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Origin of Galactic Cosmic Rays: Sources, Acceleration, and Propagation

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Rapporteur talk at the 29th International Cosmic Ray Conference in Pune (2005) based on 42 papers presented at the sessions OG.1.2 - Cosmic ray sources and composition, OG.1.3 - Cosmic ray propagation, and OG.1.4 - Cosmic ray acceleration.

1. Introduction

We discuss results on galactic propagation and acceleration of cosmic rays presented at the Conference in a broad context of the cosmic ray origin problem and with the references to some Conference papers that were not formally assigned to the present rapporteur talk.

2. Modeling of cosmic ray propagation in the Galaxy

The interaction of relativistic charged particles with galactic magnetic fields leads to high isotropy and relatively large confinement time of cosmic rays in the Galaxy. It is accepted that diffusion approximation gives an adequate description of cosmic ray propagation in the interstellar medium at energies up to about 10^{17} eV. The diffusion model makes a basis for interpretation of cosmic ray data and related radio-astronomical, X-ray and gamma-ray observations.

The modeling of cosmic-ray diffusion in the Galaxy includes solution of a transport equation with a given source distribution and the boundary conditions for all cosmic-ray species. The transport equation describes diffusion, convection by hypothetical galactic wind, and the changes of energy (the energy losses and the possible distributed acceleration by interstellar turbulence). In addition, the nuclear collisions with interstellar gas atoms resulting in the production of secondary energetic particles should be taken into account when considering the cosmic ray proton-nucleus component. Hundreds of stable and radioactive isotopes are included in the calculations of nuclear fragmentation and transformation of energetic nuclei in the course of their interaction with the interstellar gas.

The most advanced code developed for the numerical calculations of cosmic ray propagation in the Galaxy is the GALPROP code which uses a Crank-Nicholson implicit second-order scheme (Strong & Moskalenko [1], Moskalenko et al. [2]). It incorporates as much realistic astrophysical input as possible together with latest theoretical development and numerically solves transport diffusion-convection equations for all cosmic-ray species. No new results based on the GALPROP code were reported at the Conference. Instead, the combined analytical and numerical methods were used in several presentations; see also early paper by Ginzburg et al. [3]. In principle, this approach may allow faster computations. For example, the cylindrical symmetry of cosmic ray propagation region can be explicitly taken into account by the expansion of desired solution in a series of Bessel functions.

Working with this type of combined models, Castellina & Donato OG.1.3 elaborated further their diffusion-convection model Maurin et al. [4] and made predictions for future direct measurements of B/C ratio at energies above 100 GeV/n. Futo et al. OG.1.3 improved the model of Shibata et al. [5] where cosmic ray diffusion coefficient increases exponentially with distance from the galactic disk and where no sharp boundaries of galactic cosmic ray halo are assumed. New code which is well suited for the calculations of cosmic ray density with high spatial and temporal resolution was developed in a recent paper Büsching et al. [6] and in the corresponding Conference presentations Büsching et al. OG.1.3, Büsching & Potgieter OG.1.3.

No essentially new data that would change the commonly accepted values of cosmic ray transport coefficients or other key parameters of galactic diffusion model were presented at the Conference. The current status of two popular versions of a basic diffusion model with no galactic wind is illustrated in Table 1, see also Jones et al. [7]. The typical value of the diffusion mean free path is about 1 pc for particles with magnetic rigidity R = 1 GV. The height of the cosmic ray halo is approximately equal to 4 kpc.

Table 1. Popular versions of empirical diffusion model without galactic wind for cosmic rays at energies below the knee

	plain diffusion	diffusion + reacceleration ($V_a \neq 0$)
diffusion coefficient	$D \sim \beta R^{0.5}$	$D \sim \beta R^{0.3}$
spectrum of turbulence	Kraichnan	Kolmogorov
source spectrum	$q \sim R^{-2.2}$	$q \sim R^{-2.4}$
special features	$q(R)$ is more steep at < 50 GV, break of $D(R)$ at < 5 GV	$q(R)$ is more flat at < 3 GV
problems	high predicted anisotropy at energies > 10 TeV	low predicted flux of antiprotons

