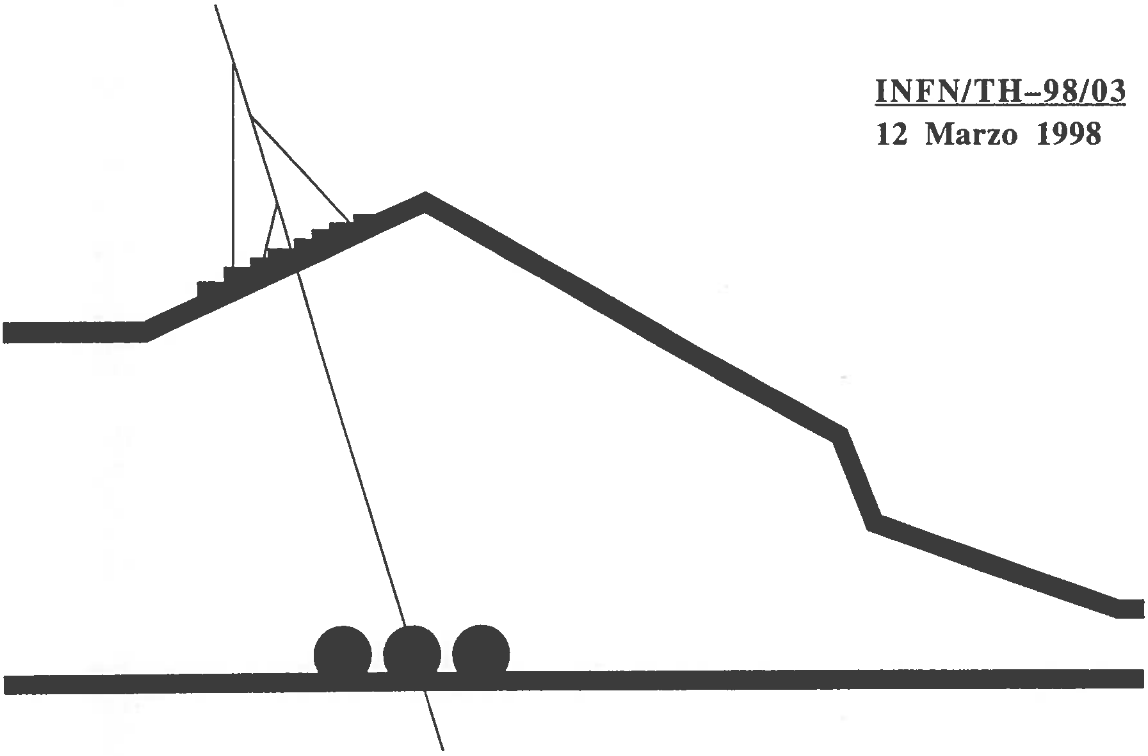
INFN/TH-98/03
12 Marzo 1998



Ultra High Energy Cosmic Rays

V. Berezinsky

Review given at the 5th International Workshop TAUP 97

INFN – Laboratori Nazionali del Gran Sasso

Published by ***SIS–Pubblicazioni***
Laboratori Nazionali di Frascati

INFN – Istituto Nazionale di Fisica Nucelare
Laboratori Nazionali del Gran Sasso

INFN/TH–98/03
12 Marzo 1998

Ultra High Energy Cosmic Rays

V. Berezinsky[a]

[a]INFN, Laboratori Nazionali del Gran Sasso, I–67010 Assergi (AQ), Italy and Institute for Nuclear Research, Moscow, Russia

The current status of Ultra High Energy Cosmic Rays (UHECR) is reviewed, with emphasis given to theoretical interpretation of the observed events. The galactic and extragalactic origin, in case of astrophysical sources of UHE particles, have the problems either with acceleration to the observed energies or with the fluxes and spectra. Topological defects can naturally produce particles with energies as observed and much higher, but in most cases fail to produce the observed fluxes. Cosmic necklaces and monopole-antimonopole pairs are identified as most plausible sources, which can provide the observed flux and spectrum. The relic superheavy particles are shown to be clustering in the Galactic halo, producing UHECR without Greisen-Zatsepin-Kuzmin cutoff. The Lightest Supersymmetric Particles are discussed as UHE carriers in the Universe.

1. Introduction

Cosmic rays (CR) are observed in a wide energy range, starting from subGeV energies and up to $3 \cdot 10^{20}$ eV (see Fig.1). Apart from the highest energies, these particles are accelerated in our Galaxy, most probably by shocks produced by SN II explosions. Up to energy $10^{15} - 10^{16}$ eV the CR flux is dominated by protons, at higher energies CR have the mixed composition, and there are indications that at energies about $\sim 10^{17}$ eV iron nuclei dominate in the CR flux. In a wide range of energies from 1 GeV up the $3 \cdot 10^{15}$ eV the spectrum is power-law $\sim E^{-2.65}$, at energy $3 \cdot 10^{15}$ eV the spectrum steepens and becomes $\sim E^{-3.1}$ at $E > 10^{17}$ eV. At $E \geq 10^{19}$ eV a new more flat component appears (see Fig.1). The highest energies detected so far are $2-3 \cdot 10^{20}$ eV.

The first steepening of the spectrum (the knee) at energy $3 \cdot 10^{15}$ $eV - 1 \cdot 10^{16}$ eV is usually explained by inefficient confinement of CR in the Galaxy. This process must be accompanied by enrichment of heavy nuclei in CR composition at energy $\sim 10^{15}$ eV and above. There are some indications that such enrichment is really observed.

There is no universal definition for Ultra High Energy Cosmic Rays (UHECR). Sometimes this term is applied for $E > 1 \cdot 10^{17}$ eV or $E > 1 \cdot 10^{18}$ eV. I shall use this term for $E > 1 \cdot 10^{19}$ eV, where the new flat component appears.

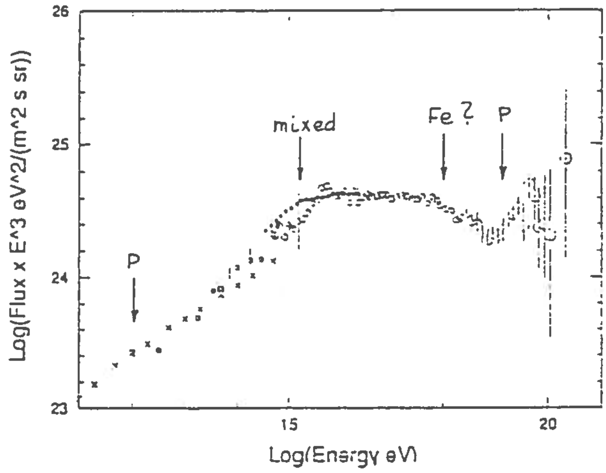


Fig1. Compilation of cosmic ray spectrum from [1]. Spectrum of UHECR is taken according to AGASA data only, because the spectrum *shape* is better seen from the data of one array.

