) = 7.2\times10^{-6} h^2 M_{15}^{-1} \exp(-5.6 h M_{15}) \qquad (1)$$

in the mass range $10^{-3}h < M_{15} < 5h$.

The presence of shock in turbulent plasma leads to regular Fermi type acceleration of particles diffusing and repeatedly crossing the shock front [17, 18]. The maximum energy of accelerated particles depends on the level of MHD turbulence which determines the value of diffusion coefficient. In the case of efficient acceleration, the level of turbulence is self-consistently set by the streaming instability of the leaving the region of acceleration accelerated particles. Using the work [13] (where the study of acceleration process was maid in application to young SNR but is valid in a more general case), one can obtain the following estimate of the maximum energy of accelerated ions of charge Ze:

All authors are with the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow region 142190 Russia (corresponding author S.I. Rogovaya phone: (496)-751-0925; fax: (496)-751-0124; e-mail: rogovaya@izmiran.ru).

$$E_{\max} \approx 10^{18} Z\eta_{cr} \left(\frac{u_{sh}}{10^3\,\text{km/s}}\right)^2 \left(\frac{n}{10^{-5}\,\text{cm}^{-3}}\right)^{1/2} \times \left(\frac{R_{sh}}{1\,\text{Mpc}}\right)\ \text{eV}, \tag{2}$$

where the parameter $\eta_{cr} = 2F_{cr} / \left(\rho u_{sh}^3\right) < 1$ characterizes the efficiency of acceleration; $F_{\rm cr}$ is the energy flux density of accelerated particles that run away upstream from the shock; ρ is the gas mass density. The development of streaming instability amplifies the background magnetic field $B_0 \approx 10^{-8}$ G to the level $\delta B = 2\times10^{-7}\eta_{cr}^{1/2}$ G. The characteristic set up time for the turbulence and particle distributions is estimated as $t_s = R_{sk} / u_{sk} \approx 1.2\times10^9 h^{-1}$ yr.

With account taken for energy losses of protons and nuclei, the particle energy reached in the course of acceleration can not exceed ~ $10^{19}Z$ eV. The bulk of accelerated particles are carried by the gas flow downstream of spherical shock and do not reach an observer outside. The exception is provided by the particles with energies $E \sim E_{\max}$ that make up the population of the runaway energetic particles, see [13, 19, 20] for detail. After averaging over the cluster mass distribution (1) one can derives the following equation for the density of cosmic ray sources determined by the particle acceleration at cluster accretion shocks:

$$q_{cl}(E,Z) \approx 2.6\times10^{14} \frac{\kappa(Z)\eta_{cr}^{1/3}}{Z^{2/3}E_{18}^{4/3}} \times \exp\left(-\frac{E_{18}}{2.8\eta_{cr}Z}\right)\ \text{particles}/(\text{s Mpc}^3\ \text{sr eV}). \tag{3}$$

Here $\kappa(Z)$ describes the relative abundance of accelerated ions of charge Z; $E_{18} = E/(10^{18}$ eV).

The direct calculation of $\kappa(Z)$ is difficult mainly because of insufficient understanding of the mechanism of thermal particles injection into the process of acceleration. The base composition of accelerated ions in our calculations was taken as identical to the galactic cosmic ray sources [21] but with the abundance of elements heavier than He decreased by a factor of 5 (it reflects the difference between the interstellar medium and the filaments of intergalactic medium). The different degree of ionization of the background plasma and the different degree of nonlinear shock modification [22] in the supernova remnants and in the galaxy clusters were also taken into account that resulted in the values $\kappa Z^{-2/3}$ = 0.79, 0.17, 0.0051, 0.016, 0.0063, 0.0041, 0.011 for H, He, C, O, Mg, Si, Fe ions respectively.

We model the propagation of cosmic ray protons and nuclei in the expanding Universe in the approximation of continuous energy losses by e^+e^- and pion production, and with account taken for the photo-disintegration of primary nuclei and the associated production of secondary nuclei. It generalizes our consideration of proton transport [14] to the case of nuclei. The details will be given in a separate paper.

The expected spectrum of cosmic rays at the Earth calculated by transport equation with the source term (3) at $\eta_{\rm cr}$ = 0.3 and without cosmological evolution of commoving source power is presented in Fig. 1 together with observations [1, 2]. Eq. (3) taken literary leads to overproduction of observed at the Earth cosmic ray flux by about order of magnitude. The spectrum shown in Fig. 1 is normalized to the observed flux of cosmic rays.

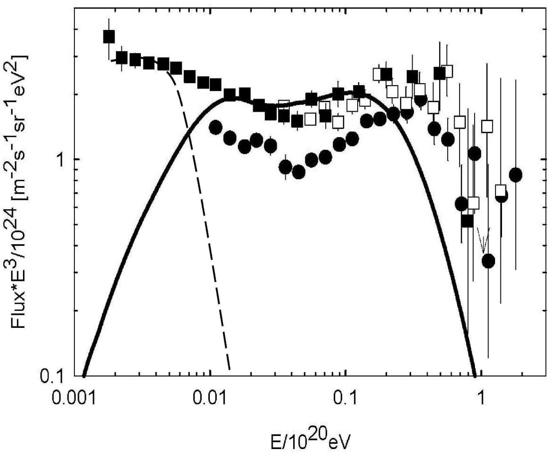

Figure 1. Calculated spectrum of cosmic rays, accelerated by galaxy accretion shocks (thick solid curve). The expected contribution of Galactic sources is shown by dash curve. The HiRes (High Resolution Fly's Eye) [1] and the Pierre Auger Observatory [2] experimental data are shown by square and circle symbols respectively.

6. Conclusion

The accretion of intergalactic gas to galaxy clusters is accompanied by the formation of strong shocks that may serve as a source of ultra-high energy particles observed at energies 2×10^{18} to 3×10^{19} eV. The model evidently can not explain the observed spectrum at higher energies. The heavy (iron) composition at energies above 10^{19} eV is the characteristic feature of the model.

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