Table 1 describes the plain diffusion model with relatively strong dependence of diffusion on rigidity that is typical for the Kraichnan-type spectrum of the interstellar turbulence, and the diffusion model with particle diffusion and stochastic reacceleration on the Kolmogorov-type spectrum of turbulence. The observed shape of cosmic ray energy spectrum can not be reproduced under the simplest assumptions that the cosmic ray source spectrum and the diffusion mean free path for energetic particles have pure power-law dependences on particle rigidity. The break of the diffusion coefficient at approximately 5 GV is needed in the plain diffusion model to explain the peaks in secondary to primary ratios of cosmic ray nuclei, e.g. B/C, at about 1 GeV/n. These peaks in the model with reacceleration are developed even at a single power-law dependence of diffusion mean free path on rigidity as a result of the trade between cosmic ray leakage from the Galaxy and the reacceleration of particles by interstellar turbulence. Table 1 indicates that the source spectra are different in the plain diffusion model and in the reacceleration model. They have different power law exponents and different breaks. These source spectra are derived from the fit to the observed spectra of primary nuclei.

The main difficulty with the plain diffusion model is a large predicted anisotropy of very high energy cosmic rays, see discussion below in Section 4.

The main difficulty with the diffusion-reacceleration model is an apparently low predicted flux of secondary antiprotons at energies below about 5 GeV, e.g. Sina et al. [8], Moskalenko et al. [9]. New calculations of antiproton fluxes in cosmic rays were presented at the Conference. The production and propagation of secondary antiprotons in the interstellar medium was studied by Davoudifar & Fatemi OG.1.2 who presented useful parameterization of $\bar{p}$ production cross sections. Stephens OG.1.3 analyzed the production of secondary antiprotons in 3-dimentional atmosphere that allows correct treatment of tertiary $\bar{p}$ production.

At small atmospheric depth, 3-D effect gives higher flux at energies less than 500 MeV compared to unidirectional flux. These theoretical results and the new data from the BESS-2002 measurements of cosmic-ray antiprotons (Haino et al. OG.1.1) reported at the Conference does not allow yet to clarify how serious is the antiproton problem in the diffusion model with reacceleration.

The extension of cosmic-ray propagation model to energies 10^{14} to 10^{19} eV was presented by Hörandel et al. OG.1.3. The knee in the cosmic ray spectrum is located in this energy range at $E_k \sim 3\times10^{15}$ eV and, in principle, it can be caused by the appropriate change of power-law dependence of cosmic-ray diffusion on rigidity. Developing earlier works of Ptuskin et al. [9] and Kalmykov & Pavlov [10], Hörandel et al. assumed that the knee is the result of interplay between diffusion along wandering magnetic field lines and the Hall diffusion across the average Galactic magnetic field. The last process has stronger dependence on rigidity and may dominate above the knee. However, at least for parameters used in the Conference paper, it turned out that resulting bending of cosmic ray spectrum is not as pronounced as it is required by the knee observations. Thus, some additional change of the slope of cosmic ray source spectrum is probably needed. Another result of Hörandel et al. OG.1.3 is that the diffusion approximation can be used up to rigidity about 3×10^{16} eV and the direct trajectory calculations of particles motion in Galactic magnetic fields should be used at higher energies.

The renovated "nested leaky box" model originally developed by Cowsik & Wilson [12] was back at this Conference. Komori OG.1.3 calculated the spectrum of cosmic ray electrons in the Galaxy taking into account the finite time T_s , which particles spend inside a SNR shell before exit to the interstellar medium. The value $T_s \approx 10^4 (E/1\mathrm{GeV})^{-0.2}$ yr at $T_G \propto E^{-0.3}$ (T_G is the cosmic ray leakage time from the Galaxy) and the source spectrum $E^{-2.2}$ were obtained from the fit to the electron spectrum observed at the Earth.

3. Principal sources of galactic cosmic rays, connection to gamma-ray astronomy

Energetically, supernovae with their remnants, which may include neutron stars, are the most probable cosmic ray sources in the Galaxy (Ginzburg & Syrovatskii [13]). About 15% of the kinetic energy of SN ejecta is needed to maintain the observed cosmic ray energy density $w_{cr} \sim 1.5$ eV/cm^3. Such efficiency is in agreement with the prediction of the theory of diffusive shock acceleration. We assume here that the kinetic energy of a SN explosion is 10^{51} erg and the supernova rate in the Galaxy is 1 every 30 years.