It is natural to think that this component has extragalactic origin, though, in principle, very large halo with regular magnetic field can confine particles of these energies, especially if they are heavy nuclei. UHECR of extragalactic origin have a signature called the Greisen-Zatsepin-Kuzmin (GZK) cutoff [2]. This phenomenon is caused by energy losses of UHE protons due to pion production in collisions with microwave photons. The energy losses start sharply increasing at $E \sim 3 \cdot 10^{19}\ eV$ (Fig.2). This energy is connected with energy of the spectrum steepening ("cutoff") in the model-dependent way. In case the sources are distributed uniformly in the Universe (standard assumption), the steepening starts at $E_{bb} \approx 3 \cdot 10^{19}\ eV$. The flux at $E > E_{bb}$ is produced by nearby sources. If there is a local enhancement of the sources, E_{bb} increases [3];in case the sources are located at large distances, E_{bb} decreases and steepening is exponential. It is more convenient to characterize steepening by energy $E_{1/2}$ [3], where the flux becomes half of the power-law extrapolation of unmodified flux. In case of uniform distribution of the sources $E_{1/2} \approx 5.8 \cdot 10^{19}\ eV$ [3] for a wide range of exponents γ of generation spectrum.

Apart from GZK cutoff, there may be two more signatures of extragalactic cosmic rays: a bump and a dip in differential spectrum which precede the cutoff [4,5]. The bump is a consequence of a number conservation of protons in the spectrum: protons loose energy and are accumulated before the cutoff. The dip is formed due to pair-production (e^+e^-) energy losses of UHE proton. The both features show up most clearly in the differential spectrum of a single distant source in the case of a flat generation spectrum. In diffuse spectra (from many sources) these features are weak or absent.

UHE nuclei spectra exhibit steepening ("cutoff") approximately at the same energy as protons, though due to different physical processes (see [3] for a review). The relevant energy losses are caused by photodisintegration of nuclei at collisions with microwave photons, and the steepening energy is determined by energy, when photodisintegration energy-losses start to dominate over adiabatic ones (Fig.2.).

UHE photons with $E_\gamma \sim 10^{19} - 10^{22}\ eV$ have an absorption length less than 10 Mpc, mainly due to interaction with radio-background [6,7].

The observation of cosmic ray particles with energies higher than $10^{20}\ eV$ gives a serious challenge to our understanding of origin of UHECR: What are the mechanisms of acceleration? Why the GZK cutoff is absent?

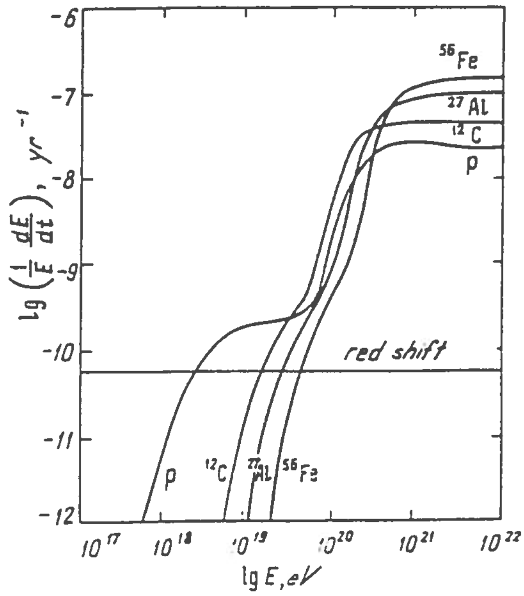


Fig.2. Energy losses of UHE protons and nuclei [3]

2. Observational data

The compilation [8] of observational data for UHECR is given in Fig.3. Two highest energy events correspond to energies $3 \cdot 10^{20}\ eV$ (the Fly's Eye event [9]) and $2 \cdot 10^{20}\ eV$ (the AGASA event [10]). These energies are well above the GZK cutoff for uniformly distributed extragalactic sources. The particles with energies above $10^{20}\ eV$ were observed in the past at the Haverah Park array [11] and Sydney array [12]. The latter detector has observed eight showers with $E > 1 \cdot 10^{20}\ eV$. It operated from 1968 up to 1979 and had large area, 87 km^2. The scintillator detectors were at 2m underground and hence only muon component of showers was measured. It is interesting to re-analyze the data using the new simulations for muon distribution [13].

One shower with $E \approx 1.2 \cdot 10^{20}\ eV$ was observed at the Yakutsk array [14,15], though eight showers were expected if the Haverah Park data are correct.

Anisotropy of UHECR is not reliably observed. Some analyses (e.g. [11] and [16]) indicate the excess of particles from Local Supercluster (LS) plane, while observations by AGASA [17] are consistent with a uniform distribution. On other hand AGASA has observed[17] clustering of UHE events: three pairs of showers with angular separation less than 2.5° (for analysis see [18]).

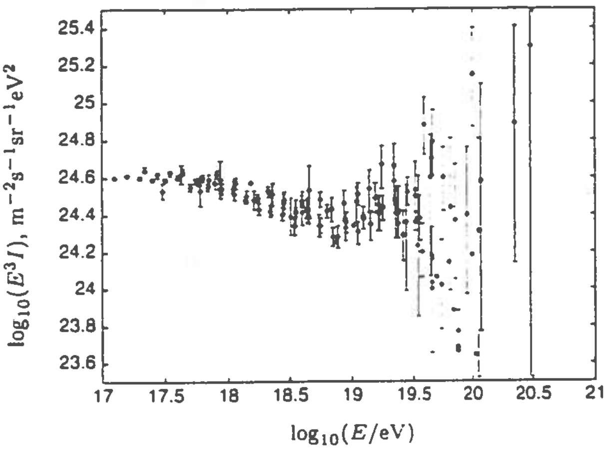


Fig.3. UHE energy spectra from different arrays, normalized at $E = 1 \cdot 10^{18}\ eV$ [1]

Chemical composition as found from analysis of the Fly's Eye data [19] is characterized by a change from predominantly heavy nuclei (iron) to the light nuclei at $E \sim 3 \cdot 10^{17}\ eV$. The fraction of protons increases with energy and reaches 90% at $10^{19}\ eV$ [19]. The change of the chemical composition at $E \sim 3 \cdot 10^{17}\ eV$ was not found in the muon data in AGASA experiment [20]. The data of Yakutsk array [21] also favors the proton composition at the highest energies.

