Space Science Reviews manuscript No.
(will be inserted by the editor)

Cosmic rays in galactic and extragalactic magnetic fields

Felix Aharonian · Andrei Bykov · Etienne Parizot · Vladimir Ptuskin · Alan Watson

Received: date / Accepted: date

Abstract We briefly review sources of cosmic rays, their composition and spectra as well as their propagation in the galactic and extragalactic magnetic fields, both regular and fluctuating. A special attention is paid to the recent results of the X-ray and gamma-ray observations that shed light on the origin of the galactic cosmic rays and the challenging results of Pierre Auger Observatory on the ultra high energy cosmic rays. The perspectives of both high energy astrophysics and cosmic-ray astronomy to identify the sources of ultra high energy cosmic rays, the mechanisms of particle acceleration, to measure the intergalactic radiation fields and to reveal the structure of magnetic fields of very different scales are outlined.

Keywords Cosmic rays, ISM- (ISM:) supernova remnants Clusters of galaxies Shock waves Magnetic fields

Felix Aharonian
Center for Astroparticle Physics and Astrophysics, DIAS, Dublin, Ireland and MPIK, Heidelberg, Germany, E-mail: Felix.Aharonian@mpi-hd.mpg.de

Andrei Bykov
A.F.Ioffe Institute for Physics and Technology, 194021 St.Petersburg, Russia also St.Petersburg State Politechnical University E-mail: byk@astro.ioffe.ru

Etienne Parizot
APC, Université Paris Diderot 10, rue Alice Domon et Léonie Duquet 75205 Paris Cedex 13 France, E-mail: parizot@apc.univ-paris7.fr

Vladimir Ptuskin
Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Science (IZMIRAN), Troitsk, Moscow Region 142190, Russia, E-mail: vptuskin@izmiran.ru

Alan Watson
School of Physics and Astronomy University of Leeds Leeds, LS2 9JT, UK, E-mail: a.a.watson@leeds.ac.uk

1 Introduction

To a first approximation, the all-particle spectrum of cosmic rays (CR) - ionized atomic nuclei with energies extending from the MeV to more than 10^{20} eV, can be described by a power law over 11 decades on particle energy, so that the dependence of cosmic ray intensity on particle energy is close to $E^{-2.7}$ above 10 GeV/nucleon see Figure 1. Spectra of different CR species are different however. Closer examination reveals some structures in the galactic cosmic ray spectrum that includes more flat low energy part at $E < 10$ GeV/nucleon (mainly due to the modulation of the Galactic cosmic ray intensity by the solar wind flow), the knee at about 4×10^{15} eV, the possible second knee at $\sim 4 \times 10^{17}$ eV, the ankle at $\sim 4 \times 10^{18}$ eV where the spectrum flattens again, and finally the suppression of flux above $\sim 5 \times 10^{19}$ eV. The latter can be interpreted as the so-called Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen 1966, Zatsepin and Kuzmin 1966) caused by the interaction of the ultra-high-energy cosmic rays (UHECRs) with the cosmological microwave background (CMB). Therefore, the suppression of the UHECR flux, taken together with the detection of an anisotropy in their arrival direction (Abraham et al. 2007) and the absence of any anisotropy associated with galactic structure is often taken as evidence of the extragalactic origin of these particles. However, it should be noted that the reported cutoff at 10^{20}eV could also be related to the limited capability of even extreme cosmic accelerators to boost the energy of individual particles up to 10^{20}eV. In any case, it is widely believed that the highest energy cosmic rays above 10^{19}eV are of extragalactic origin (see however Blasi et al. 2000, Calvez et al. 2010).

On the other hand, the energy region below 10^{15} eV is dominated by particles produced by Galactic sources. A strong argument for this is provided by gamma-ray observations of the Galactic disk, and the comparison with the corresponding observations in the Magellanic clouds. Furthermore, it is likely that even low-intensity magnetic fields in the intergalactic space prevent low-energy CRs from reaching us from distant galaxies on cosmological timescales. Therefore, a transition from galactic to extragalactic cosmic rays is expected to occur somewhere between 10^{17} eV and 10^{19} eV, while it is tempting to associate the flattening of the spectrum at the so-called ankle in the energy spectrum as marking the transition region. However, different interpretations have been proposed, with a transition at lower energy (Berezinsky et al. 2004, Lemoine 2005, Aloisio et al. 2007), and this important part of high-energy CR phenomenology is still much debated (Allard et al. 2007, Berezinsky 2009). It is interesting to note that this question is strongly related to that of the source composition of extragalactic CRs (Allard et al. 2005), and of course, the energy scale of the transition depends on the capacity of the Galaxy to confine cosmic rays up to high energies, and thus on the intensity and structure of the Galactic magnetic field.

The spectra of both Galactic and extragalactic cosmic rays are shaped by two basic processes - the acceleration in the sources and the subsequent propagation in cosmic magnetic fields and radiation fields. We concentrate here only on the CR propagation and acceleration while the extensive review of

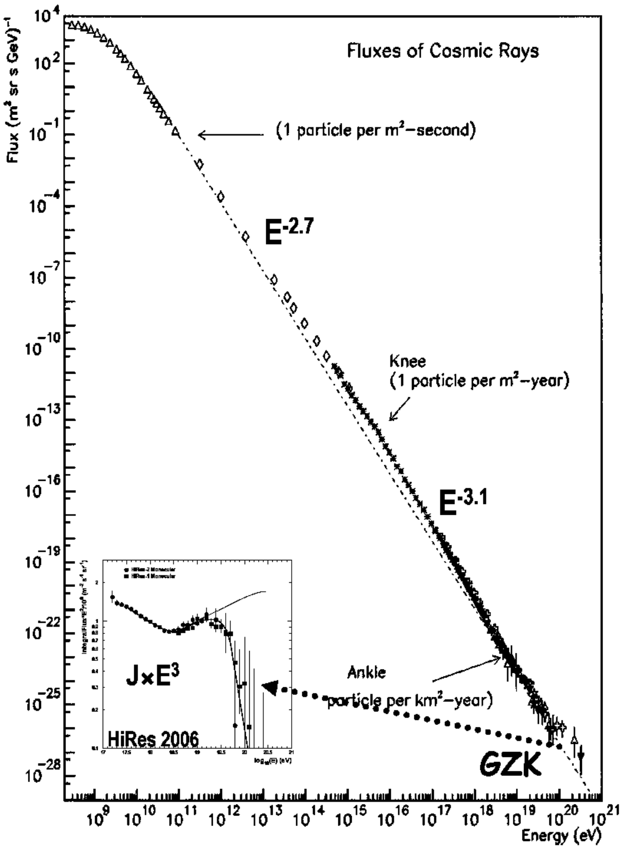

Fig. 1 All particle spectrum of cosmic rays (after S. Swordy and from Abbasi et al. (2008a) – insert).

the galactic and extragalactic magnetic fields is presented in the other chapters of the volume (see also Ferrière 2001, Beck 2008, Kulsrud and Zweibel 2008, and the references therein).

2 Potential sources

If one uses the cosmic ray energy requirements and the nonthermal radiation as a guideline, then the most powerful accelerators of relativistic particles in the Galaxy should be supernovae and supernova remnants, pulsars, neutron stars in close binary systems, winds of young massive stars, and possibly gamma-ray bursts or hypernovæ. The total power $L_{\rm cr}$ needed to maintain the observed energy density of cosmic rays is estimated as 10^{41} erg/s. For the acceleration by a supernovae, this estimate implies the release of energy in the form of cosmic rays of approximately 1.5×10^{50} erg per supernova if the supernova rate in the Galaxy is 1 every 50 years. This value comes to about 10–20% of the kinetic energy of the ejecta, which is compatible with the expectations of the theory of diffusive shock acceleration. This assumes 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 the progenitor star.

The rotational energy of a young pulsar with period P that remains after the supernova explosion is estimated to be $2 \times 10^{50} (10\ \mathrm{ms}/P)^2$ erg. It is an additional energy reservoir for particle acceleration and in particular it could be the source of very high energy electron-positron pairs. The production of relativistic positrons by pulsars may explain their presence in cosmic rays, see e.g. Profumo (2008). A general dimensional analysis by Hillas (1984, 2005) provided a useful tool to estimate the maximal CR energies that can be achieved by electromagnetic acceleration of charged particles in a source of given size and magnetic field magnitude. It follows that the highest energy CR particles of energy $\gtrsim 10^{20}$ eV can occur either in the compact sources with very large magnetic fields or in the most extended cosmological objects, though the particle energy losses may affect the maximal CR energy estimations.

2.1 Supernova remnants as CR accelerators and gamma-ray astronomy

The observations of non-thermal radio emission of supernova remnants have established the presence of effective acceleration of cosmic ray electrons in these objects, e.g. Lozinskaya (1992), Drury et al. (2001). Shell-type supernova remnants exhibit a broad range of spectral indices, centered roughly on $\alpha = -0.5$. This implies a power-law distribution of electrons with an average index $\gamma = 2\alpha + 1 \approx 2.0$, but it varies in a broad range from about 1.4 to 2.6. The analysis of the synchrotron emission in the young supernova remnant Cas A (Jones et al. 2003) showed the presence of electrons with energies up to 200 GeV with a magnetic field strength of about 500 μG. The interpretation of nonthermal radio emission from external galaxies proved that supernova remnants are the sites of acceleration of relativistic electrons with an efficiency similar to the one needed to provide the observed intensity of Galactic cosmic-ray electrons (Duric et al. 1995).

In the case of young SNRs, the spectra of nonthermal synchrotron radiation continues into the X-ray region. In particular, bright nonthermal X-ray structures have been observed from SN 1006, RX J1713.7-3946, RCW 86, and Cas A. The only viable explanation of this emission is the synchrotron radiation of ultrarelativistic electrons accelerated to energies as high as 100 TeV (for a review, see Vink 2008, Reynolds 2008). Inverse Compton scattering of background photons by these electrons, together with gamma rays produced via π^0 decays are two major mechanisms of gamma-ray production related to the forward and reverse shocks.

It is generally believed that gamma-ray astronomy has a key role to play in solving the problem of origin of galactic cosmic rays. The basic concept is simple and concerns both the acceleration and propagation aspects of cosmic rays. Namely, while the localized gamma-ray sources exhibit the sites of production/acceleration of cosmic rays, the angular and spectral distributions of the diffuse galactic gamma-ray emission provide information about the character of propagation of relativistic particles in galactic magnetic fields. The crucial outcome of current efforts involving both the ground-based and space-borne gamma-ray detectors is hoped to be a decisive test of the popular hypothesis that supernova remnants (SNRs) are responsible for the bulk of the observed cosmic ray flux. Three factors, (i) high efficiency of transformation of the available kinetic energy of bulk motion into nonthermal particles, (ii) the predicted, within the DSA paradigm, hard energy spectra of protons extending to multi-TeV energies and (iii) relatively high density of the ambient gas - make the young supernova remnants viable sources of gamma-rays resulting from production and prompt decay of secondary π^0-mesons. Thus, the most straightforward test of acceleration of proton and nuclei in SNRs can be performed via search for π^0-decay gamma-rays - either directly from shells of young SNRs (Drury et al. 1994) or from nearby clouds interacting with an expanding SNR shell (Aharonian et al. 1994).