The scenario of cosmic ray acceleration implies the acceleration of cosmic rays by the outward propagating shock which results from the supernova explosion and propagates in the interstellar medium or in the wind of progenitor star. After correcting for atomic selection effects, current propagation models yield a composition of accelerated material similar to the solar photosphere and to the local interstellar medium composition. The acceleration process includes the acceleration of ions and grains (Meyer et al. [14]). The relatively high and close-to-the-solar value of the ratio ^{59}Co/^{56}Fe testifies that the major part of originally synthesized ^{59}Ni has decayed by the K-capture of an orbital electron into ^{59}Co before the acceleration started, see Weidenbeck et al. [15]; this test was suggested by Casse & Soutoul [16]. The delay between synthesis of this material and acceleration is larger than 10^5 yr. This result was confirmed at this Conference at higher energies 0.8 – 5 GeV/n by measuring elemental ratio Co/Ni in the long duration balloon experiment TIGER (De Nolfo et al. OG.1.1).

Binns et al OG.1.2 discussed the most prominent isotope anomaly of cosmic ray source material. The ratio ^{22}Ne/^{20}Ne is enhanced by a factor of ~ 5 compared with the solar reference value. It can be explained only by the special conditions of nucleosynthesis. The enhancement of neutron rich isotopes is expected in highly evolved very massive stars in their Wolf-Rayet stage when their surfaces contain large excesses of the products of core helium burning, including ^{22}Ne (Casse & Paul [17]). The popular scenario (Higdon & Lingenfelter [18]) assumes the acceleration of cosmic rays in hot bubbles where 20% of the source material may go from the Wolf-Rayet stars. It is of interest that we might see the accelerated and partly destroyed grains from the population that experienced shock acceleration in a form of GEMS (the Glass with Embedded Metal and Sulfides) embedded in the interplanetary dust particles (Westphal et al. OG.1.2).

The direct evidence of particle acceleration in supernova remnants is given by the observations of nonthermal radio, X-ray, and gamma-ray radiation. The synchrotron radio emission of supernova remnants testifies the presence of electrons with energies 50 MeV - 30 GeV in such supernova remnants as Cas A, IC 433 and Cygnus Loop, see Lozinskaya [19]. In the case of Cas A, this synchrotron emission was detected in the infrared waveband that proves the presence of electrons with energies about 2×10^{11} eV. The detection of non-thermal X-rays radiation from supernova remnants SN1006 (Koyama et al. [20]), Cas A, RXJ 1713.7-3946, RCW 86, G266.2-1.2 and some other is considered as evidence of the synchrotron emission of electrons with much higher energies up to 10^{14} eV. The inverse Compton scattering of background photons by these electrons and the production of gamma-rays generated by protons and nuclei with energies up to 10^{14} eV/n via pi-zero channel are the mechanisms of the emission of TeV gamma rays detected from about 8 SNRs, see invited talk by Hofmann at this Conference. In two most remarkable cases of shell supernova remnants RX J1713.7-3946 (Berege et al. OG.2.2) and SNR RX J0852.0-4622/Vela Jr. (Komin et al. OG.2.2), the H.E.S.S. telescopes provided TeV gamma-ray images with detailed angular resolution.

The acceleration of charged particles is an integral part of the plasma processes in many astronomical objects. The rotation energy of a young pulsar is $2\times10^{50}(10\text{ ms}/\tau)^2$ erg, where τ is the rotation period. It comprises 20% of the supernova kinetic energy and may provide a significant energy reservoir for cosmic ray acceleration in the Galaxy. The particle acceleration may go at the shock which terminates the ultrarelativistic electron-positron wind coming from the pulsar. The H.E.S.S. detection of TeV gamma ray fluxes from a few pulsar wind nebulae testifies the presence of PeV electrons and the production of gamma rays through the inverse Compton scattering mechanism (Khelili et al. OG.2.2). The hadronic component probably exists in the pulsar magnetosphere and may be accelerated in parallel with leptons. The analysis of particle acceleration in pulsars was presented by Bhadra OG.1.2. He showed that the Vela pulsar and the Geminga pulsar may contribute about 1% of the observed cosmic ray flux below the knee. Wolfendale & Erlykin OG.1.2 argued that the pulsars like Vela may be the main sources of observed cosmic ray electrons.