3. Galactic origin of UHECR

There are two difficulties in an attempt to explain the observed events by sources in the Galaxy: the maximum acceleration energy is considerably less than $3 \cdot 10^{20}\ eV$ and galactic magnetic fields are too weak to isotropize UHE particles.

Acceleration to very high energies in the Galaxy can occur at the SN shocks, at galactic wind terminal shock and in young pulsars.

The maximum energy for acceleration by shocks in the interstellar medium does not exceed $10^{16}\ eV$ [22]. It can be higher when the SN shock propagates through the region of pre-supernova stellar wind with strong magnetic field [23], though the maximum energy is still less than $3 \cdot 10^{18}\ eV$ [24]. The galactic wind is expected to be terminated by a standing shock, where, in case of extreme values of parameters used in ref.([25]), particles can be accelerated up to energies $E \sim 10^{20}\ eV$ for iron nuclei. Most probably this energy is an order of magnitude less (see [3] and references therein).

Another potential source of acceleration is young pulsar: in this case the maximum energy can in principle reach $10^{19}\ eV$ [3]. However, in the concrete models of pulsar magnetosphere the maximum energy is less.

Propagation of UHECR in galactic magnetic fields was studied numerically in many works [26–29]. The crucial element of this analysis is presence of regular magnetic field in galactic halo. All workers agree that at the highest observed energies there must be very strong disc anisotropy, which obviously contradicts observations.

We shall describe here the results of calculations of ref.([27].

Magnetic field is taken according to the model of ref.([30]). Several versions of the halo field is considered. The size of the halo is varied, but generically the large size of the halo from 10 to 30 kpc is used. The sources of UHECR are assumed to be distributed uniformly in the disc. The trajectories of the antinuclei with rigidity $R = E/Z$, where Z is a charge of a nucleus, were followed step by step in the magnetic fields of the disc and halo. The flux in a given direction is proportional to the length of trajectory *in the disc*. An example of trajectories with rigidity $3 \cdot 10^{18}\ V$ is shown in Fig.4.The particles are emitted from the Earth in the different directions in Galactic plane $z = 0$, where z is the height over galactic plane. One can see that at energy $E \sim 3 \cdot 10^{18}\ eV$ protons propagate almost rectilinearly in the disc, producing thus strong disc anisotropy. In Fig.5 the lifetimes of the particles in the disc, T_d, and calculated anisotropy, A, are shown as a function of rigidity E/Z for two sizes of the halo. Since the flux is proportional to T_d, one concludes from Fig.5 that at $E > 3 \cdot 10^{18} Z\ eV$ the particles typically do not return from the halo to disc. This conclusion is confirmed by the lower part of Fig.5, which shows large (disc) anisotropy at energies $E > 3 \cdot 10^{18} Z\ eV$. Note, that these calculations are performed for extreme case of very large magnetic halo.

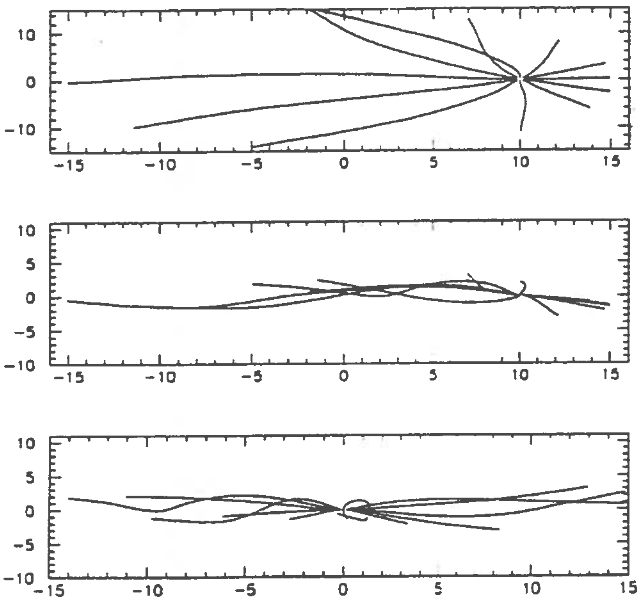


Fig.4. Trajectories of antinuclei with rigidity $E/Z = 3 \cdot 10^{18}\ eV$ emitted in the different directions in the Galactic plane ($z = 0$). The upper figure gives projection of the trajectories on the galactic plane (x, y); two lower figures - projections on the planes (z, x) and (z, y) , perpendicular to the Galactic plane. The distances are in kpc.

Relativistic dust grains of galactic origin can be the carriers of UHE signal [31]. The Lorentz factor of a dust grain should be large enough $\Gamma > 10^3$ to produce a nuclear-electromagnetic shower with muon component as observed in e.g. Sydney or AGASA arrays. Approaching the sun such a grain accumulates the electric charge due to photoeffect produced by solar optical radiation (in the rest frame of a dust grain this is X-ray radiation). As a result a grain breaks up due to electric repulsion [32]. The dust grain hypothesis is also in contradiction with observed properties of UHE showers (J.Linsley).

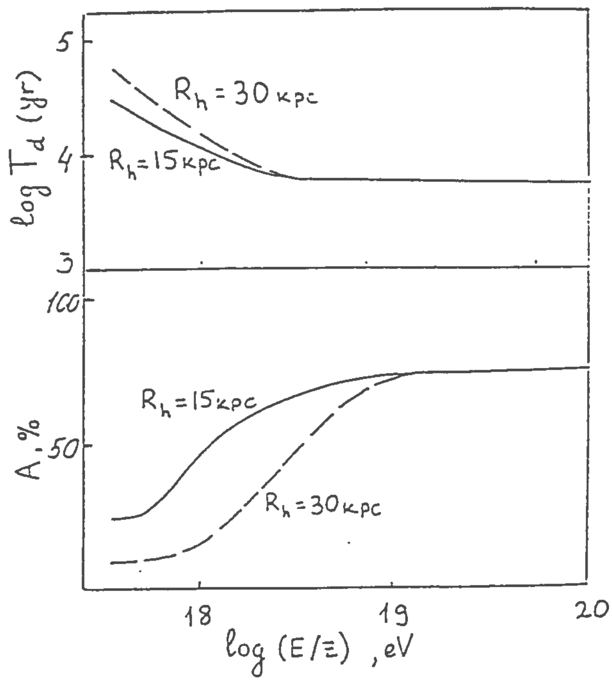


Fig.5. Lifetime T_d of particles in the Galactic disc (upper figure) and anisotropy A (lower figure), as functions of rigidity.