One may argue that the TeV gamma-ray domain is the best energy band to explore this possibility - from the point of view of the superior performance of the detection technique and because of the key information about particle acceleration carried by TeV gamma-rays. On the other hand, TeV gamma-rays are expected only from young SNRs, when the shock speed can be as high as 3000 km/s - a key condition for acceleration of protons to energies 100 TeV and beyond. With the age, typically $t \geq 2000$ yr, the shock speed and the magnetic field in the expanding shell are decreased to the point when the particle acceleration significantly slows down. Moreover, the highest energy particles accelerated at the early epochs, effectively leave the remnant. This results in dramatic reduction of gamma-ray emissivity at TeV energies. Meanwhile the production of GeV gamma-rays continues. Thus we expect MeV and GeV gamma-rays not only from young, but, to a large extent, also from mid-age SNRs. In this regard we expect significantly more GeV emitting SNRs compared to the TeV emitting SNRs. Unfortunately, due to relatively low gamma-ray fluxes, as well as very high gamma-ray background in the crowded regions of the galactic disk, the detection of GeV gamma-rays from SNRs is quite difficult. In the case of mid-age SNRs we expect also "delayed" gamma-ray emission produced by cosmic rays which have left the source and interact with nearby massive gas molecular clouds. The spectrum of cosmic rays, and, consequently, gamma-rays produced in p-p interactions depends on several factors, including the spectrum of protons that escaped the supernova remnant, the character of diffusion, the age of the source and the distance between the source and cloud. In this regard one should expect gamma-ray emission with GeV-to-TeV flux ratio which can vary significantly from a source to source.

Over the last several years TeV gamma-ray emission has ben reported from several SNRs. Presently six young shell type SNRs - Cas A, RX J1713.7-3946, RX J0852-4622 (Vela Jr), RCW 86, SN 1006, Tycho - are identified as TeV gamma-ray emitters. Several others, in particular IC 433, W28 and CTB 37B are, most likely, SNR/molecular-cloud interacting systems. Also, several galactic TeV gamma-ray sources spatially coincide with the so-called composite supernova remnants, objects with characteristic features of both standard shell-type SNRs and Pulsar Wind Nebulae (see e.g. Aharonian et al. 2008).

In Fig.2 we shown the TeV and X-ray images of the strongest and best studied gamma-ray emitting SNR - RX J1713.7-3946.

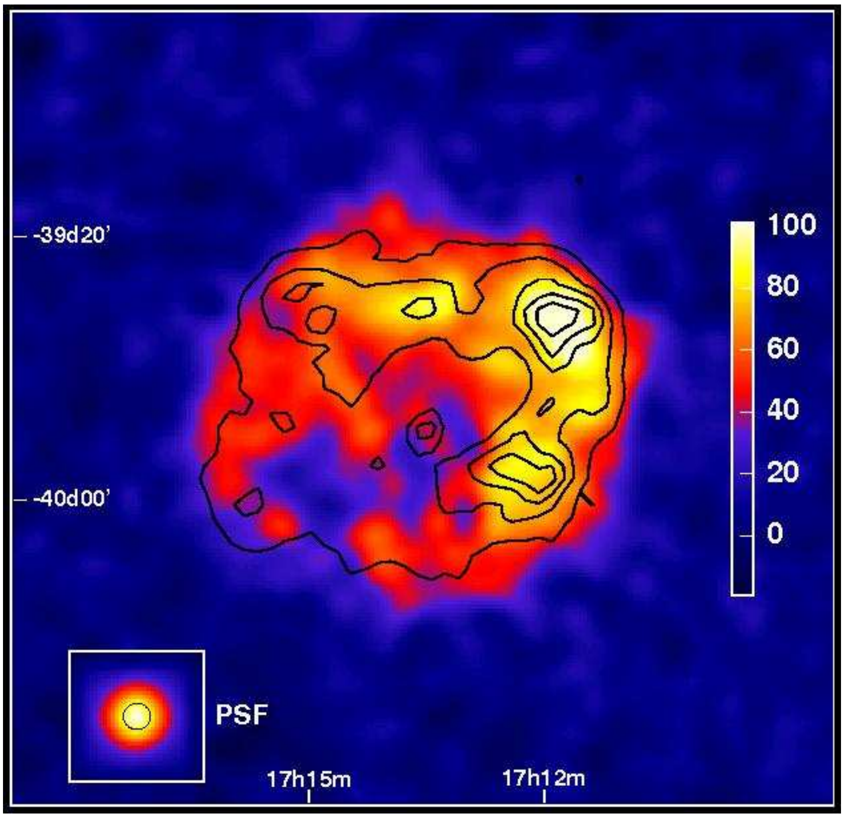

Fig. 2 The gamma-ray image of RX J1713.7-3946 obtained with the H.E.S.S. telescope array (Aharonian et al. 2007b). In the *left-hand side*, the overlaid light-gray contours illustrate the significance of the different gamma-ray features at 8, 18, and 24σ levels. In the *right-hand side*, the black-lines show the X-ray contours.

The age of this SNR RX J1713.7−3946 at a distance of about 1 kpc is estimated between 1 to 3 thousand years. Therefore, it can be formally teated as a representative of young galactic SNRs like SN 1006, Vela Junior, Tycho, Kepler, Cas A. However, RX J1713.7-3946 seems to be a unique object with quite unusual characteristics. This circumstance makes the identification of the gamma-ray mechanism, and hence the nature of the parent particles a nontrivial problem. Meanwhile the question of the origin of gamma-rays has a fundamental implication related to the role of SNRs to the production of galactic cosmic rays.

Remarkably, both the hadronic (gamma-rays produced in pp interactions) and leptonic models (gamma-ray produced via inverse Compton scattering) provide, with more or less success, but yet acceptable fits to the measured gamma-ray spectra and explain also the spatial distributions of gamma-rays and X-rays Zirakashvili and Aharonian (2010). So the test of these models relies essentially on multiwavelength data.

One of the most puzzling features of RX J1713.7-3946 is the lack of thermal X-ray emission which is a serious argument against the hadronic models of of this source. The tight upper limit on the thermal X-ray flux of RX J1713.7-3946 is explained by the supernova explosion inside a wind-blown bubble with a very low gas density $n_{\rm gas} \ll 1$ cm^{-3}. This allows to suppress the free-free component of thermal emission but not the X-ray lines (Ellison et al. 2010, Zirakashvili and Aharonian 2010), thus an additional assumption about the peculiar composition with reduced content of heavy elements is required to avoid the conflict with X-ray data (Zirakashvili and Aharonian 2010). The hadronic models demand quite large magnetic field of order of 100 μG or larger. This, for the given flux of synchrotron radiation, requires only $\approx 10^{46}$ erg in electrons. On the other hand, the total energy in protons should be 10^{50} erg or significantly larger if the background gas density $n \ll 1$ cm^{-3}. Thus, in the hadronic scenario the electron-to-proton ratio is close to $K_{\rm ep} = 10^{-4}$. This is a two orders of magnitude smaller than the "standard" electron/proton ratio observed in local cosmic rays.

A major challenge for the leptonic models is the demand for a small magnetic field in the shocked shell of the remnant. Within the framework of a one-zone model in which the electron acceleration and gamma-ray emission take place in the same region, the magnetic field cannot significantly exceed 10 μG, otherwise it leads, for the given X-ray flux, to significant suppression of IC gamma-rays.

A possible solution to the problems related to the pure (oversimplified) one-zone leptonic and hadronic models could be effective acceleration of electrons and protons in both forward and reverse shocks with an additional assumption of existence of dense condensations embedded in very low density shell. In this scenario the overall VHE gamma-ray emission is dominated by the IC scattering of electrons, but in addition to the leptonic component one should expect non-negligible contribution from hadronic gamma-rays produced at interactions of protons with dense gas condensations. Moreover, in this scenario both the low energy, $E \leq 100$ GeV and highest, $E \geq 10$ GeV gamma-rays should arrive from specific regions occupied by dense gas condensation (see Fig.3). The "composite" scenario allows a quite relaxed parameter space compared to the "pure" hadronic model and leptonic models, and at the same time, provides better fits to the broad-band spectral energy distribution of the source.

Independent of the ability of different models to describe the spectral and morphological features of gamma-ray emission of RX J1713.7-3946, it is obvious that we deal with a source that effectively accelerates electrons and protons to energy of 100 TeV and beyond. On the other hand, this object has many unique features, and in this regard it could be misleading if we treat this source as a representative of the whole population of young SNRs. Therefore, the studies of other TeV emitting SNRs is crucial for definite

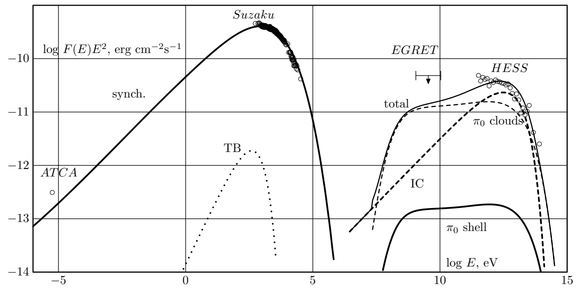

Fig. 3 Broad-band emission of RX J1713.7-3946 for the "composite" scenario of gamma-rays with non-modified forward and reverse shocks and dense clouds in the shell Zirakashvili and Aharonian (2010).

conclusions concerning the role of SNRs in production of galactic cosmic rays.

The realization of different possible scenarios of particle acceleration and radiation in general, and the uncertainties in relevant model parameters like the strength of the magnetic field and the density of ambient gas, prevent us from unambiguous conclusions concerning the fraction of the hadronic component in the flux of observed gamma-rays, and consequently do not allow model-independent estimates of thew total energy released in accelerated protons and nuclei. The best hope in this regard is related to the detection of high energy neutrinos produced in interactions of accelerated protons and nuclei with the ambient plasma. Although the fluxes of neutrinos are quite similar to the gamma-ray fluxes, because of limited sensitivity of the neutrino detectors, this extremely important channel of information unfortunately remains unexplored. Even for the largest neutrino telescopes like the recently completed *IceCube* and the planned several km-cube underwater detector in the Mediterranean Sea, the high energy neutrino signal from RXJ 1713.7-3946 is expected to be marginal even under the extreme assumption that the flux of detected TeV gamma-rays is fully consists of photons of hadronic origin (see e.g. Vissani et al. 2011, Morlino et al. 2009, and the references therein).

2.2 OB-associations, starburst, superbubbles

Collective stellar winds and supernovae in clusters and associations of massive stars in galaxies can be potentially efficient cosmic ray accelerators (see e.g. Cesarsky and Montmerle 1982, Bykov and Fleishman 1992, Axford 1994, Higdon et al. 1998, Bykov 2001, Bykov and Toptygin 2001, Binns et al. 2007).

The young rich open cluster Westerlund 2 is spatially coincident with TeV photon source HESS J1023-575 (Aharonian et al. 2007a). The reported source extension excludes a single star origin of the observed VHE emission and argues in favor of the production of cosmic rays by collective stellar winds from the ensemble of at least a dozen of hot massive O-type and a few WR-type stars in the stellar cluster Westerlund 2 (of an estimated age of about a few million years).

Recently, TeV gamma-ray emission has be reported from two star-burst galaxies, NGC 253 and M82, by H.E.S.S. (Acero et al. 2009) and VERITAS (Acciari et al. 2009), respectively. Starburst galaxies exhibit in their central regions a highly increased rate of supernovae that are likely to be efficient producers of cosmic rays. As they are extended, with radii up to $\sim$ 100 pc, the superbubbles (SB) containing dozens of supernova remnants and winds of massive stars are difficult to identify in the Galaxy, and are thus currently best studied in the Magellanic Clouds. Nonthermal X-rays were detected by Bamba et al. (2004) from the shells of the superbubble 30 Dor C in the LMC. The X-ray observations revealed the SB morphology as a nearly circular shell with a radius of 40 pc, which is bright on the northern and western sides. The non-thermal X-ray shell traces the outer boundary of the radio shell. These features of thin thermal and non-thermal X-rays are similar to those of SN 1006, a prototype of a synchrotron X-ray shell, but the non-thermal component of 30 Dor C is about 10 times brighter than that of SN 1006. The source is also much older than that of SN 1006, so the particle acceleration time in this superbubble may be longer than those in normal shell-like supernova remnants.