Other potential accelerators are stellar winds that release about 10% of kinetic energy in the interstellar medium as compared to the supernova explosions, and the Galactic GRB events with the release of 10^{51} erg in one burst every 10^5 yr that on average amounts to about 10^{-3} of the supernova energetics. The TeV emission was detected by H.E.S.S from the microquasar LS 5039 (de Naurious et al. OG.2.2) but the total contribution of microquasars to the cosmic ray flux is probably small. Kantharia et al. OG.1.4 analyzed cosmic ray acceleration in the nova remnant GK Persei. The total contribution of such objects to galactic cosmic rays is estimated as 10^{-4} of the supernova contribution. A significant contribution of flares on yellow and red dwarfs to the observed cosmic ray density was claimed by Kopysov & Stozhkov OG.1.2.

4. Random nature of sources (SNRs), local galactic cosmic rays

The supernovae explosions that give rise to the galactic cosmic rays are essentially statistical events, discrete in space and time. This poses the question as to whether the fluctuations of cosmic ray density and anisotropy are significant (Jones [21], Lee [22]). The random nature of cosmic ray sources attracted increased interest in the Conference papers. This interest was stimulated by two major aspects of this problem. First, the diffuse Galactic gamma ray spectrum at energies above 300 MeV measured in EGRET experiment is too flat to be generated by cosmic rays with energy spectrum observed at the Earth; see Hunter et al. [23], Strong et al. [24]. The variations of cosmic ray spectrum over the Galaxy could in principle solve this puzzle (Pohl & Esposito [25]. Second, as more accurate data on cosmic ray spectrum at very high energies become available, one expects to see effects of fluctuations that are due to relatively short confinement time of these particles in the Galaxy. In particular, Erlykin & Wolfendale ([26], OG.1.2) argued that there is a fine structure in the spectrum at the knee that indicates the contribution of cosmic ray flux from a single nearby supernova.

The analytical calculations of a "typical" fluctuations of cosmic ray density in the model with random SN bursts lead to the estimate $\delta N/N \sim \left(D/\sigma_{SN}\right)^{1/4} H^{-1}$ for the amplitude of fluctuations, where σ_{SN} is the surface supernova rate in the galactic disk (Ptuskin et al. OG.1.3). It gives the fluctuations at the level 3% to 6% at the knee energy. The actual deviation of cosmic ray density from its average value for an observer at a given location in the Galaxy critically depends on distances to nearby supernova remnants and their ages. A young nearby SNR may produce the fluctuation which is much larger than the "typical" one.

The numerical simulations by Jones & Streitmatter OG.1.3 are in good agreement with the analytical results. They found that the fluctuations of cosmic ray intensity about average value are rising with energy and are becoming significant at the knee. Developing her earlier scenario of cosmic ray acceleration in SNRs (Sveshnikova [27]) where the dispersion of SN properties was taken into account, Sveshnikova OG.1.2 discussed the expected irregularities of the cosmic ray spectrum that is shaped by only a small number of SNRs at energies close to the knee. The distribution $F(E_{\max}) \sim E_{\max}^{-1.15}$ of the maximum energy of accelerated particles was assumed in this work. The source spectrum below E_{max} was $q \sim E^{-2.15}$, and the diffusion coefficient scaled as $D \sim E^{0.3}$. The strong effects of sporadic SN bursts were announced by Erlykin & Wolfendale OG.1.2. They suggested that the hypothetical giant galactic halo that magnetically keeps cosmic ray particles would wash out the irregularity of the cosmic ray spectrum caused by discrete explosions.

Assuming random distribution of SN bursts, Büsching et al. OG.1.3 numerically studied possible temporal variations of primary (^{12}C) and secondary (^{11}B) nuclei at energy 10 GeV/n for an observer at the Sun location in the Galaxy. The density of primaries exhibits characteristic spikes which reflect the emission of cosmic rays after close SN events. At the same time, the density of secondary nuclei demonstrates only a very small variation that is in agreement with the analytical theory, see Berezinskii et al. [28]. Thus the data on secondaries at the Sun are representative of the whole Galaxy that in principle can not be said about primaries.