4. Extragalactic acceleration sources

Shock acceleration (including ultra-relativistic shocks) and unipolar induction are the "standard" acceleration mechanisms to UHE, considered in the literature. These mechanisms can operate in the various astrophysical objects, such as Active Galactic Nuclei (AGN), large scale structures (e.g. the shocks in AGN jets or shocks in the clusters of galaxies), in gamma-ray bursters (ultra-relativistic shocks), in the accretion discs around massive black holes (due to large electric potentials produced by unipolar induction) etc. A comprehensive list of possible sources was recently thoroughly studied in ref.([34]) with a conclusion, that maximum energy of acceleration does not exceed $10^{19} - 10^{20}\ eV$. The most promising source from this list is a hot spot in radio-galaxy produced by a jet [35-37].

A powerful jet ejected from the AGN supplies energy to a gigantic radiolobe. A hot spot observed at the termination of the jet is interpreted as a location of a standing shock. This is an ideal place for acceleration of protons to very high energies: magnetic field is strong and the energy density of radiation, responsible for proton energy losses, is relatively small. The maximum energy can be estimated as [35]

$$E_{max} = 1 \cdot 10^{20} H_{-4}(R/1\ kpc) v_j\ eV, \qquad (1)$$

where H_{-4} is the magnetic field in units of 10^{-4} G, R is radius of the shock and v_j is velocity of the jet in units of sound speed. However, the powerful radio sources are at large distances from our Galaxy, and the maximum energy is strongly attenuated. The discussed sources can provide the observed flux up to energies $6 - 7 \cdot 10^{19}$ eV.

Unipolar induction produces very large potential drop in the accretion discs around massive black holes (see ref.([38,39] and also [3] for a discussion). The electrical potential for a rotating disc, at the distance r from a black hole is

$$\phi(r) = \frac{1}{\sqrt{6}} H_c r_c \ln R/r, \qquad (2)$$

where $r_c = 9 \cdot 10^5 (M_h/M_\odot)$ is the radius of the last stable orbit for a black hole with mass M_h, H_c is magnetic field at the last stable orbit, and R is a radius of accretion disc. The maximum potential given by Eq.(2) is $\phi_c \sim 3 \cdot 10^{21}$ V for $M_h \sim 1 \cdot 10^9 M_\odot$ and $H_c \sim 1 \cdot 10^4$ G. This mechanism is attractive because it can operate not only in AGN, but also for the old black holes, which lost their activity ($\dot{M}$ in the disc is small). Such sources can be located nearby, e.g. in the Local Supercluster, from where UHE protons can reach us without appreciable energy losses.

Relativistic shocks can in principle provide very high maximum energy . A particle reflecting from a relativistically moving mirror increases its energy by a factor proportional to Γ^2, where Γ is a Lorentz factor of the mirror. This acceleration phenomenon is known from the time of the pioneering work by E.Fermi [40]. The less known phenomenon is capturing of accelerated particles behind relativistically moving shock front. One can easily reconstruct this principle considering head-on collision of a particle with a transverse relativistic shock (magnetic field is perpendicular to the shock normal). Let us assume that magnetic field behind the shock is homogeneous on the scale of the particle Larmor radius. Then at the moment a particle finishes semi-circle, the shock front run away to a distance $cT_L/2$ from a particle, where T_L is the Larmor period. The confinement described above can be illustrated by numerical simulation in ref.([41]) shown in Fig.6.

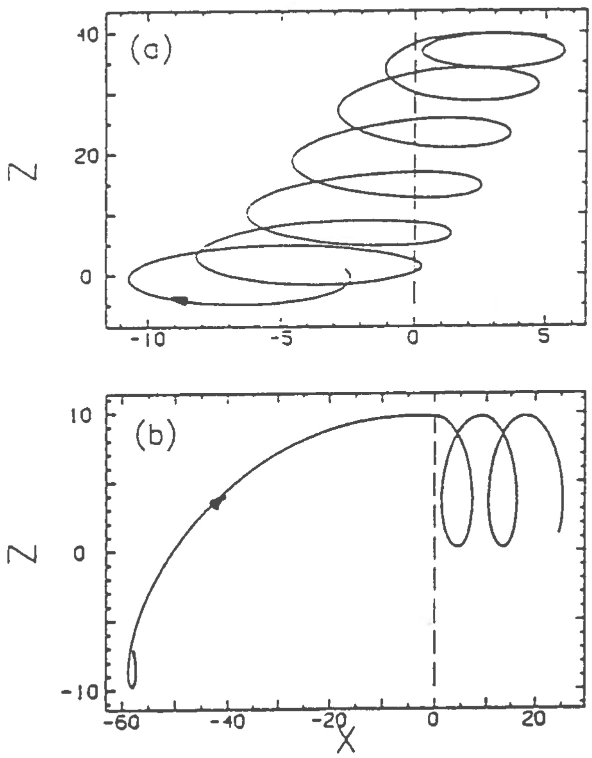


Fig.6. Capturing of accelerated particles behind the front of relativistic shock [41]. Fig. 6a corresponds to non-relativistic shock, $v_{sh} = 0.1c$, and Fig. 6b – to relativistic shock $v_{sh} = 0.87c$. Position of the shock is shown by dashed line, direction of velocity – by an arrow.

In Fig.6a the shock velocity is non-relativistic ($0.1c$) and a particle reflects many times from a shock. In Fig.6b the shock is relativistic, $0.87c$, and a particle is captured behind the shock. The same phenomenon is clearly seen in the relativistic transverse shocks in electron-positron plasma, (Fig.4 from [42]). Somewhat more complicated, but similar mechanism operates for parallel shock, i.e. when magnetic field is parallel to the shock velocity.

The capturing mechanism described above, does not exclude completely the Γ^2-regime of acceleration at relativistic shocks; it restricts the incident angles at which particles escape and thus the flux of accelerated particles. The most interesting objects where Γ^2-mechanism might operate are gamma-ray bursters [43,44]. The Lorentz factor of the shock here can reach $10^2 - 10^3$. However, the capturing properly taken into account might dramatically decrease the output of accelerated particles. As to the explanation of the observed UHECR, the protons from cosmologically remote gamma-ray bursts strongly degrade in energy on the way to our Galaxy.