Nonlinear modeling of CR acceleration in superbubbles by Bykov (2001) predicted a high efficiency of the kinetic energy conversion to the CRs that can be $\sim 20\%$ and even higher with a significant temporal evolution of particle spectra inside the superbubble. Magnetic field inside the superbubble can be amplified up to about 30 μG providing the maximal energies of CR protons to be about 10^8 GeV and higher for CR nuclei that dominate the accelerated CR composition at highest energies in the model (see Bykov and Toptygin 2001). To model the CR composition in superbubbles a number of components including the ^{22}Ne-rich Wolf-Rayet and dust material must be accounted for (Binns et al. 2007, Meyer et al. 1997, Ellison et al. 1997).

2.3 CR abundance constraints on potential CR sources

The correction of the cosmic ray composition observed at the Earth for the effects of nuclear fragmentation in the interstellar medium makes it possible to determine the initial elemental and isotopic composition of accelerated particles, to clarify the process of cosmic ray acceleration and the nature of cosmic ray sources.

The relative abundance of chemical elements in cosmic ray sources is in general similar to the solar and local galactic abundances but with some interesting deviations. The popular scenarios which explain the cosmic ray source composition include the acceleration of grains together with relatively less abundant volatile ions by shocks in the interstellar medium (Meyer et al. 1997, Ellison et al. 1997), the acceleration of freshly formed material, particularly grains in young supernova remnants (Lingenfelter et al. 1998), and the acceleration in hot superbubbles with multiple supernova remnants (see e.g. Binns et al. 2007).

The isotopic composition of cosmic rays is now measured for all stable isotopes for elements from H to Ni. The isotopic composition of cosmic ray sources is strikingly similar to the composition found in the solar system (Wiedenbeck et al. 2001). However, a well-established anomaly in the isotopic composition of galactic cosmic rays is the excess of ^{22}Ne. The ratio ^{22}Ne/^{20}Ne is enhanced by a factor of 4 compared with the solar reference value (Duvernois et al. 1996a). It can be explained only by the special conditions of nucleosynthesis. The enhancement of neutron rich isotopes would be expected in the 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 and Paul 1982). An increased cosmic ray ratio C/O by a factor of 2 is also in favor of Wolf-Rayet stars.

Using the data from *Cosmic Ray Isotope Spectrometer* aboard the *ACE* spacecraft Binns et al. (2007) measured the isotopic abundances of neon and a number of other species in the galactic cosmic rays. The authors found that the three largest deviations of galactic cosmic ray isotope ratios from solar-system ratios, namely ^{12}C/^{16}O, ^{22}Ne/^{20}Ne, and ^{58}Fe/^{56}Fe, are consistent with a model of CR source consisting of about 20% of Wolf-Rayet wind material mixed with about 80% material of the solar-system composition. Therefore Binns et al. (2007) concluded that OB associations within superbubbles are the likely source of at least a substantial fraction of GCRs.

The analysis of the ^{59}Co/^{56}Fe abundance ratio also provides important information. Indeed, the relatively high, close to the solar value, of this ratio (Mewaldt 1999) testifies that the major part of the originally synthesized ^{59}Ni, which is stable when it is ionized (i.e. when it is accelerated among the cosmic rays), has decayed by the K-capture of an orbital electron into ^{59}Co before the acceleration started. Thus, the delay between the synthesis of this material and its acceleration has to be larger than 10^5 yr severely constraining the models with the acceleration of freshly ejected matter in SNRs.

The production of cosmic rays with power $L_{cr} = 10^{41}$ erg/s per normal galaxy can provide a cosmic-ray energy density of $w_{Mg} = L_{cr} N_g T_H = 3 \times 10^{-17}$ erg cm^{-3}, where $N_g = 2 \times 10^{-2}$ Mpc^{-3} is the number density of galaxies and $T_H = 1.4 \times 10^{10}$ yr is the Hubble time. This is almost 5 orders of magnitude smaller than the energy density of cosmic rays observed in the solar system. The contribution of active galaxies can reduce this discrepancy by only a factor of 10. All this is in agreement with the picture described in the Introduction, where the main part of the cosmic rays we observe at the Earth is produced by galactic sources (e.g. supernova remnants) and slowly diffuse in galactic magnetic fields out of the Galaxy to the intergalactic space, where the cosmic ray density is much smaller. The efficiency of the confinement of energetic particles is decreasing with energy, and because of that the difference between the cosmic ray densities inside and outside the Galaxy is also decreasing. The densities become equal at some energy between 10^{17} and 10^{19} eV and the extragalactic sources dominate at higher energies. The list of potential extragalactic sources includes in particular the active galactic nuclei, the progenitors of gamma-ray bursts, the accretion shocks of the size of galactic clusters and larger (see Torres and Anchordoqui

2004, Sigl 2009, for a review). These objects are probably able to provide the required power $q_{Mg} = 3 \times 10^{36}$ erg s^{-1} Mpc^{-3} in cosmic rays with energies $> 10^{19.5}$ eV. This estimate of q_{Mg} is based on the cosmic ray flux determined using the Auger Observatory (Pierre Auger Collaboration et al. 2010a) and it takes into account the energy loss time due to the GZK effect. It is notable that the entire population of supernovae in the Universe also meet the required power condition (Aublin and Parizot 2006), but as far as we know the highest energy particles can not be accelerated in such sources. The origin of the highest energy CRs in extragalactic sources remains a mystery, whose solution will require enhanced detections capabilities (because of the very low fluxes involved, see below), but will have a strong impact on the whole field of high-energy astrophysics.

3 Transport in the Galaxy

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

3.1 Empirical model of cosmic ray propagation

The procedure to model the cosmic ray diffusion in the Galaxy can be summarized as follows. One must first specify the cosmic ray sources, define the shape of the cosmic ray halo and the conditions at its boundaries (it is usually assumed that energetic particles exit freely into the intergalactic space where the cosmic ray density is negligible). The basic diffusion-convection equations for different cosmic ray species describe the diffusion of relativistic charged particles and, if needed, their convective transport in the models including a galactic wind. The equations should incorporate all possible energy loss and gain processes in the interstellar medium, nuclear fragmentation, and the radioactive decay of unstable nuclei. One can then calculate the distribution functions of protons, electrons and the different types of nuclei. The transport coefficients of cosmic rays (diffusion coefficient and convection velocity), the properties of the cosmic ray sources (total power, energy spectra of the different components, elemental and isotopic composition), and the size of the confinement region of cosmic rays in the Galaxy can be inferred by fitting all the available data on cosmic rays. Hundreds of stable and radioactive isotopes are included in the calculations of nuclear fragmentation and the transformation of the energetic nuclei as they interact with the interstellar gas. The most advanced code developed for the numerical modeling of cosmic ray propagation in the Galaxy is the GALPROP code which uses a Crank-Nicholson implicit second-order scheme (Strong and Moskalenko 1998, Strong et al. 2007). It incorporates as much realistic astrophysical input as possible, together with the latest theoretical development, and numerically solves the transport diffusion-convection equations for all cosmic-ray species.

One of the key channels of information about cosmic-ray propagation is the abundance of the secondary energetic nuclei Li, Be, B , Sc, V, Ti, ^{2}H, ^{3}He and others produced as a result of the spallation of heavier primary nuclei interacting with the interstellar gas. The observed flux ratios between secondary and primary nuclei, for example the boron to carbon ratio, show a maximum at about $E = 1$ GeV/nucleon (e.g., (Engelmann et al. 1990, Yanasak et al. 2001, Ahn et al. 2008). The mass distribution of secondary nuclei can be understood in terms of their propagation through about 10 g/cm^2 of interstellar material. This quantity, referred to as the escape length, can be approximately expressed through the parameters of the plain diffusion model with a flat cosmic ray halo of total thickness $2H \approx 8$ kpc as $X \approx v\mu_g H/2D$, where v is the particle velocity, $\mu_g \approx 2.4$ mg/cm^2 is the surface gas density of galactic disk, and D is the cosmic ray diffusion coefficient. This allows an estimate of the diffusion coefficient: $D \sim 3\times10^{28}$ cm^2/s at $E = 1$ GeV/nucleon.

The primary-to-secondary ratios decrease at higher energies (at least up to a few hundred GeV/nucleon where the measurements exist) as well as at lower energies. The understanding of this behavior is provided by the kinetic theory of particle interaction with the interstellar magnetic fields.

3.2 Kinetic theory of cosmic ray diffusion in galactic magnetic fields

The theory of energetic particle transport in the galactic magnetic fields is constructed in much the same way as in the better studied case of particle transport in the interplanetary magnetic fields. The detailed treatment of cosmic ray diffusion in magnetic fields can be found in monographs (Toptygin 1985, Berezinskii et al. 1990, Schlickeiser 2002) (see also Ptuskin et al. 2006).

On the “microscopic level” the spatial and momentum diffusion of cosmic rays results from the particle scattering on random MHD waves and discontinuities. The effective ”collision integral” for energetic charged particles moving in small-amplitude random fields $\delta B \ll B$ can be taken from the standard quasi-linear theory of plasma turbulence, see e.g. Kennel and Engelmann (1966). The wave-particle interaction is of resonant character and depends on the particle gyroradius, which is equal to $r_g = pc/ZeB = 10^{12} R_{GV}$ cm in a typical interstellar magnetic field $B = 3$ μG (here R_{GV} is the particle magnetic rigidity in GV and μ is the cosine of particle pitch angle). The particle is predominantly scattered by the irregularities of magnetic field δB that have the projection of the wave vector on the magnetic field direction equal to $k_{\parallel} = \pm s/(r_{\rm g}\mu)$. The integers $s = 0, 1, 2...$ correspond to the cyclotron resonances of different orders. The efficiency of particle scattering depends on the polarization of the waves and on their distribution in **k**-space. The first-order resonance $s = 1$ is the most important for the isotropic and also for the one-dimensional distribution of random MHD waves along the average magnetic field, $\mathbf{k} \parallel \mathbf{B}$. In some cases – for calculation of scattering at small μ and for calculation of perpendicular diffusion – the broadening of resonances and magnetic mirroring effects should be taken into account. Locally, the cosmic ray diffusion is anisotropic and goes along the local magnetic field. The isotropization of diffusion is accounted for by the presence of strong large-scale (~ 100 pc) fluctuations of the galactic magnetic field. The problem of calculation of the average diffusion tensor is not trivial even in the case of relatively weak large scale random fields, since the field is almost static and the strictly one-dimensional diffusion along the magnetic field lines does not lead to non-zero diffusion perpendicular to $\mathbf{B}$, see Casse et al. (2002), Webb et al. (2009).

The following simple equations for the diffusion coefficient are useful for estimates:

$$D = vr_{\mathrm{g}}B^2/\left[12\pi k_{\mathrm{res}}W(k_{\mathrm{res}})\right] = \frac{vr_{\mathrm{g}}^a}{3(1-a)k_{\mathrm{L}}^{1-a}}\frac{B^2}{\delta B_{\mathrm{L}}^2}, \tag{1}$$

here $k_{\mathrm{res}} = 1/r_g$ is the resonant wave number, and $W(k)$ is the spectral energy density of waves normalized as $\int dkW(k) = \delta B^2/4\pi$. The random field at the resonance scale is assumed to be weak, $\delta B_{\mathrm{res}} \ll B$. The principle wave number of the turbulence is k_L and the amplitude of random field at this scale is δB_L. The second equation in (1) is valid for particles with $r_{\mathrm{g}} < k_{\mathrm{L}}^{-1}$ under the assumption of a power law spectrum of turbulence $W(k) \propto 1/k^{2-a}$, $k > k_{\mathrm{L}}$. The diffusion coefficient has then a power law scaling on momentum $D \propto v(p/Z)^a$.