The account of sporadic nature of cosmic ray sources is essential to the interpretation of data on cosmic ray anisotropy. The observed galactic cosmic rays are highly isotropic. The amplitude of anisotropy in the interstellar medium is about 10^{-3} at energies 10^{12} to 10^{14} eV. The data of Super-Kamiokande-I detector reported at the Conference (Guillian et al. HE1.1) allowed creating the first accurate 2-dimesional mapping of cosmic ray anisotropy at 10^{13} eV (see also the paper Amenomori et al. SH.3.2 by the Tibet collaboration). Such a map is much more informative than the traditional presentation of anisotropy map projected onto the right ascension axis. The calculation of cosmic ray anisotropy should include effects of the global leakage of cosmic rays from the Galaxy and the contribution of prominent local sources. The diffusion from nearby SNRs may in principle explain the non-monotonous dependence of observed anisotropy on energy. The results presented by Ptuskin et al. OG.1.2 showed that the global leakage and the individual close SNRs are almost equally important for the interpretation of anisotropy data (see also Sveshnikova OG.1.2). The SNR Vela probably determines the observed anisotropy at energies below 10^{13} eV. The rise of cosmic ray diffusion coefficient with energy can not be stronger than $E^{0.3}$ to be compatible with the measurements of cosmic ray anisotropy up to 10^{17} eV.

The usual assumption of free diffusion of energetic particles through the Galaxy with constant or only weakly dependent on position diffusion coefficient was challenged by Streitmatter & Jones OG.1.2. They developed early ideas of Streitmatter et al. [29] and assumed that the cosmic rays that we observe below the knee are produced and well confined inside the superbubble of hot low density gas around the Sun. Only ultra high energy cosmic rays can penetrate from the exterior region to our cavity. The new interpretation of the knee and the low anisotropy is suggested in this model but the basic assumption on the existence of very efficient magnetic barrier that separates two reservoirs of cosmic rays requires a comprehensive physical justification.

Another dramatic modification of the standard picture of cosmic ray transport in the interstellar magnetic fields was considered by Lagutin et al. [30], Lagutin et al. OG.1.3. With the reference to the fractal structure of interstellar gas and magnetic field, they described the cosmic ray transport as anomalous diffusion or the fractal random walks when particles experience Levy flights (the long jumps) and the random localizations (the long rests in magnetic traps). The spatial dispersion of moving particles increases with time faster than in the usual diffusion process and is characterized by the relation $r \sim t^{8/3}$. The derived cosmic ray source spectrum $E^{-2.85}$ is unusually steep.

5. Shock acceleration

The diffusive shock acceleration by supernova blast waves is commonly accepted process of cosmic ray acceleration in the Galaxy; see Drury et al. [31], Malkov & Drury [32] for review. The acceleration of a fast particle diffusing near the shock front is a version of Fermi type acceleration. Fast particles are scattered on the inhomogeneities of magnetic field frozen into the background plasma and gain energy at the shock where plasma is compressed. The condition of acceleration at the spherical shock $u_{sh}R_{sh}/D > 10$, where u_{sh} and R_{sh} are the shock velocity and the shock radius, is not fulfilled for relativistic particles at the standard value of the interstellar diffusion coefficient. The diffusion should be anomalously slow near the shock, both in the upstream and the downstream regions. It can be provided by the cosmic ray streaming instability in the shock precursor. Thus the entire pattern of cosmic ray acceleration at supernova shocks critically depends on the assumption that the energetic particles themselves produce the needed turbulence at the site of acceleration. As a result, the diffusion coefficient may fall down to the Bohm value $D_B = vr_g/3$ calculated at the interstellar value of magnetic field, where r_g is the Larmor radius of accelerating particles. The maximum energy of accelerated particles reaches then approximately 10^{14} Z eV at the beginning of the Sedov stage of SNR evolution (here Z is the particle charge). The assumption about Bohm value of the diffusion coefficient in the vicinity of strong shocks was commonly used in the simulations of cosmic ray acceleration in supernova remnants, e.g. Berezhko et al. [33].