Astrophysical sources of observed UHECR must satisfy the observational constraints. The absence of GZK cutoff at $E_{1/2} \approx 6 \cdot 10^{19}$ eV contradicts the uniform distribution of the sources in extragalactic space. If the sources are located as a dense group around our Galaxy, $E_{1/2}$ increases with increasing of density contrast, i.e. the ratio of number density of sources inside the group and outside it [3]. The Local Supercluster LS) can realize this possibility. This model was developed in ref.([45]). The UHECR sources in LS can be the old massive black holes with large electric potential induced in the accretion discs by unipolar induction. For increasing $E_{1/2}$ up to $1 \cdot 10^{20}$ eV the density contrast larger than 10 is needed. The anisotropy can be smaller than the observed one if magnetic field in superclusters is as large as $H \sim 10^{-7}$ G [46].

5. Topological defects and relic particles.

Topological defects, TD, (for a review see [47]) can naturally produce particles of ultrahigh energies (UHE). The pioneering observation of this possibility was made by Hill, Schramm and Walker [48] (for a general analysis of TD as UHE CR sources see [49] and for a recent review [50]).

In many cases TD become unstable and decompose to constituent fields, superheavy gauge and Higgs bosons (X-particles), which then decay producing UHECR. It could happen, for example, when two segments of ordinary string, or monopole and antimonopole touch each other, when electrical current in superconducting string reaches the critical value and in some other cases.

In most cases the problem with UHECR from TD is not the maximal energy, but the fluxes. One very general reason for the low fluxes consists in the large distance between TD. A dimension scale for this distance is the Hubble distance H_0^{-1}. However, in some rather exceptional cases this dimensional scale is multiplied to a small dimensionless value r. If a distance between TD is larger than UHE proton attenuation length, then the flux at UHE is typically exponential suppressed.

Ordinary cosmic strings can produce particles when a loop annihilate into double line [51]. The produced UHE CR flux is strongly reduced due to the fact that a loop oscillates, and in the process of a collapse the two incoming parts of a loop touch each other in one point producing thus the smaller loops, instead of two-line annihilation. However, this idea was recently revived due to recent work [52]. It is argued there that the energy loss of the long strings is dominated by production of very small loops with the size down to the width of a string, which immediately annihilate into superheavy particles. A problem with this scenario is too large distance between strings (of order of the Hubble distance). For a distance between an observer and a string being the same, the observed spectrum of UHE CR has an exponential cutoff at energy $E \sim 3 \cdot 10^{19}$ eV.

Superheavy particles can be also produced when two segments of string come into close contact, as in *cusp* events [53]. This process was studied later in ref.([54]) with a conclusion that the resulting cosmic ray flux is far too small. An interesting possibility suggested in ref.([53]) is the *cusp* "evaporation" on cosmic strings. When the distance between two segments of the cusp becomes of the order of the string width, the cusp may"annihilate" turning into high energy particles. , which are boosted by a very large Lorentz factor of the cusp [53]. However, the resulting UHE CR flux is considerably smaller than one observed [55].

Superconducting strings [56] appear to be much better suited for particle production. Moving through cosmic magnetic fields, such strings develop electric currents and copiously produce charged heavy particles when the current reaches certain critical value. The CR flux produced by superconducting strings is affected by some model-dependent string parameters and by the history and spatial distribution of cosmic magnetic fields. Models considered so far failed to account for the observed flux [57].

Monopole-antimonopole pairs ($M\bar{M}$) can form bound states and eventually annihilate into UHE particles [58], [59]. For an appropriate choice of the monopole density n_M, this model is consistent with observations; however, the required (low) value of n_M implies fine-tuning. In the first phase transition $G \to H \times U(1)$ in the early Universe the monopoles are produced with too high density. It must then be diluted by inflation to very low density, precisely tuned to the observed UHE CR flux.

Monopole-string network can be formed in the early Universe in the sequence of symmetry breaking

$$G \to H \times U(1) \to H \times Z_N. \quad (3)$$

For $N \geq 3$ an infinite network of monopoles connected by strings is formed. The magnetic fluxes of monopoles in the network are channeled into into the strings that connect them. The monopoles typically have additional unconfined magnetic and chromo-magnetic charges. When strings shrink the monopoles are pulled by them and are accelerated. The accelerated monopoles produce extremely high energy gluons, which then fragment into UHE hadrons [60]. The produced flux is too small to explain UHE CR observation [61].

Cosmic necklaces are TD which are formed in a sequence of symmetry breaking given by Eq.(3) when $N = 2$. The first phase transition produces monopoles, and at the second phase transition each monopole gets attached to two strings, with its magnetic flux channeled along the strings. The resulting necklaces resemble "ordinary" cosmic strings with monopoles playing the role of beads. Necklaces can evolve in such way that a distance between monopoles diminishes and in the end all monopoles annihilate with the neighboring antimonopoles [62].

An important quantity for the necklace evolution is is the dimensionless ratio $r = m/\mu d$, where m is the monopole mass, μ is is the string tension, determined by $U(1)$ symmetry scaling scale η_s, and d is a distance between two neighbouring monopoles. In ref.([62]) it is argued that in the process of the necklace evolution $r(t)$ is driven towards large values $r \gg 1$. The characteristic length scale. equal to the typical separation of necklaces.

$$\xi \sim r^{-1/2}t. \quad (4)$$

is much smaller than horizon t, when r becomes large.

A requirement for all models explaining the observed UHE events is that the distance between sources must be smaller than the attenuation length for UHE particles. Otherwise the flux at the corresponding energy would be exponentially suppressed. This imposes a severe constraint on the possible sources. For example, in the case of protons with energy $E \sim (2-3) \cdot 10^{20}$ eV, the proton attenuation length is 19 Mpc . If protons propagate rectilinearly, there should be several sources inside this radius; otherwise all particles would arrive from the same direction. If particles are strongly deflected in extragalactic magnetic fields, the distance to the source should be even smaller. Therefore, the sources of the observed events at the highest energy must be at a distance $R \leq 15$ Mpc in the case or protons.

For the necklaces the distance between sources, given by Eq.(4), satisfies this condition for $r > 3 \cdot 10^4$. This is in contrast to other potential sources, including supeconducting cosmic strings and powerful astronomical sources such as AGN, for which this condition imposes severe restrictions.