Eq. (1) can be used to describe the turbulence which consists of random isotropic distribution of Alfvén and fast magnetosonic waves and it gives correct order of magnitude estimates for the wave distribution concentrated around the direction of average magnetic field. It should be pointed out however that the isotropization of the diffusion tensor does not occur in the case of a pure parallel wave propagation ($\mathbf{k} \parallel \mathbf{B}$). Another special case is 2D turbulence with perpendicular propagation of waves ($\mathbf{k} \perp \mathbf{B}$). In this case, the scattering occurs only for magnetosonic waves through the resonance $s = 0$ which leads to a very large diffusion coefficient, about a factor $(v/V_{\mathrm{a}})^2$ larger than given by eq. (1).

The diffusion in momentum is approximately described by the equation:

$$D_{pp} = p^2V_{\mathrm{a}}^2/\left(9D\right). \tag{2}$$

Here equal intensities of waves moving along the magnetic field in opposite directions are assumed. The momentum diffusion is vanished ($D_{pp} = 0$) if all waves move in one direction along the magnetic field with the same phase velocity. The flow of waves carry particles along the field in this case and the convection with velocity determined by the phase velocity of waves appears in the transport equation for cosmic rays, see Skilling (1975a), Berezinsky et al. (1990) for detail. Clearly the cosmic ray convection also arises as a result of the large scale motion of the interstellar gas with frozen magnetic field.

The random component of interstellar magnetic field with an extended spectrum of inhomogeneities can give the resonant particle scattering and spatial diffusion of cosmic rays. Information on the interstellar turbulence spectrum have been obtained from radio scintillation and refraction observations (sensitive to fluctuations of thermal electron density), measurements of the differential Faraday rotation angles from distant sources (mainly produced by fluctuations in the interstellar magnetic field), and the observations of random motions in the interstellar gas. These data are consistent with the assumption that a single close-to-Kolmogorov spectrum extends from scales 10^8 to 3×10^{20} cm, see Armstrong et al. (1995) and references therein. The Kolmogorov spectrum is of the form $W(k) \propto k^{-5/3}$. Other types of spectra frequently used to describe the interstellar turbulence are $W(k) \propto k^{-2}$ for the shock-dominated turbulence, see e.g. the model by Bykov and Toptygin (1987), and spectrum $W(k) \propto k^{-3/2}$ suggested by Iroshnikov (1964) and Kraichnan (1965) in their phenomenological theory of MHD turbulence. Comprehensive reviews of MHD turbulence with application to the interstellar conditions have been given by Zhou et al. (2004), Elmegreen and Scalo (2004), and Scalo and Elmegreen (2004).

The estimate based on the empirical value of the diffusion coefficient for GeV particles (see section 3.1) gives the level of turbulence at the principal scale $k_{\mathrm{L}} = 10^{-21}$ cm^{-1} of the order $\delta B_{\mathrm{tot}}/B \sim 0.2$ for an Iroshnikov-Kraichnan spectrum $W(k) \propto k^{-3/2}$ ($a = 1/2$) and $\delta B_{\mathrm{tot}}/B \sim 1$ for a Kolmogorov-type spectrum $W(k) \propto k^{-5/3}$ ($a = 1/3$). At the same time, the data on Faraday rotation angles favor the Kolmogorov spectrum with $\delta B_{\mathrm{tot}}/B \sim 1$ and $k_{\mathrm{L}} = 10^{-21}$ cm^{-1}. The cascades of Alfvén waves (with the scaling $k^{-5/3}$) and the fast magnetosonic waves ($k^{-3/2}$) are independent and may coexist in the Goldreich and Sridhar (1995) model of MHD turbulence. The amplitude of Alfvén wave cascade may dominate at the principle scale.

There are two physical explanations of the observed secondary-to-primary nuclei ratios in the diffusion model with a static cosmic ray halo.

The first explanation (Simon et al. 1986, Seo and Ptuskin 1994) refers to the diffusion model with distributed reacceleration of cosmic rays by the interstellar MHD turbulence which scatters particles and provides their spatial diffusion. The Kolmogorov-type spectrum is assumed that leads to the rising with rigidity of the diffusion coefficient $D \propto v(p/Z)^{1/3}$. For typical value of Alfvén velocity $V_a \sim 30$ km s^{-1}, the reacceleration is not essential for nuclei with energies $E > 40$ GeV/nucleon and the abundance of secondary nuclei is a decreasing function of rigidity. The impact of reacceleration on spectra of primary and secondary nuclei becomes stronger at smaller energies so that the characteristic time of distributed acceleration in the Galaxy becomes equal to the time of diffusion from the Galaxy at about 1 GeV/nucleon. In consequence the pronounced peak in the secondary-to-primary ratio arises, see Figure (4). The asymptotic behavior of the escape length is $X \propto v(p/Z)^{-1/3}$ at $E > 40$ GeV/nucleon.

The second explanation (Ptuskin et al. 2006) assumes that the Iroshnikov-Kraichnan spectrum describes the interstellar MHD turbulence. It is characterized in particular by a relatively slow nonlinear cascade of wave from small to large wave numbers. The resonant wave-particle interaction results in the significant wave damping on cosmic rays and termination of the cascade at $k \sim 10^{-12}$ cm^{-1} (in contrast to the case of Kolmogorov cascade which is fast and not noticeably affected by cosmic rays). The amplitude of short waves is suppressed and the low energy particles rapidly exit the Galaxy without producing many secondaries. It explains the peaks in secondary/primary nu-

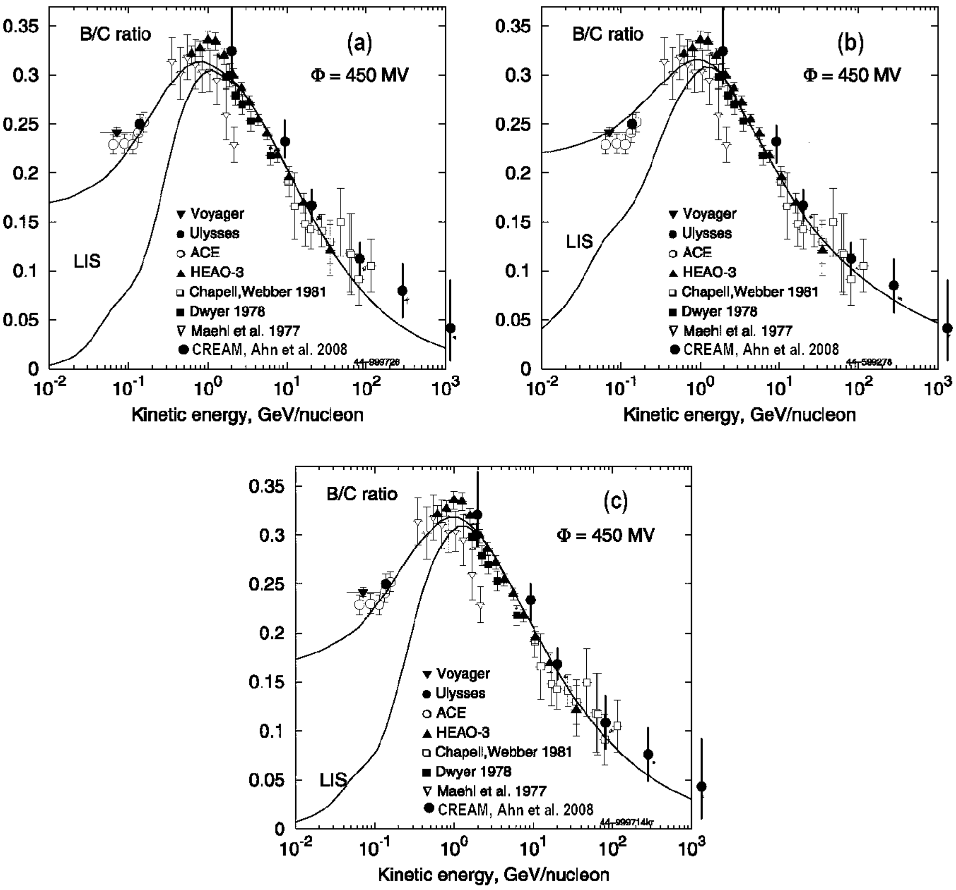

Fig. 4 B/C ratio as calculated in plain diffusion model with unphysical break of the diffusion coefficient(a), reacceleration model (a), and diffusive reacceleration with damping model (c). Lower curve – local interstellar spectra, upper – modulated (with modulation parameter $\Phi = 450$ MV). Data below 200 MeV/nucleon: ACE (Davis et al. 2000), Ulysses (Duvernois, Simpson, and Thayer 1996b), Voyager (Lukasiak 1999); high energy data: HEAO-3 (Engelmann et al. 1990), CREAM (Ahn et al. 2008) for other references see Stephens and Streitmatter (1998).

clei ratios at about 1 GeV/nucleon, see Figure (4). The asymptotic behavior of the scape length in this case is $X \propto v(p/Z)^{-1/2}$ at $E > 3$ GeV/nucleon.

It is clear from Figure (4) that the experimental data on the abundance of secondary nuclei are well described by both physical models. Also illustrated in Figure (4) are the results of calculations in the plain diffusion model with the empirical diffusion coefficient of the form $D \propto \beta^{-2}$ and $\beta^{-2}(p/Z)^{0.6}$ below/above 3 GV chosen to fit the B/C data (the "unphysical" model).

It must be emphasized that the theoretical description of MHD turbulence is a complicated and not completely solved problem even in the case of small-amplitude random fields. Since the mid 1990s, there has been a renewed interest in understanding of magnetohydrodynamic turbulence as it applies to the interstellar magnetic field and density fluctuations (Goldreich and Sridhar 1995, 1997, Galtier et al. 2000). Goldreich and Sridhar (1995) exploited anisotropy in MHD turbulence and obtained Kolmogorov-like spectrum for the energy density of Alfvén waves. The main part of the energy density in this turbulence is concentrated perpendicular to the local magnetic field wave vectors $k_\perp \approx k$, while the parallel wave numbers are small: $k_\parallel \sim \left[kW(k)/\left(B_0^2/4\pi\right)\right]^{1/2} k_\perp$. The cascade is anisotropic with energy confined within the cone $k_\parallel \propto k_\perp^{2/3}$. This turbulence does not significantly scatter cosmic rays. The distribution of slow magnetosonic waves passively follows that of Alfvén waves (Lithwick and Goldreich 2001). They are not damped on cosmic rays (because of the property $k_\perp \gg k_\parallel$) and are probably responsible for the observed interstellar electron density fluctuations. The fast magnetosonic waves with the Iroshnikov - Kraichnan spectrum $W(k) \propto k^{-3/2}$ may have an independent nonlinear cascade which is isotropic and can efficiently scatter cosmic rays. These conclusions were supported by numerical simulations by Cho and Lazarian (2002). This concept of the MHD turbulence favors the second of the discussed above scenarios where cosmic rays are scattered by fast magnetosonic waves with the Iroshnikov-Kraichnan spectrum and suppress the turbulence at large wave numbers $k \geq 10^{-12}$ cm^{-1}.