The recent numerical simulations of streaming instability for very strong shocks showed that the excited random field may considerably exceed the average upstream magnetic field (Bell & Lucek [34], Bell [35]) that leads to the abandonment of the standard Bohm limit hypotheses. Under the extreme condition $u_{sh} \sim 0.1c$, the random magnetic field is $\sim 10^3$ μG and the maximum energy of accelerated particles reaches $\sim 10^{17}Z$ eV. However, the amount of particles involved in the process of acceleration at highest energies is small and the calculated overall particle spectrum injected into interstellar medium during the life of a SNR has a sharp break at $\sim 4\times10^{15}Z$ eV (Ptuskin & Zirakashvili [36]). These results suggest that the knee may mark the transition from the ejecta-dominated to the adiabatic evolution of SNR shocks which accelerate cosmic rays. The data on the composition and energy spectra of elemental groups around the knee obtained in the KASCADE experiment (Ulrich et al. HE.1.2) are, in general, consistent with this theoretical concept. The comprehensive study of cosmic ray streaming instability in young SNRs was undertaken by Marcowith et al. OG.1.4. They analyzed strong resonant and non-resonant instabilities produced by accelerating cosmic rays and took into account the non-linear interactions of waves in the generated anisotropic MHD turbulence. The spatial evolution of this turbulence was determined and it was shown that the development of instability critically depends on the Alfvenic Mach number of the shock.

The evidence of strong amplification of magnetic field in Tycho's SNR and in other young shell-type SNRs was discussed by Völk et al. OG.1.4. The shock profile observed in these objects in the synchrotron X-ray emission at several keV can be explained by the energy losses of very high energy electrons which produce this radiation. The calculated magnetic field downstream of the shock is about $B \sim \rho^{1/2} u_{sh} \sim 300$ μG in the case of Tycho's SNR (ρ is the gas density upstream of the shock), and it has similar strength in other SNRs with large enough shock speed $u_{sh} > 10^3$ km/s: Cas A, SN 1006, RCW 86, Kepler, RX J1713.7-3946, and Vela Jr. It is indirect but strong evidence of the proton - nucleus acceleration by the SNR shocks because this acceleration is accompanied by the streaming instability which generates strong turbulent magnetic field in the upstream and downstream regions. It is remarkable that according to Berezhko & Völk OG.2.2 the interpretation of radio data and in particular the brightness-diameter relation for shell SNRs requires similar amplification of magnetic field with scaling $B \sim \rho^{1/2} u_{sh}$. In principle, the random field downstream the shock can decay because of the strong nonlinear wave damping that changes the profile of the synchrotron emission (Pohl et al. [37], Zirakashvili & Ptuskin OG.2.2). The detailed consideration of the magnetic field distribution in SNR shells (Ellison & Cassam-Chenaï OG.2.2) should probably include this effect.

The injection of thermal particles in the process of shock acceleration in collisionless space plasma is important and unsolved theoretical problem. The consistency of the description of particle injection in the semi-analytical model of nonlinear shock acceleration suggested by Blasi [38] and the Monte Carlo model developed by Ellison et al. [39] was demonstrated in the work of Ellison et al. OG.1.4.

The process of injection and the rate of acceleration depend on the orientation of the shock relative the direction of average external magnetic field. The non-parallel to external magnetic field shocks provide faster acceleration but higher injection threshold, Jokipii [40], Ellison et al. [41]. In the Conference paper Giacalone & Jokipii OG.1.4 showed that the presence of a large scale random magnetic field can considerably lighten the injection of thermal particles. On the other hand, the SN explosion in an extended wind of a rotating progenitor star with a tight spiral magnetic field gives higher maximum energy of accelerated particles than the SN explosion in the uniform external field (Meli et al. OG.1.4) because of favorable orientation of the shock. The analogous problem for super-luminal shocks in application to the Active Galactic Nuclei hot spots and the Gamma Ray Burst sites was considered by Meli et al. OG.1.4.

The considerable density of energetic particles in the vicinity of high Mach number shock causes the modification of gas flow through the action of energetic particle pressure. The change of the flow by cosmic ray pressure leads to the deviation of the spectrum of accelerated particles from the simple power-law form derived in a test particle approximation. The full-scale plasma simulations of the shock acceleration with the account of shock modification and the inclusion of plasma microphysics are enormously time consuming. Because of this the alternative approach which includes the simultaneous numerical solution of the diffusion-convection equation for cosmic ray distribution function on momentum and the hydrodynamical equations for compressible fluid is employed. Many important results on cosmic ray acceleration were obtained with such kind of code developed by Berezhko et al. [33] where the varying spatial grid in tune with the ratio $D(E)/u(r)$ was used. Another code of this type with the highest resolution at the subshock region was worked out by Kang et al. [42]. The new scheme was suggested at the Conference by Jones & Kang OG.1.4. It includes the compressible MHD equations and does not employ the usual finite differences method. The equations for waves can be incorporated into the code. The test calculations of cosmic ray reacceleration by the spherical SNR shock were demonstrated at the Conference.