The diffuse fluxes of UHE protons and photons from necklaces are given in Fig.7. One can see that at $E \sim 1 \cdot 10^{20}$ eV the gamma-ray flux is considerably lower than that of protons. This is mainly due to the difference in the attenuation lengths for protons (110 Mpc) and photons (2.6 Mpc [7] and 2.2 Mpc [6]). At higher energy the attenuation length for protons dramatically decreases (13.4 Mpc at $E = 1 \cdot 10^{12}\ GeV$) and the fluxes of protons and photons become comparable [62].

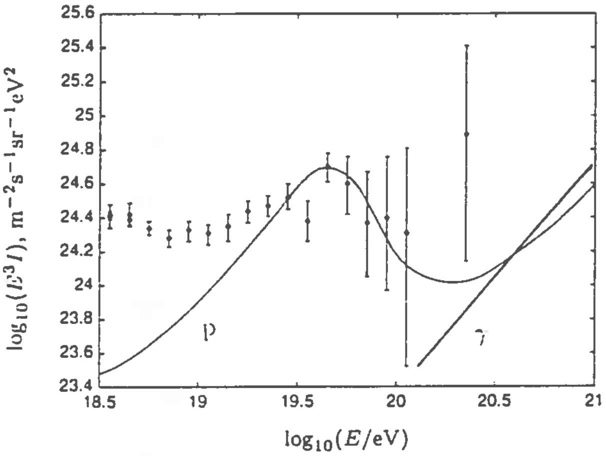


Fig.7. UHE proton flux from cosmic necklaces with $r^2\mu \sim 1 \cdot 10^{28}\ GeV^2$ and $m_X \sim 1 \cdot 10^{14}\ GeV$. Curve p shows the proton flux, γ is for photon flux [62].

The predictions in Fig.7. are compared with the AGASA data [63]. The agreement is rather good for $E > 2 \cdot 10^{19}\ eV$. The contribution of UHE photons increases the total flux at $E > 2 \cdot 10^{20}\ eV$. The contribution of low-energy component (e.g. from radiogalaxies [35]) can easily improve the agreement at lower energies.

The radiation from Topological Defects can explain the diffuse gamma-ray background above 10 GeV [64].

Superheavy relic particles can be sources of UHE CR [65–67]. In this scenario Cold Dark Matter (CDM) have a small admixture of long-lived superheavy particles. These particles must be heavy, $m_X > 10^{12}\ GeV$, long-lived $\tau_X > t_0$, where t_0 is the age of the Universe, and weakly interacting. The required life-time can be provided if this particle has (almost) conserved quantum number broken very weakly due to warmhole [66] or instanton [65] effects. Several mechanisms for production of such particles in the early Universe were identified. Like other forms of non-dissipative CDM , X-particles must accumulate in the halo of our Galaxy [66] and thus they produce UHE CR without GZK cutoff and without appreciable anisotropy.

The more detailed discussion as well as calculated fluxes of UHE protons and photons are given in the paper by M. Kachelriess (these Proceedings).

The characteristic and unavoidable feature of this model is an excess of gamma-ray flux over the nucleon flux. It follows from the more effective production of pions than nucleons in the QCD cascades from the decay of X -particles and from absence of absorption in the Galactic halo.

The spectrum of the observed EAS is formed due to fluxes of gamma-rays and nucleons. The gamma-ray contribution to this spectrum is rather complicated. In contrast to low energies, the photon-induced showers at $E > 10^{18}$ eV have the low-energy muon component as abundant as that for nucleon-induced showers [68]. The shower production by the photons is, in principle, suppressed by the LPM effect [69] and by absorption in geomagnetic field. However, as was noted in [68] cascading in geomagnetic field results in arrival of a bunch of photons (each with a smaller energy than the primary one) at the top of atmosphere. They produce one shower with LPM effect reduced because of the smaller energies of photons in the bunch (see [70] and references therein for further discussion). Experimental discrimination of gamma-ray induced showers from that produced by protons is very important task.

The UHE carriers can be, in principle, not only protons and photons, but other particles, such as neutrinos, gluinos [71–73], neutralinos [73] and monopoles [74,72]. In the next section we shall shortly discuss discuss the Lightest Supersymmetric Particle as a candidate for a carrier of a signal in UHECR detectors.

6. LSP as UHE carrier

The Lightest Supersymmetric Particle (LSP) can be either stable, if R-parity is strictly conserved, or unstable. if R-parity is violated. To be able to reach the Earth from most remote regions in the Universe, the LSP must have lifetime longer than $\tau_{LSP} \geq t_0/\Gamma$, where t_0 is the age of the Universe and $\Gamma = E/m_{LSP}$ is the Lorentz-factor of the LSP. In case $m_{LSP} \sim 100\ GeV$, $\tau_{LSP} > 1\ yr$.

Theoretically the best motivated candidates for LSP are the neutralino and gravitino; the latter is practically undetectable as UHE particle.

In all elaborated SUSY models the gluino is not the LSP. From experimental point of view there is some controversy if the low-mass window $1\ GeV \leq m_{\tilde{g}} \leq 4\ GeV$ for the gluino is still allowed [75,76]. Recently the light-gluino was claimed to be ruled out on the basis of its contribution to β function for the strong interaction [77]. Finally, there is one more argument about light gluino [78]: If gluino is stable or quasi-stable and if the lightest gluino-baryonic state is $\tilde{g}uud$, this heavy hydrogen is overproduced by cosmic rays in the Earth atmosphere. Nevertheless, we shall discuss the gluino as UHE carrier [71–73]. We shall refer to any colorless hadron containing gluino as $\tilde{g}$-hadron. The lightest $\tilde{g}$-hadron is most probably *glueballino* $\tilde{g}g$. It is stable if gluino is LSP. The lightest gluino-baryonic state, *gluebarino*, is almost stable because of very weak violation of baryonic number. Light glueballinos as UHE particles with energy $E \geq 10^{16}$ eV were considered in some detail in the literature in connection with Cyg X-3 [79,80].

UHE LSP are most naturally produced at the decays of unstable superheavy particles, either from TD or the relic ones [73].

The QCD parton cascade is not a unique cascade process. A cascade multiplication of partons at the decay of superheavy particle appears whenever a probability of production of extra parton has the terms $\alpha \ln Q^2$ or $\alpha \ln^2 Q^2$, where Q is a maximum of parton transverse momentum. Regardless of smallness of α, the cascade develops as far as $\alpha \ln Q^2 \geq 1$. Therefore, for extremely large Q^2 we are interested in, a cascade develops due to parton multiplication through $SU(2) \times U(1)$ interactions as well (see [73] for calculations). LSP take away a considerable fraction of the total energy ($\sim 40\%$).