The knowledge of the diffusion coefficient is absolutely essential for understanding the nature of the spectrum of galactic cosmic rays that is determined by the processes of acceleration in the sources (supernova remnants) and propagation in galactic magnetic fields. Two specific asymptotic power laws of the diffusion coefficient $D \propto (p/Z)^{1/3}$ and $D \propto (p/Z)^{1/2}$ at very high energies together with the observed spectrum approximated by the power law $J \propto E^{-2.7}$ imply the cosmic ray source spectra close to $q \propto E^{2.2}$ and $q \propto E^{2.4}$ respectively.

The contemporary modelling of cosmic ray production by supernova remnants was achieved by Ptuskin et al. (2010). The spectra of high-energy protons and nuclei accelerated by supernova remnant shocks were calculated taking into account magnetic field amplification and Alfvénic drift both upstream and downstream of the shock for different types of supernova remnants during their evolution. Four different types of SNRs (Ia, Ib/c, IIP and IIb) with corresponding burst rates were included in the calculations. The action of cosmic ray pressure on the shock structure was taken into account in the calculations. It was found that the maximum energy of accelerated particles may reach $5 \cdot 10^{18}$ eV for Fe ions in Type IIb SNRs. The steady state spectrum of cosmic rays produced by SNRs in the Galaxy was calculated with the deduced source spectra of protons and different kind of nuclei up to Iron. The escape length with a high energy asymptotic $X \propto (p/Z)^{-0.54}$ determined by Jones et al. (2001) by the accurate fit to B/C data was used in the calculations. The derived energy spectrum of cosmic rays including the knee structure around 3×10^{15} eV is in good agreement with the spectrum measured at the Earth from low energies to about 5×10^{18} eV. This result is strongly in favor of the cosmic ray galactic diffusion on the MHD turbulence with spectrum close to $k^{-3/2}$. The Kolmogorov type spectrum $k^{-5/4}$ is unlikely.

The diffusion approximation cannot be used when the diffusion mean free path $l = 3D/v$ exceeds the size of cosmic ray halo $H \approx 4$ kpc that occurs at $E > 2 \times 10^{16} Z$ eV if $D \propto (p/Z)^{1/2}$. Calculations of particle trajectories in galactic magnetic field are needed to study cosmic ray propagation at these ultra high energies. At weaker dependence, $D \propto (p/Z)^{1/3}$, the diffusion approximation breaks at higher energies. The main limitation in this case is the inefficiency of particle scattering at $r_g k_{\mathrm{L}} > 1$ when the diffusion coefficient along the average magnetic field rapidly rises with energy as $D \sim v r_g^2 k_{\mathrm{L}}$, see e.g Toptygin (1985). This regime is realized at $E > Z \times 10^{17}$eV. The direct numerical modelling of particle motion in the regular and random galactic magnetic fields (Hörandel et al. 2007) confirmed the presented order of magnitude estimates. The most essential feature of cosmic ray transport at ultra-high energies above about 10^{17}eV is the prevalence of the drift motion across predominantly azimuthal average galactic magnetic field (Zirakashvili et al. 1998). It leads to the inverse dependence of the exit time from the Galaxy on particle momentum $T \propto (p/Z)^{-1}$.

3.3 Instabilities and plasma effects

Cosmic rays not always can be treated as test particles moving in given regular and random magnetic fields (Ginzburg 1965, Wentzel 1974, Cesarsky 1980, Kulsrud 2005). The energy density of cosmic rays estimated as $w_{cr} = 1 - 2$ eV cm^{-3} is approximately equal to the energy density of the magnetic field and to the energy density of turbulent motions of the interstellar gas. The presence of relativistic charged particles in the interstellar medium leads to collective (plasma) effects during cosmic ray propagation.

A notable example is the cosmic ray streaming instability which develops when the bulk velocity of cosmic rays exceeds the Alfvén velocity V_a. The growth rate of MHD waves amplified by relativistic charged particles with number density $n_{cr}(E) \propto E^{-\gamma+1}$ at the resonance wave number $k_{\mathrm{res}} = r_g^{-1}(E)$ is

$$\Gamma_{\mathrm{cr}} \approx \Omega_{\mathrm{p}} \frac{n_{\mathrm{cr}}}{n} \left(\frac{v\delta_{\mathrm{cr}}}{(\gamma+2)V_{\mathrm{a}}} - 1 \right), \tag{3}$$

where Ω_{p} is the gyrofrequency of thermal protons, δ_{cr} is the amplitude of cosmic ray anisotropy. Even for small anisotropy, $\delta_{\mathrm{cr}} \approx 10^{-3}$, the instability for galactic cosmic rays with energies ~ 100 GeV develops in about 10^5 years, i.e. rather rapidly for the galactic timescale. The development of the instability leads to isotropisation of the angular distribution of particles and turbulence amplification, see Zweibel (2003), Farmer and Goldreich (2004) and references cited therein. Plasma effects make the overall picture of cosmic ray diffusion in the Galaxy more complicated than it was discussed in Section 3. In principle, the cosmic ray diffusion coefficient should be calculated selfconsistently with the account taken for the generation of turbulence by streaming cosmic rays. The examples of such approach and the corresponding transport equations can be found in the papers by Skilling (1975a,b) and Ptuskin et al. (2008). The necessity of considering the variety of dissipation processes of linear and nonlinear wave dissipation in the interstellar medium adds complexity to the investigation and makes the results strongly dependent on the interstellar gas parameters: the density, the state of ionization, the temperature. The wave dissipation makes the effect of streaming instability not efficient at high energies since the cosmic ray density is going down with particle energy and the growth rate Eq. 3 is decreasing correspondingly. One of the exceptions is the model of galactic wind driven by cosmic rays in a rotating galaxy developed by Zirakashvili et al. (1996) (it is briefly described at the end of the present Section). Moving predominantly along the very long spiral magnetic field lines, the cosmic rays have enough time to amplify the resonant waves even at high energies of the order 10^{15} eV.

The effect of the streaming instability is more significant in the vicinity of the sources. The amplification of magnetic field by the cosmic-ray streaming instability at the shock in supernova remnant is an integral part of cosmic ray acceleration (Bell 1978, Blandford and Eichler 1987, Malkov and Drury 2001, Bell 2004, Zirakashvili and Ptuskin 2008, Marcowith and Casse 2010, Bykov et al. 2011). The cosmic rays produce turbulence which selfconsistently determines the cosmic ray diffusion coefficient in the shock vicinity.

Cosmic rays may induce, in addition to kinetic effects, significant hydrodynamic effects in the Galaxy. Accounting for cosmic ray pressure is principally important for the formation of a halo filled with gas, magnetic field, and relativistic particles. The equilibrium distribution of the interstellar medium above the galactic plane in the gravitational field of stars is subject to the Parker instability (Parker 1966). Cosmic rays play a significant role in the development of this instability. The instability gives rise to large-scale turbulence and helps sustain an almost equipartition energy distribution among cosmic rays, magnetic fields, and turbulent gas motions. The characteristic time for instability development is $\sim 10^7$ years in the gaseous galactic disk, and $\sim 10^8$ years in the gas halo. Parker (1992) showed that magnetic arches and loops appearing above the galactic disk due to the action of cosmic rays are necessary for $\alpha\omega$ dynamo to operate, which is primary mechanism of magnetic field generation in the Galaxy. A numerical model of the magnetohydrodynamical dynamo, driven by cosmic rays in the interstellar medium was developed by Hanasz et al. (2004). The cosmic rays in the model were accelerated in randomly occurring supernova remnants. The cosmic ray propagation was accounted with the diffusion-advection equation supplementing the MHD equations (see also Hanasz et al. 2006). The other essential elements of the model are: vertical gravity of the disk, differential rotation and resistivity leading to reconnection of magnetic field lines. They obtain amplification of the large-scale magnetic field on a timescale of galactic rotation. The model includes the ideas of a fast, cosmic ray driven, galactic dynamo proposed by Parker (1992). The authors find that both the resistivity and the introduced SN activity enhance the efficiency of the cosmic-ray dynamo. The timescale of magnetic field amplification in this model was as short as 140 Myr (Hanasz et al. 2006). The models assumed some CR diffusion prescriptions. A linear study of the effect of the anisotropic CR diffusion with very different but finite parallel ($\kappa_{\|}$) and transverse diffusion coefficients was performed by Ryu et al. (2003). It has been shown that the finiteness of parallel

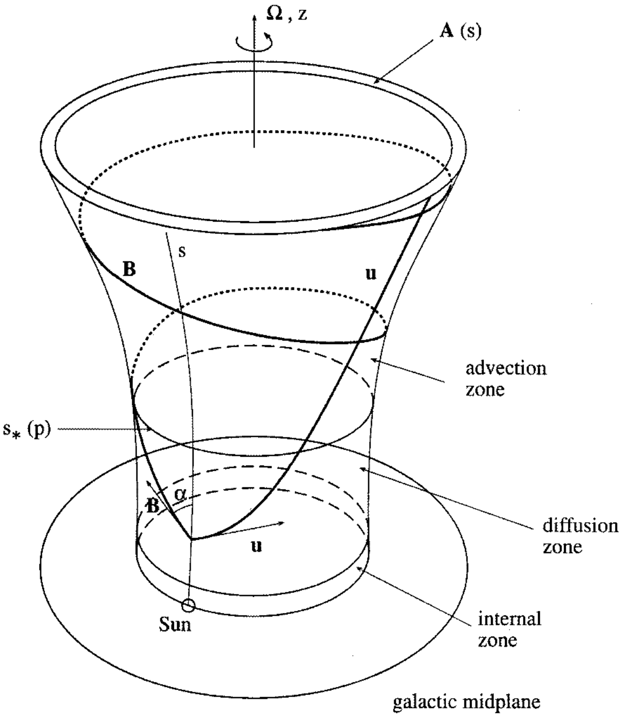

Fig. 5 The structure of the galactic wind flow driven by cosmic rays (Ptuskin et al. 1997). The large-scale magnetic field lines, the flow streamlines and the trajectories of cosmic ray bulk motion from the Galaxy are confined in the same flux tubes. The cylindrical flux tube with the cross section $\mathbf{A}(s)$ originating at the Sun location is shown (here s is the coordinate along the flux tube). Diffusion mainly determines the cosmic-ray transport in the diffusion zone (the analog of the boundary layer), whereas convection mainly makes it in the advection zone. The boundary between two zones $s_*(p)$ is moving up with energy of cosmic-ray particles.

diffusion slows down the development of the Parker instability. However, with a realistic value of $\kappa_{\|} = 3 \times 10^{28}$ cm^2 s^{-1} in the ISM, the maximum growth rate is smaller by only a couple percent than that for $\kappa_{\|} \to \infty$, and the range of unstable wavenumbers remains the same. The inclusion of perpendicular diffusion with $\kappa_{\|} = 0.02\kappa_{\perp}$ does not change the growth rate noticeably. It should be noted however, that the turbulent advection due to magnetic fluctuations of scales larger than the CR mean free path would make the diffusion coefficient nearly isotropic on scales interesting for the Parker instability (see Bykov and Toptygin 1993). A non-linear development of Parker instability was simulated by Kuwabara et al. (2004). They stated that the growth rate of the instability is larger in the models with smaller diffusion coefficient only in the early linear stage. On the later stages the growth rate becomes smaller when compared to that of the large diffusion coefficient model. The growth of instability is impeded by the CR pressure gradient force interfering with the falling motion of the matter in the small- $\kappa_{\|}$ model, while the magnetic loop can grow up to larger scales in the models with large $\kappa_{\|}$.