The largest shock, which one can suggest for cosmic ray acceleration in the Galaxy, is the hypothetical galactic wind termination shock of a few hundred kpc radius (Jokipii & Morfill [43]). Zirakashvili et al. OG.1.4 considered this problem again and developed a selfconsistent model where the cosmic ray pressure was essential for sustaining the wind flow, and the cosmic ray streaming instability determined the level of MHD turbulence and consequently the value of the diffusion coefficient $D(r,E)$. The accelerated particles had a very flat spectrum $\sim E^{-1}$ with a cutoff at $\sim 10^{16}Z$ eV inside the galactic wind cavity.

Even larger shocks can be found beyond the Galaxy. Using the X-ray and the radio images of the galaxy cluster Abell 3376, Bagchi et al. OG.1.4 discussed particle acceleration that may give the maximum proton energy $\sim 3\times10^{19}$ eV limited by the process of pion photoproduction on the microwave background photons.

The old problem (Ginzburg & Ozernoi [44]) of possible HI reionization of the intergalactic medium by cosmic rays at redshifts $z > 2$ was studied by Samui et al. HE.2.3. It was found that cosmic rays accelerated in supernovae and in star forming galaxies were essential for the thermal history of intergalactic medium in the ΛCDM model. The cosmic rays can explain the observed temperature $\sim 10^4$K at $z = 2 - 4$. The derived ratio of energy densities in the intergalactic medium and in the Galaxy is 1.5×10^{-4} to 6×10^{-3} at the present epoch.

6. Acceleration limit for Galactic sources, transition to extragalactic cosmic rays

The overall spectrum of high energy cosmic rays is well described by a power law with two pronounced features: the steepening (the knee) at 3×10^{15} eV, and the flattening (the ankle) at about 5×10^{18} eV, see Figure 1 taken from the work of Hillas [45]. The knee can be an inherent characteristic of the

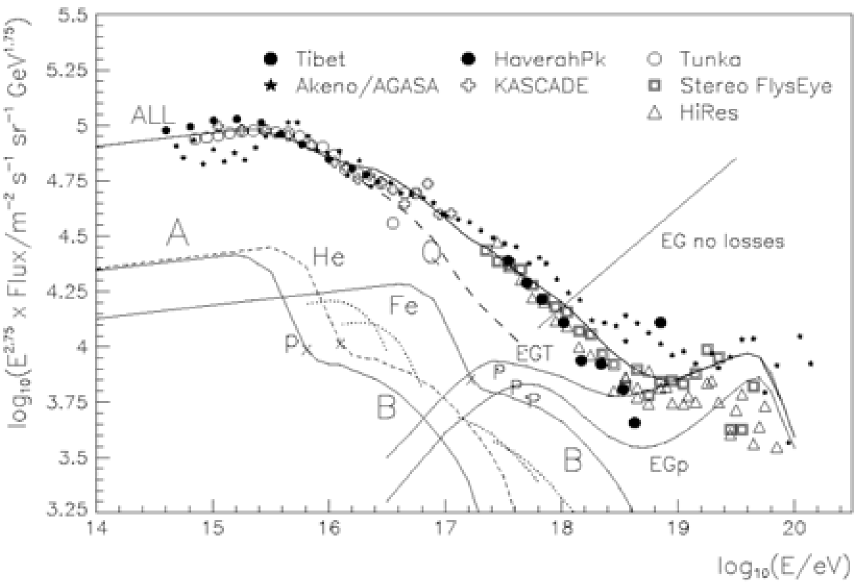

Figure 1. The cosmic ray spectrum as the sum of galactic H, He, CNO, Ne-S and Fe components with the same rigidity dependence, and extragalactic H + He (total EGT) having a spectrum $\sim E^{-2.3}$ before suffering losses by CMBR and starlight interactions. The galactic components were given a turn-down shape based on KASCADE knee shape as far as the point marked x. The dashed line Q is the total if the extended tail B of the galactic flux is omitted (Hillas [45]).

acceleration by an evolving SNR shock as it was discussed in Section 5. The ankle feature can be understood as the transition to extragalactic cosmic rays when the falling with energy flux produced by Galactic sources gives way to the hard extragalactic component, see also the caption to Figure 1 for detail. It is interesting to note that both Galactic and extragalactic source spectra have the same power law form $E^{-2.3}$. An additional argument in favor of extragalactic origin of the highest energy cosmic rays is their high isotropy. The most probable sources of extragalactic cosmic rays are the Active Galactic Nuclei and the Gamma Ray Burst events. Also, the top-down mechanism with the decays of hypothetical relic X particles with masses $m_X > 10^{20}$ eV can not be excluded as the source of events above 10^{20} eV, see Bhattachrjee HE.2.3.