Neutralino as UHE carrier has no much advantages over neutrino: the neutralino fluxes, produced at the decay of superheavy particles, are less than neutrino fluxes and neutralino-nucleon cross-section at very high energy is less than that for neutrino [73].

Light gluino is effective as the UHE carrier. The energy losses of glueballino on a way from a source to the Earth is less than for a proton. The dominant energy loss is due to pion production in collisions with microwave photons. Pion production effectively starts at the same Lorentz-factor as in the case of the proton. This implies that the energy of the GZK cutoff is a factor $m_{\tilde{g}}/m_p$ higher than in case of the proton. The attenuation length also increases because the fraction of energy lost near the threshold is small, $\mu/m_{\tilde{g}}$, where μ is a pion mass. Therefore, even for light glueballino, $m_{\tilde{g}} \geq 2\ GeV$. the steepening of the spectrum is less pronounced than for protons [73].

A very light UHE glueballino interacts with the nucleons in the atmosphere similarly to UHE proton. The cross-section for heavy glueballino with $m_{\tilde{g}} > 150\ GeV$ is small for large energy transfer needed for production of extensive air showers, and thus these particles cannot be responsible for the observed UHE events.

Thus, only UHE gluino from the low-mass window $1\ GeV \geq m_{\tilde{g}} \leq 4\ GeV$ could be a candidate for observed UHE particles. but it is disfavored by the arguments given above.

7. Conclusions

At $E \geq 1 \cdot 10^{19}\ eV$ a new component of cosmic rays with a flat spectrum is observed. Two highest energy events have $E \approx 2 - 3 \cdot 10^{20}\ eV$. According to the Fly's Eye and Yakutsk data the chemical composition is better described by protons than heavy nuclei. The AGASA data are consistent with isotropy in arrival of the particles, though theoretical analysis reveals some correlation of arrival direction with Local Supercluster plane. AGASA has observed clustering of UHE events: three pairs of particles with small angular separation.

The galactic origin of UHECR is disfavored: the maximal observed energies are less than that known for the galactic sources, and the strong Galactic disc anisotropy is predicted even for the extreme magnetic fields in the disc and halo.

The signature of extragalactic UHECR is GZK cutoff. The position of steepening is model-dependent value. For the Universe uniformly filled with sources, the steepening starts at $E_{bb} \approx 3 \cdot 10^{19}$ eV and has $E_{1/2} \approx 6 \cdot 10^{19}$ eV (the energy at which spectrum becomes a factor of two lower than a power-law extrapolation from lower energies). The spectra of UHE nuclei exhibit steepening approximately at the same energy as protons. UHE photons have small absorption length due to interaction with radio background radiation.

The extragalactic astrophysical sources theoretically studied so far, have either too small E_{max} or are located too far away. The Local Supercluster (LS) model can give spectrum with $E_{1/2} \sim 10^{20}$ eV, if density contrast for the sources (the ratio of densities inside LS and outside) is larger than 10.

Topological Defects naturally produce particles with extremely high energies, much in excess of what is presently observed. However, the fluxes from most known TD are too small. So far only necklaces and monopole-antimonopole pairs can provide the observed flux of UHE CR.

Another promising sources of UHE CR are relic superheavy particles. These particles should be clustering in the halo of our Galaxy, and thus UHECR produced at their decays do not have the GZK cutoff. The signatures of this model are dominance of photons in the primary flux and Virgo cluster as a possible discrete source.

Apart from protons and photons, the light gluinos can be successful UHE carriers, but they are disfavored in mass interval at interest.

8. Acknowledgements

I am grateful to my co-authors Michael Kachelriess and Alex Vilenkin for many useful discussions when preparing this talk. Michael Kachelriess is thanked also for the help in the calculations which were performed for this presentation. I much benefited from conversations with J. Cronin and M.Nagano.

REFERENCES

1. H.Hayashida et al., Proc. of Int. Symposium "Extremely High Energy Cosmic Rays" (ed. M.Nagano), Univ. of Tokyo (1996) 17.
2. K.Greisen, Phys. Rev. Lett. 16 (1966) 748; G.T.Zatsepin and V.A.Kuzmin, JETP Lett. 4 (1966) 78.
3. V.S.Berezinsky, S.V.Bulanov, V.A.Dogiel, V.L.Ginzburg and V.S.Ptuskin, Astrophysics of Cosmic Rays. chapter 4, North-Holland, 1990.
4. C.T.Hill and D.N.Schramm, Phys. Rev. D 31 (1995) 564.
5. V.S.Berezinsky and S.I.Grigorieva Sov. Phys. JETP 66 (1987) 457 and Astron. Astroph. 199 (1988) 1.
6. V.S.Berezinsky , Sov. J. Nucl. Phys. 11 (1970) 222.
7. R.J.Protheroe and P.L.Biermann, Astrop. Phys. 6 (1996) 45.
8. S.Yoshida et al., Astrop. Phys., **3**, 105, (1995).
9. D.J.Bird et al, Ap.J. 424 (1994) 491.
10. N.Hayashida et al.. Phys. Rev. Lett. 73 (1994) 3491.
11. G.Canningham et al., Ap.J. 236 (1980) L71.
12. M.M.Winn et al. J. Phys. G: Nucl. Phys. 12 (1986) 653.
13. Similar remark was made recently by J. Linsley.
14. A.V.Glushkov et al., J. Nucl. Phys. Preprint (1994).
15. B.N.Afanasiev et al, Proc. of Tokyo Workshop on Techniques for the study of Extremely High Energy Cosmic Rays, (eds G.Loh et al), Institute for Cosmic Ray Research, Tokyo 1993. 35.
16. T.Stanev et al, Phys. Rev. Lett. 75 (1995) 3056.
17. N.Hayashida et al., Phys. Rev. Lett. 77 (1996) 1000.
18. G.Sigl, M.Lemoine and A.Olinto, astro-ph/9704204