It is possible that the gas in the galactic halo is not in static equilibrium but is involved in large-scale convective motion - the galactic wind. The data on galactic soft X-ray emission suggest that a wind exists in our Galaxy, see Everett et al. (2007). It can be supported by cosmic ray pressure (Ipavich 1975, Breitschwerdt et al. 1991). A model was constructed by Zirakashvili et al. (1996) where cosmic rays, after leaving the sources (supernova remnants), determine the wind outflow in the rotating Galaxy with a frozen magnetic field. see Figure (5). Here, the streaming instability of cosmic rays exiting the Galaxy along the spiral magnetic field lines leads to the MHD turbulence generation, that self-consistently determines the diffusion-convection transport of relativistic particles. The level of turbulence is regulated by the nonlinear Landau damping on thermal ions. The outflow velocity is ~ 30 km s^{-1} at a distance ~ 20 kpc, and the speeds up to a velocity of ~ 400 km s^{-1} several hundred kpc away. The external pressure of the intergalactic gas produces a termination shock at a distance of ~ 300 kpc. In this model, the diffusion coefficient of cosmic ray is not given independently and is self-consistently calculated, being dependent on the power of sources and the spectrum of accelerated particles (Ptuskin et al. 1997). Remarkably, the obtained transport coefficients and other model parameters are consistent with the empirical diffusion-convection model, e.g. Bloemen et al. (1993), for cosmic ray propagation in the model with galactic wind. It should be emphasized that the existence of a galactic wind, either thermal or driven by cosmic rays, remains hypothetical. However, Everett et al. (2008) found that the observed galactic soft X-ray emission can be better explained by a wind than by the static gas models and the cosmic ray pressure is essential to drive the wind.

4 The highest energy cosmic rays

The "Hillas diagram" discussed above predicts that the compact sources like gamma ray bursts (GRB) (see e.g. Mészáros 2006, for a review) are potential sources of UHECRs (Vietri 1995, Waxman 1995, Milgrom and Usov 1995, Waxman 2004), as well as the cosmological sources like active galactic nuclei (AGN), radio galaxies (see e.g. Longair 2010, Blasi 2006), and clusters of galaxies (e.g. Norman et al. 1995). The observed widespread warm-hot intergalactic gas was likely heated by large scale cosmological shocks. The shocks in the Large Scale Structure formation scenario are driven by gravitationally accelerated flows (e.g. Kang et al. 2005). Non-thermal emission observed from clusters of galaxies indicate the presence of accelerated particles in scales larger the galactic halo sizes (e.g. Ferrari et al. 2008). Large-scale accretion shocks in the cluster of galaxies and more generally cosmological shocks in Large Scale Structure can accelerate particles to energies above 10^{19} eV. Namely, Norman et al. (1995) argued that cosmological shocks can be good sites for UHECR acceleration if there is an intergalactic field of order 10^{-9} G and even more important if microgauss regime fields can be self-generated in shocks accelerating particles. The maximal energies cosmic rays accelerated in the large scale shocks like the cluster accretion shocks or hot spots in radio galaxies can reach $\sim 10^{19}$ eV regime only if indeed microgauss fields can be produced (Norman et al. 1995). Current cosmological shock simulations (e.g. Bykov et al. 2008, Dolag et al. 2008) and the non-thermal emission models (e.g. Kushnir et al. 2009) are in favor of the reality of microgauss regime magnetic fields in clusters of galaxies. On the other hand the losses caused by interactions of the UHECRs with photons of the Cosmic Microwave Background Radiation could limit the maximal energies of protons accelerated in clusters of galaxies (see e.g. Vannoni et al. 2009).

4.1 Ultra-high energy cosmic rays as probes of magnetic fields

At the highest energies, the gyroradius of the cosmic rays becomes extremely large, especially in the intergalactic space where the magnetic fields are expected to be much lower than in the Galaxy. Their mode of propagation thus changes from being diffusive to being asymptotically rectilinear, so at extreme energies it is realistic to think of the possibility of a cosmic ray astronomy, with the sources of ultra-high energy cosmic rays (UHECRs) being identifiable directly. For example a proton of energy $6\,10^{19}$ eV will be deflected by $1°$ to $5°$ in the galactic magnetic field depending upon the direction and length of the trajectory.

On the one hand, being able to actually *see* the UHECR sources would be a remarkable breakthrough: i) it would (at least partially) solve the mystery of their origin, ii) it would put strong constraints on the acceleration mechanism and its efficiency, teaching us a lot about the physics of particle acceleration in the universe in its most extreme manifestations, and iii) it would offer an important piece of information, complementary to that gathered from multi-wavelengths observations of photons, to guide us in the astrophysical modeling of the sources. This would indeed enhance the power of current multi-messenger analysis, which are mostly relying on upper limits.

On the other hand, if we could be sure to know the source of (at least a set of) UHECRs, we could use these particles as messengers, not only to gather new information about the sources, but also to probe the intervening magnetic fields, by studying the deflections they suffered along their journey to the Earth.

In the following, we review the current status of UHECR observations, and discuss some of their implications. We also discuss why a new generation of detectors can be expected to lead to the above-mentioned breakthrough, and what can already be learned from the current data, including from the fact that its statistics is still insufficient. But to understand the data, we first need to understand the transport of UHECRs, and see how it can modify their energy spectrum, their composition and their arrival directions.

4.2 UHECR transport: energy, mass and direction

The key ingredient of UHECR transport in the extragalactic space is the so-called GZK effect, which refers to the interactions of the high-energy cosmic rays with the background radiation fields in the universe (Greisen 1966, Zatsepin and Kuzmin 1966). In the case of high-energy protons, the dominant interactions are with the photons of the cosmological microwave background (CMB), producing electron-positron pairs and/or pions as soon as the proton energy is high enough for the CMB photons to exceed the reaction threshold, when boosted in the proton rest frame. These interactions lead to strong energy losses, especially above $\sim 6\,10^{19}$ eV, when photopion production becomes important, which significantly limits the distance UHE protons can propagate in the universe (see e.g. Bhattacharjee and Sigl 2000, for a review). This translates into an effective horizon, from beyond which extragalactic sources cannot contribute to the observed UHE protons, and this in turn implies an expected strong suppression of the flux, referred to as the GZK cutoff. At lower energy, energy losses due to photopair-production on the CMB photons also modify the spectrum of UHE protons, producing a dip around $3\,10^{18}$ eV, where the ankle is observed in the overall CR spectrum (Blumenthal 1970, Berezinskii and Grigor'eva 1988). Another simple interpretation of the ankle, however, is that it marks the transition from galactic to extragalactic cosmic rays.

As already noted in the original work of Greisen (1966) and Zatsepin and Kuzmin (1966), a similar effect holds for heavier nuclei, which can be photodissociated by CMB and/or infrared photons as they propagate through the intergalactic space. The propagation of ultra-high-energy nuclei in the intergalactic space was studied in detail by Puget et al. (1976), and recently revisited with updated and additional cross-sections (Khan et al. 2005, Allard et al. 2005). A key result is that photodissociation is very efficient at ultra-high-energies, and lead to: i) a modification of the composition of UHECRs as they propagate from their sources to the Earth, as well as ii) energy losses associated with the loss of nucleons (although pair production also plays a role at lower energy, to a first approximation the nuclei essentially keep a constant Lorentz factor).

The energy threshold for the photodissociation of UHE nuclei depends on the energy of the background photons, as well as on the mass of the nuclei. At the threshold, the dominant process is the excitation of the giant dipole resonance, involving photons around 10 MeV in the nucleus rest frame. Photons in the tail of the CMB distribution reach this energy for nuclei with a Lorentz factor of the order of $\Gamma \gtrsim 10^9$, and energies $E \sim A \times \Gamma m_{\mathrm{p}} c^2$, where A is the mass number of the nucleus. Thus, heavier nuclei can survive photodissociation up to higher energies. By a striking coincidence of Nature, although the processes involved are very different, and the cross section thresholds and sizes are also different, the energy loss length for UHE protons and for Fe nuclei are essentially the same in the intergalactic space, so both species have a very similar horizon structure. Therefore, their elemental GZK cutoff leads to the same spectral shape, and indeed the energy distribution of UHECRs can be understood just as well in terms of pure proton sources or of pure Fe sources (or a combination of both, provided the source spectral index and/or the evolution of the source luminosity as a function of redshift is adjusted correspondingly). In principle, intermediate mass nuclei may also be accelerated in the same UHE sources. However, at a given energy, their Lorentz factor is smaller than the Lorentz factor of Fe nuclei, so they see higher energy photons and get dissociated more rapidly. As a consequence, the very highest energy cosmic rays are likely to be mostly protons and/or Fe nuclei (heavier nuclei would also survive, but *a priori* they are much less abundant in the sources).

The studies on the propagation of UHE nuclei by Allard et al. (2005, 2007) also drew a renewed attention to the question of the galactic/extragalactic transition, whose energy scale turns out to depend on the assumed UHECR source composition. Schematically, a pure proton composition (at the sources) would allow one to fit the high energy spectrum down to below 10^{18} eV, assuming a steep source spectrum (in $E^{-\alpha}$, with $\alpha \sim 2.6$ or 2.7, depending on the assumptions on the cosmological source evolution), and would then imply a galactic/extragalactic transition at a few times 10^{17} eV. Conversely, a mixed source composition (e.g. similar to that of low energy cosmic-rays in the Galaxy) would allow one to fit the energy spectrum with a source spectral index $\alpha \sim 2.3$, and imply that the extragalactic component overcomes the galactic one at the ankle (Allard et al. 2005). We note in passing that this question is also related to the question of the galactic magnetic fields, which must be able to confine the cosmic rays up to the transition energy.

Any information about the UHECR composition would thus have important implications for the general phenomenology of cosmic rays, including low energy ones. Unfortunately, a corollary of the above remarks is that the overall UHE spectrum cannot be used, on its own, to constrain the source composition of the UHECRs. A direct measurement of the mass of UHE particles is thus very important, and although this is experimentally difficult, noticeable progress has been made recently (see below). However, it is fair to say that the experimental situation is not clear yet, and since the measurements also rely on hadronic physics at energies well beyond the energy accessible through direct experiments, it is not clear how conclusively this kind of measurements can resolve the issue in the near future.

In this context, two other aspects of UHECR transport can play a role, which are worth mentioning here since they also involve magnetic fields. First, the interactions associated with the above-mentioned GZK effect(s) produce secondary particles, including the so-called cosmogenic neutrinos and the electromagnetic cascades initiated by secondary gamma-rays (from pion decay) or electrons and positrons. These cascades involve the usual mechanisms of synchrotron radiation, pair production and inverse Compton interactions (see e.g., in the context of UHECR propagation, Bhattacharjee and Sigl 2000). These secondary particles can in principle be detected (or their fluxes constrained). In the case of secondary neutrinos, the expected flux and energy distribution strongly depends on assumptions about the phenomenology of the UHECR sources (for a recent update, including scenarios with a mixed composition, see Allard et al. 2006, Kotera et al. 2010, and references therein). It should also be noted that secondary particles produced in the acceleration site may be detected or constrained, and thus provide additional, multi-messenger information about the UHECR sources and their environment, as well as about the acceleration mechanism itself. Finally, extragalactic magnetic fields can also be constrained by the observation of TeV gamma-ray halos around potential acceleration sites. Recently Taylor et al.

(2011) discussed the constraints on the strength of extragalactic magnetic field derived from the simultaneous detections of TeV emitting blazars in GeV photons by the *Fermi* telescope. The measured GeV flux was found to be lower than that calculated in the cascade model under the assumption of zero magnetic field. Assuming that the reason for the suppression of the cascade component is the extended nature of the cascade emission, the authors concluded that the extragalactic magnetic field above 10^{-15} G of correlation length of 1 Mpc is consistent with the data.