There is an obvious problem with the interpretation of Galactic part of cosmic ray spectrum illustrated in Figure 1. To fit the overall spectrum at energies from about 3×10^{16} eV to 3×10^{18} eV, some supplementary component B is needed in addition to the main Galactic component A. The component A is presumably comprised of the protons, helium and other nuclei accelerated in SNRs. In principle, the component B can be caused by rare extremely energetic SN events (the hypernova, the GRBs) (Sveshnikova [27]) or by the cosmic ray acceleration at the Galactic wind termination shock (Zirakashvili et al. OG.1.4).

There is no need for the component B in the model developed by Berezinsky et al. OG.1.3, Berezinsky et al. [46]. The authors challenged the standard interpretation of the ankle and agued that the Galactic component merges with the extragalactic component at relatively low energy ~ 5×10^{17} eV. They worked with steep extragalactic source spectrum ~ $E^{-2.7}$ and discovered that the observed cosmic ray spectrum at 10^{18} to 4×10^{19} eV with its characteristic "dip" can be explained as the spectrum of extragalactic protons. These particles experience interactions with the microwave background and lose energy chiefly on the e^+e^- pair production. The source spectrum $E^{-2.7}$ coincides with the spectrum of particles accelerated by the pinch mechanism considered by Trubnikov et al., see Petrukhin OG.1.2. The suggested interpretation may be somewhat altered if the source material has a fraction of nuclei larger than 10 – 20 %, the cosmological evolution of cosmic ray sources is significant (De Marco & Stanev [47]), and the energy losses on infrared background are essential at ~ 10^{19} eV (Bugaev et al. HE.2.1).

Allard et al. OG.1.3 presented their calculations of cosmic ray transport in the intergalactic space based on the revised photonuclear cross sections (Khan et al. [48]). Two scenarios described above for the extragalactic cosmic rays at ultra high energies were examined in detail. The first scenario assumes the source spectrum $E^{-2.2}$ – $E^{-2.3}$ and the "standard" source composition similar to the Galactic sources at ~ 1 GeV. The second scenario assumes the source spectrum $E^{-2.6}$ and should reproduce the dip at 10^{18} – 3×10^{19} eV. The last condition requires the light composition with the proton fraction exceeding 85 %. The alternative scenarios predict very distinct elemental compositions of ultra high energy cosmic rays and it gives the key to selecting between them when the reliable data on cosmic ray composition will become available.

7. Conclusions

We shortly described the results on cosmic ray propagation and acceleration reported at the Sessions OG.1.2, OG.1.3, and OG.1.4. The Conference papers were discussed in line with the current status of research on the problem of cosmic ray origin.

New numerical codes presented at the Conference offered more thorough description of cosmic ray transport in the Galaxy. However the oversimplified assumptions about cosmic ray transport coefficients are still used in these codes and in many cases the independent on position diffusion is assumed. The serious check of the diffusion model will be possible when the planned GLAST space experiment will give accurate data on Galactic gamma-ray emission.

The attention to the random nature of cosmic ray sources and to the local conditions of cosmic ray propagation was evident in the Conference papers. The low observed anisotropy imposes severe restrictions on cosmic ray diffusion coefficient and the parameters of nearby cosmic ray sources.

The impressive results of TeV gamma-ray astronomy reported at the Conference and first of all the observations of supernova remnants and the pulsar wind nebulae by the H.E.S.S. instrument are of paramount importance for studies of cosmic ray accelerations. New theoretical results can be expected now.

In the absence of statistically warranted data on cosmic rays over the region of the GZK cutoff and under the influence of the KASCADE experimental results, the theorists devoted more attention to the interpretation of cosmic ray spectrum at 10^{17} to 10^{19} eV and to the problem of transition from Galactic to extragalactic component in cosmic rays.

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