19. D.Bird et al., Phys. Rev. Lett. 71 (1993) 4301.
20. N.Hayashida et al., J.Phys. G: Nucl. Phys. 21 (1995) 1101.
21. B.N.Afanasiev et al, Proc. of Int. Workshop "Extremely High Energy Cosmic Rays" (ed. M.Nagano), Institute for Cosmic Ray Research, Tokyo (1996) 32.
22. C.J.Cesarsky and P.O.Lagage, Astron. Astrophys. 125 (1983) 294.
23. H.J.Volk and P.L.Biermann, Ap.J.Lett. 333 (1988) 65.
24. P.L.Biermann and J.P.Cassinelli, Astron Astroph., 277 (1993) 691.
25. J.R.Jokipii and G.Morfill. Ap.J. 312 (1987) 170.
26. A.G.K.Smith and R.W.Clay, Austr. J.Phys. 43 (1990) 373.
27. V.Berezinsky, S.Grigorieva. A.Mikhailov, H.Rubinstein, A. Ruzmaikin. D.Sokoloff, A.Shukurov, Proc. of Int. Workshop "Astrophys. Aspects of Most Energetic Cosmic Rays" (eds N.Nagano and F.Takahara), World Scientific, (1991) 134.
28. M.Giler, J.L.Osborne, J.Wdowczyk, and M.Zielinska, 23 Int. Cosm. Ray Conf., (Calgary) 2 (1993) 81.
29. D.N.Pocherkin, V.S.Ptuskin, S.I.Rogovaya and V.N.Zirakashvili, 24th Int. Cosm. Ray Conf. (Rome) 3 (1995) 136.
30. D.D.Sokoloff and A.M.Shukurov, Nature 347 (1990) 51.
31. S.Hayakawa, Atroph. Sp. Sci 229 (1972) 237.
32. V.S.Berezinsky and O.F.Prilutsky, Astroph. Sp. Sci., 21 (1973) 475.
33. C.A.Norman, D.B.Melrose, and A.Achtenberg, Ap. J. 454 (1995) 60.
34. P.L.Biermann and P.A.Strittmatter, Ap.J. 322 (1987) 643.
35. W.H.Ip and W.I.Axford, Astrophysical Aspects of the Most Energetic Cosmic Rays (ed. M.Nagano), World Scientific, 273 (1991).
36. J.P.Rachen and P.L.Biermann, Astron. Astroph. 272 (1993) 161.
37. R.D.Blandford, Mon.Not.Roy.Astr.Soc. 176 (1976) 465.
38. R.V.E.Lovelace, Nature 262 (1976) 649.
39. E.Fermi, Phys.Rev. 75 (1949) 1169.
40. M.C.Begelman and J.G.Kirk, Ap.J. 353 (1990) 66.
41. M.Hoshino, J.Arons, Y.Gallant, and A.Langdon, Ap.J. 390 (1992) 454.
42. M.Vietri, Ap.J. 453 (1995) 883.
43. E.Waxman, Phys. Rev. Lett. 75 (1995) 386.
44. V.S.Berezinsky and S.I.Grigorieva. Proc. 16th Int. Cosm. Ray Conf. (Kyoto) 2 (1979) 81.
45. K.T.Kim, P.P.Kronberg, G.Giovannini, and T.Venturi, Nature 341 (1989) 720.
46. A. Vilenkin and E.P.S. Shellard. Cosmic Strings and Other Topological Defects. Cambridge University Press, Cambridge. 1994; M.B. Hindmarsh and T.W.B. Kibble. Rep. Prog. Phys. **55**, 478 (1995).
47. C.T. Hill, D.N. Schramm and T.P. Walker, Phys. Rev. D36 (1987) 1007;
48. P. Bhattacharjee, C.T. Hill and D.N. Schramm, Phys. Rev. Lett. 69 (1992) 567; G. Sigl, D.N. Schramm and P. Bhattacharjee, Astropart. Phys. 2 (1994) 401;
49. G.Sigl, astro-ph/9611190.
50. P.Bhattacharjee and N.C.Rana. Phys. Lett. **B 246**, 365 (1990).
51. G.Vincent, N.Antunes and M.Hindmarsh, hep-ph/9708427.
52. R.Brandenberger, Nuclear Physics. B **293**, 812 (1987).
53. A.J. Gill and T.W.B. Kibble, Phys. Rev. D50 (1994) 3660.
54. J.H. MacGibbon and R.H. Brandenberger, Nucl. Phys. **B331**, 153 (1990); P. Bhattacharjee, Phys. Rev. **D40**, 3968 (1989).
55. E. Witten, Nucl. Phys. **B249**, 557 (1985).
56. V.Berezinsky and A.Vilenkin, in preparation.
57. C.T. Hill, Nucl. Phys. **B224**, 469 (1983).
58. P. Bhattacharjee and G. Sigl, Phys. Rev. **D51**, 4079 (1995).
59. V. Berezinsky, X. Martin and A. Vilenkin, Phys. Rev **D 56**, 2024 (1997) .
60. V.Berezinsky, P.Blasi and A.Vilenkin, in preparation.
61. V.Berezinsky and A.Vilenkin, Phys. Rev. Lett. 79 (1997) 5202.
62. We thank M.Nagano for providing us with these data.
63. P.Bhattacharjee, Q.Shaffi and F.W.Stecker, hep-ph/9710533.
64. V.A.Kuzmin and V.A.Rubakov , Talk at the

Workshop "Beyond the Desert", Castle Rindberg 1997, astro-ph/9709187.
65. V.Berezinsky, M.Kachelriess and A.Vilenkin, Phys. Rev. Lett. 79 (1997) 4302.
66. P.H.Frampton, B.Keszthelyi, and Y.J.Ng, astro-ph/9709080.
67. F. A. Aharonian, B. L. Kanevsky and V. A. Sahakian, J. Phys. **G17**, 1909 (1991).
68. L. D. Landau and I. Pomeranchuk, Dokl. Akad. Nauk SSSR, **92**, 535 (1953); A. B. Migdal, Phys. Rev.,**103**, 1811 (1956).
69. R. Protheroe and T. Stanev, Phys. Rev. Lett. **77**, 3708 (1996) and erratum.
70. D.J.H. Chung, G.R.Farrar and E.W.Kolb, astro-ph/9707036.
71. R.N.Mohapatra and S.Nussinov, hep-ph/9708497.
72. V.Berezinsky and M.Kachelriess, hep-ph/9709485.
73. T. Kephart and T.Weiler, Astrop. Phys. **4**, 271 (1996).
74. Particle Data Group, Phys. Rev. **D54** (1996) 1.
75. Aleph collaboration, CERN-PPE-97/002, to be published in Z. Phys. C; G. R. Farrar, hep-ph/9707467.
76. F.Csikor and Z.Fodor, Phys. Rev. Lett. 78 (1997) 4335.
77. M. B. Voloshin and L. B. Okun. Sov. J. Nucl. Phys. 43 (1986) 495.
78. G. Auriemma, L. Maiani and S. Petrarca, Phys. Lett. **B164** (1985) 179.
79. V. S. Berezinskii and B. L. Ioffe. Sov. Phys. JETP **63** (1986) 920.