The second aspect, directly associated with magnetic fields, is the deflection of UHE particles between their sources and the Earth. If the source of each individual cosmic ray was known, the angular distance between the source and the arrival direction would give a very precious measurement of the deflection integrated along the path of the cosmic ray. Since the deflection, in a ballistic or semi ballistic regime, is proportional to the particle charge, an analysis of the deflection patterns would provide information about the UHECR charges and/or about the intervening magnetic fields. Although the identification of sources apparently remains out of reach of the current detectors, we shall mention below what the current observational situation can nevertheless teach us, and why this situation is expected to change with a ten times larger statistics at the highest energies. It should also be mentioned that additional hints about the composition of UHECRs might come from the study of their anisotropies, comparing patterns in the arrival directions at different energies and/or angular scale. The basic idea is that protons of energy E have the same gyroradius as heavier nuclei with energy $Z \times E$. Now, in a regime where energy losses can be neglected in a first approximation (say, below the GZK energy scale), the angular transport of the different UHE particles only depend on their gyroradii. Therefore Fe nuclei from a given source follow exactly the same path as protons at an energy 26 times lower. This has recently been turned into a very interesting argument by Lemoine and Waxman (2009), relating anisotropy studies at different energies to composition assertions. Extensive studies with larger statistics should provide important clues about this crucial issue in the future. Likewise, at the highest energies, if the number of sources is low and a few hot spots appear in the UHECR sky, halos of different angular sizes around the centroid of the source should appear, corresponding to different nuclear species (essentially protons and Fe or sub-Fe nuclei, if both are present at the source).

More generally, it is clear that the study of the UHECR angular deflections have a lot to teach us, both about the cosmic rays and about the intervening magnetic fields. The main aspects of this transport can be summarized as follows. We may distinguish deflections occurring: i) at or around the sources, ii) in the intergalactic space, and iii) in the Milky Way. Even though the sources remain unknown, it is not unlikely that they are embedded in environments where large scale magnetic fields exist, e.g. in galactic clusters. These magnetic fields may be able to deflect even the highest energy CRs significantly, or even confine them for some time before they escape from the source environment. This can have an effect of the energy spectrum reaching out in the intergalactic space, if the confinement time becomes comparable to the energy loss time. It may also affect the composition of the UHECR leaving the sources, since, at a given energy, heavier nuclei are more easily confined. However, this would require effective lengths of several tens of Mpc at $\sim 10^{20}$ eV. While such a confinement would increase the angular size of the source on the sky, turning it, say, from a localized source to the size of a whole cluster of galaxies for instance, this should not affect our ability to identify clusters of events from individual sources on the sky, as long as the number of sources is limited (as expected at the highest energies) and their typical angular separation is larger than the apparent size of the confinement halo. Finally, it is worth noting that a specificity of UHE cosmic rays, compared to the low-energy, galactic ones, is that the constancy of the fluxes cannot be assumed anymore, since the dynamical timescales of the sources can be shorter than the confinement timescales around them and/or the differential propagation timescales to the Earth. This may result in time dependent effects (on time scales of typically thousands to tens of thousands of years) as to which sources contribute to the observed flux at different energies, as well as in different mass ranges, depending on the elapsed time since their activity as UHECR sources.

Once they leave their sources, UHECRs may also be deflected by magnetic fields in the intergalactic voids, if their strength is large enough. This, however, is highly uncertain. Among the interesting effects that may be associated with such magnetic fields, the existence of a magnetic horizon has received particular attention, as it was realized that it could act as an anti-GZK effect, i.e. essentially a high-pass filter for energetic particles, preventing lower energy cosmic rays from reaching us from distant sources, if they wander around in the extragalactic space (due to magnetic diffusion) for a time longer than the energy loss timescale, or even the age of the universe (Parizot 2004, Lemoine 2005, Aloisio and Berezinsky 2005). This can have an impact on the matching between the galactic and extragalactic components, and also on the cosmic-ray composition in the corresponding energy range: at a given energy, heavier nuclei diffuse for a longer time than light ones, and thus extragalactic Fe nuclei should not be able to reach us from distant galaxies at a energy as low as protons do. It should be noted, however, that the actual outcome of such propagation effects on the UHECR spectrum and composition depend on the granularity of the sources (Deligny et al. 2004, Aloisio and Berezinsky 2005). If the sources were uniformly distributed in the universe, no effect at all would be expected, so no definite prediction can be made at our current stage of ignorance about the sources, the source density and of course the intergalactic magnetic fields. More recent works have focused on the propagation of UHECRs in strongly inhomogeneous extragalactic magnetic (Kotera and Lemoine 2008c,a). This is indeed a much more plausible assumption, under which UHECRs appear to propagate essentially in straight lines between more localized interactions with large scale magnetized structures, acting as scattering centers. As a consequence, potential hot spots in the UHECR sky may reveal the position of the most nearby scattering centers rather than that of the most nearby sources (Kotera and Lemoine 2008a).

Different aspects of propagation of cosmic rays in IGMF recently have been comprehensively studied Dolag et al. (2005), Globus et al. (2008), Kotera and Lemoine

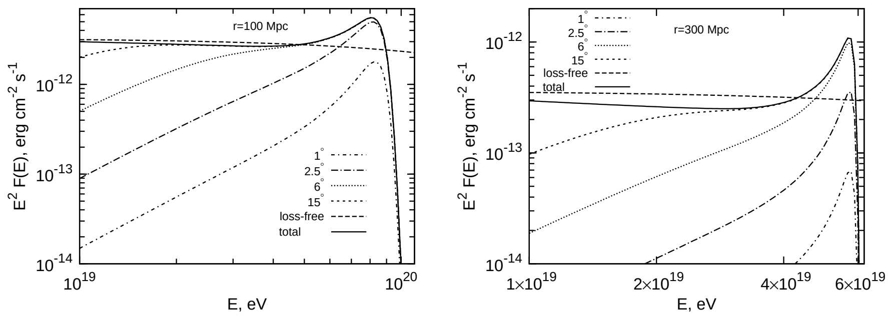

Fig. 6 Energy distributions of protons observed within different angles for the source at distances $r = 100$ Mpc (left panel) and $r = 300$ Mpc (right panel). The energy spectrum of protons is assumed in the form of power-law with exponential cutoff, with $\alpha = 2$ and $E_0 = 3 \times 10^{20}$eV; the rate $L = 10^{44}$erg/s.

(2008b). The conclusions of these studies are generally different, basically because of different assumptions and approaches in the modeling of the IGMF. The propagations of protons and accompanying them gamma-rays and neutrinos recently have been studied by Aharonian et al. (2010) in small angle approximation limit. In Fig.6 we show the energy distributions of protons within different angles arriving from a point source located at distances 100 and 300 Mpc. It is assumed that the source is injects protons into the intergalactic medium with magnetic field 1nG and correlation length $\lambda = 1$ Mpc. The upper dashed lines in Fig.6 correspond to the case when protons propagate in empty space; flux is determined by the geometrical factor $1/r^2$. The solid line present the case when the deflections in the magnetic field are ignored. Comparison of these two curves demonstrates strong dependence of the energy distribution of protons on the solid angle within which they are detected; the flux of protons at highest energies is concentrated along the direction to the source. This is the result of selective deflection of of protons depending on their energy. In addition to this effect there are additional two spectral features – a bump and a sagging at lower energies. The bump preceding the cutoff is due to strong growth of energy losses at the threshold of photomeson production that makes particles to be accumulated in this energy region; the sagging is a consequence of the energy losses due to the electron-positron pair production. However, as it is seen in Fig.6, the maximum due to the deflection is more distinct than the "photoproduction energy loss bump".

Finally, at the other end of the propagation track, the galactic magnetic fields also deflect the UHECRs, with deflections of the order of a degree times the charge of the particle, or possibly much more if an extended magnetized wind surrounds our Galaxy. However, the exact deflection patterns (both size and direction) depend on the structure of the magnetic field, which remains highly uncertain. The regular component should provide a global shift on the sky of the image of the actual UHECR sources, while the turbulent component essentially broadens the apparent cosmic-ray source around that image. Finally, the deflections are expected to be inversely proportional to energy, which should lead to characteristic structures in the arrival direction/energy space. Chains of UHECR events, ordered in decreasing energy away from what would be a common source, have been sought in the various data sets, with no conclusive result so far. Obviously, while such structures would be extremely informative about the source positions as well as about the magnetic field lines responsible, they can be detected only if the sources do not overlap (i.e., at the highest energies, but then, unfortunately, with a limited lever arm in energy), or with much larger statistics, to allow the detection of these patterns on top of a background mixing UHECRs from overlapping sources, with a large enough significance.

In conclusion, the study of UHECR transport in the energy space, mass space and angular space, makes it clear that the road to a better understanding of the sources and phenomenology of UHECRs passes through the joint study of the three fundamental observables (energy spectrum, composition and arrival directions). It should also be stressed that the GZK cutoff, while implying a limitation of the UHECR energies in the universe (independently of the sources) and strongly reducing the expected flux, is also the best chance we have to answer the central questions about UHECRs. As the current data show (see below), no obvious source and/or pattern has appeared in the sky yet. This implies either that the sources are numerous, and we have not seen multiplets (i.e. several events coming from the same astrophysical source), or not strong enough for angular associations in the sky to be significant, or that the overall deflections of UHECRs are large, and the sources largely overlap. The obvious way out is by reducing the number of sources as well as the deflections. This is precisely what the GZK allows (and actually imposes). By reducing the horizon scale as the energy increases, the GZK effect guarantees that fewer and fewer sources contribute at the highest energies. In addition, the number of sources capable of accelerating cosmic rays up to a given energy is likely to be a decreasing function of that energy. In addition, the deflections are inversely proportional to energy, so by concentrating on the UHECR sky at 10^{20} eV or so, we are bound to face a situation where a (very) limited number of sources contribute to the observed flux, with limited deflections and well separated "centroids" of the corresponding hot spots in the UHECR sky. The price to pay for such a situation, of course, is that the corresponding cosmic ray fluxes are very low, so further progress is conditioned by the resolution on an important observational challenge. The target has been set at the level of a total exposure of the sky of several 10^5 up to 10^6 km sr yr (see the recent white papers on UHECRs: Olinto et al. 2009), i.e. more than an order of magnitude larger than what is currently available.

4.3 UHECR Observations

The highest-energy particles are so rare that they are detectable only by means of the giant cascades or extensive air showers they create in the atmosphere. Details of how these extensive air showers are observed and of how the parameters of importance are measured can be found in reviews (e.g. Nagano and Watson 2000). The results that are most relevant to the topic of this chapter have been obtained with the Pierre Auger Observatory (Abraham et al. 2004, Dawson and for the Auger Collaboration 2008) in Argentina and with the HiRes instrument (Boyer et al. 2002) operated in the Dugway Desert, Utah, USA. The HiRes device uses telescopes comprising mirrors and photomultipliers to detect the fluorescence radiation emitted from the excitation of atmospheric nitrogen by the shower particles passing through the atmosphere. The Auger Observatory has similar telescopes but in addition has an array of water-Cherenkov detectors deployed over 3000 km^2 to measure the particles in the showers at ground level. The fluorescence telescopes are used to obtain a measure of how the cascade grows and decays in the atmosphere while the water-Cherenkov detectors are used to obtain the pattern of the distribution of shower particles on the ground from which a shower size, closely proportional to the primary energy, is obtained. With both devices the direction of the incoming cosmic ray is measured with an accuracy of $\sim 1^\circ$ using GPS-based timing.

A 21$^{\text{st}}$ century innovation has been to build instruments combining the fluorescence and the surface detector techniques. This combination has allowed what is known as the hybrid method to be developed in which the time of the shower front traversing one of the detectors on the ground is combined with the times of arrival of light at the photomultipliers of the fluorescence telescopes, to enhance significantly the precision with which the direction, energy and depth of maximum of the showers can be determined. The fluorescence technique has the unique advantage of enabling the energy of a shower to be found without resorting to assumptions about hadronic physics. This makes it possible to calibrate the shower size found with the surface array, and so exploit the near 100% on-time of a surface array. Two implementations of the hybrid approach are now operating: the Pierre Auger Observatory in Argentina and the Telescope Array in Utah (Kawai et al. 2005). Data from the Telescope Array are not yet available and the exposure from the Auger Observatory (early 2010) is about 10 times greater.

4.4 Status of measurements of the energy spectrum

An energy spectrum based on an exposure of 12,790 km^2 sr yr has recently been reported by the Auger Collaboration (Pierre Auger Collaboration et al. 2010b). This exposure is a factor 4 higher than achieved with the HiRes detector at the highest energies and even greater than this at lower energies. When deriving the primary energy from fluorescence measurements, an estimate of the missing energy carried into the ground by hadrons, muons and neutrinos must be made based on assumptions about the mass of cosmic rays and of the hadronic model. For a primary beam that is a 50/50 mixture of protons and iron, it has been found from simulations of showers with the QGSJET01 model of hadronic interactions that the energy found from the fluorescence signal should be increased by 10% (Barbosa et al. 2004). The systematic uncertainties on the energy scale sum to 22% with the largest coming from the absolute fluorescence yield (14%), the absolute calibration of the fluorescence telescopes (9%) and that due to the reconstruction method

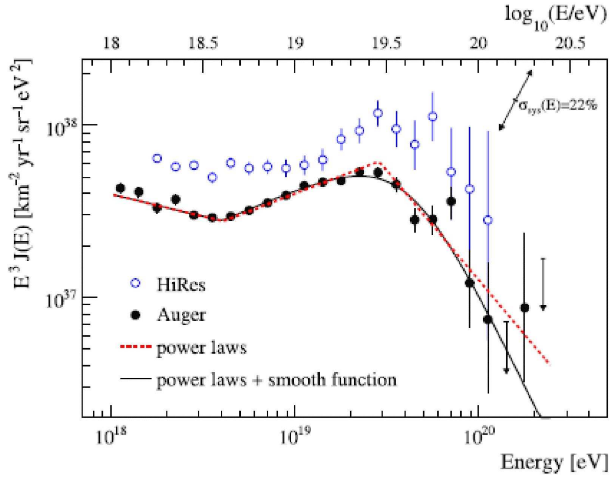

Fig. 7 The Auger energy spectrum. The spectrum is fitted with two functions [see Pierre Auger Collaboration et al. (2010b) for details] and the data are compared with the stereo spectrum of HiRes (Abbasi et al. 2009). The uncertainty of the flux scaled by E^3 arising from the systematic uncertainty in the energy scale of 22% is indicated.

of the longitudinal shower profile (10%). Efforts are underway to reduce these uncertainties.

The Auger spectrum reported in Pierre Auger Collaboration et al. (2010b), and based on over 36,000 events, is shown in Fig. 7 together with the final measurement from the HiRes instrument (Abbasi et al. 2009). It is customary to represent parts of the spectrum with a differential form, $J = kE^{-\gamma}$. It is seen that there is clear evidence of a flattening of the slope at an energy of $\log E(\mathrm{eV}) = (18.61 \pm 0.01)$ where γ changes from (3.26 ± 0.04) to (2.59 ± 0.02). At $\log E(\mathrm{eV}) = (19.46 \pm 0.03)$ the slope increases very sharply to (4.3 ± 0.2). This suppression of the flux is what would be expected because of the GZK-effect and is significant at the level of 20 standard deviations.

An intriguing question is whether the slopes in the region of the suppression are different in the Northern and Southern Hemispheres. This would be expected if the source distribution was different in the two hemispheres with the region with sources at a closer average distance being expected to show a less suppressed slope, assuming that the mean injection spectra are the same. However the present measurements of (5.5 ± 1.8, HiRes) and (4.3 ± 0.2, Auger) are not significantly different and as the HiRes instrument is not longer operating the possibility of any difference will need to be explored with future instruments.

In any case, one may expect that the flux at the very highest energies, namely *in the GZK cutoff region* itself, will be dominated by only a few sources within the horizon. For this reason, the assumption of a uniform source distribution usually made to produce the synthetic spectra used to fit the observed spectrum should not be valid anymore. Even with infinite statistics, the overall spectrum around 10^{20} eV will not be of much interest, as it will be shaped mostly by the most luminous sources that just happen to be here or there in the local sky – in other words, *cosmic variance* is the dominant factor in the region of the spectrum.

The flux above 10^{20} eV, as estimated from the 3 Auger events and 1 HiRes event, is $(2.4^{+1.9}_{-1.1}) \times 10^{-4}\,\mathrm{km}^{-2}\mathrm{sr}^{-1}\mathrm{yr}^{-1}$ or about 1 per square kilometre per millennium. It is really quite remarkable that the energy of such rare events can be measured to within about 20% and indeed estimates of the energies of particle initiating showers at the highest energies are more certain than at 10^{15} eV where there has to be greater reliance on models of hadronic physics.

4.5 Current status of measurements of the arrival direction distribution

From a quick look at the first data recorded with the Auger Observatory at the highest energies it was evident that no strong sources stood out. It is not clear what classes of objects are likely to provide the necessary acceleration sites so a well-defined search strategy to look for signals was adopted. Active galactic nuclei, radio-galaxy lobes and gamma-ray bursts have all been suggested as possibilities and if these are anisotropically distributed and are not too numerous within the distance associated with the GZK-suppression then an anisotropy might be expected. However there is no prediction for source features as compelling as was that of the GZK-effect for the spectral shape. Faced with this dilemma the Auger Collaboration made the decision to search for correlations on different angular scales with objects in a particular catalogue using energy and distance as additional parameters. The catalogue chosen was the Véron-Cetty and Véron (2006) catalogue (VCV) of quasars and active galactic nuclei. Using data recorded between 1 January 2004 and 26 May 2006 a scan was made for a minimum in the probability P for a set of N events expected from an isotropic flux to contain k or more events at a maximum angular distance Ψ from any object in the VCV catalogue. P is given by the cumulative binomial distribution $\sum_{j=k}^{N} C_j^N p^j (1-p)^{N-j}$, where p is the fraction of the sky (weighted by exposure) defined by the region at angular separation less than ψ from a selected source. The parameter space was defined by the angular separation ψ, the maximum red-shift z_{max} and the threshold energy E_{th}. A minimum in P was found with $\psi = 3.1°$, $z_{\mathrm{max}} = 0.018$ ($\sim$ 120 Mpc) and $E_{\mathrm{th}} = 5.6 \times 10^{19}$ eV. With these values, 12 events among 15 correlated with AGNs in the catalogue, whereas only 3.2 would have been expected by chance. These numbers were found after a search and so no probability could be attached to the significance of the association. However the observation led to the definition of a test to validate the result with an independent data set using these parameters a priori. Details of the test are given in Abraham et al. (2007, 2008). The test was applied to data collected between 27 May 2006 and 31 August 2007 using exactly the same reconstruction algorithms as for the initial period. In this independent data set, which had almost exactly the same exposure, 8 of 13 events above the same energy threshold were found to correlate with events in the VCV catalogue. The probability of this occurring by chance is 1.7×10^{-3} and the

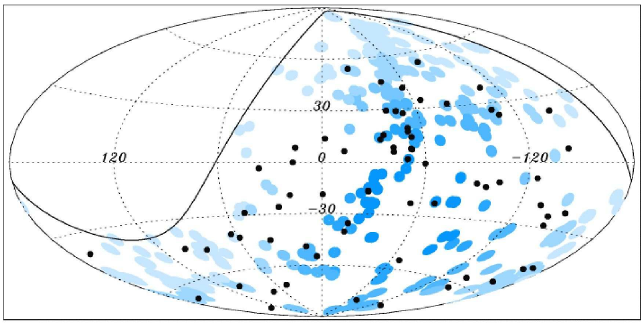

Fig. 8 The directions, in galactic coordinates, of 69 events above 5×10^{19} eV recorded at the Pierre Auger Observatory up to 31 December 2009 (Abreu et al. 2010). The events are shown as black dots on an Aitoff-Hammer projection with the galactic plane across the centre of the diagram. The shaded circles of 3.1° are centered at the positions of 318 AGNs in the VCV catalogue that lie within 75 Mpc and are within the field of view of the Observatory. The darker shading corresponds to greater relative exposure: the exposure weighted-fraction covers 21% of the sky

result was reported (Abraham et al. 2007). This correlation corresponds to an association of (69^{+11}_{-13})%.

The Auger Collaboration has continued to take data and as at 31 December 2009 a total of 69 events above the threshold energy have been recorded (Abreu et al. 2010). The correlation with objects in the VCV catalogue, excluding the 15 events used to define the correlation parameters, is now (38 ± 6)% with 21 events correlated. The fraction expected from an isotropic distribution of event directions is 0.21. From an isotropic flux the cumulative probability of such a correlation is $P = 0.003$. A sky map using an Aitoff-Hammer projection is shown in Fig. 8. With the current estimate of the correlation at 38%, a 5 sigma signal ($P < 3 \times 10^{-5}$) will require 110 events which should be obtained with about 2 further years of operation.

Using a cross-correlation study the Auger Collaboration have also noted that there is an excess of events from the region around Centaurus A (Abraham et al. 2007, 2008, Abreu et al. 2010) with 13 of the arrival directions within 18° of Centaurus A forming 6 pairs separated by less than 4° and 28 pairs separated by 11°. Clearly this is a region of sky that will be studied carefully but as the search was made *a posteriori* no statistical significance can be attached to the observation. No similar object lies as close to us in the Northern Hemisphere.

The HiRes collaboration does not find a similarly correlation of their events with AGNs in the VCV catalogue (Abbasi et al. 2008b). They find that 2 events out of 13 are correlated with VCV objects: this compares with 5 that would be expected assuming that the correlation is really 38%. The difference between 2 and 5 does not rule out a 38% correlation in the northern hemisphere, the part of the sky dominantly observed with the HiRes detector. It may be that the source distributions are different in the two parts of the sky and, with the steeply-falling spectrum, there may be a small difference in the definition of the energy threshold. The situation is inconclusive and will not be clarified until new Observatories are built.

However that may be, keeping in mind that the excess of correlation observed by Auger does not necessarily imply that the AGNs of the catalog are related with the sources, and may simply reflect the accidental correlation between these AGNs and the actual sources in that part of the sky (convolved with the deflections in the intervening magnetic fields), one must be prepared to a situation where other sources in the Northern hemisphere lead to a different level of correlation with the AGNs of that hemisphere. In other words, there is no direct conflict between the observations currently available, and a systematic study of the entire sky with comparable data sets should tell us more about the origin of the detected anisotropy, and what it implies concerning the UHECR sources and deflections.

In the mean time, it is interesting to note that the current data sets do not reveal obvious multiplets or close correlations with known sources. This may be due to a very large number of sources, from which only one event at most has typically been observed so far, or to relatively large deflections, causing the sources to overlap in the sky. In both cases, the observational solution consists in increasing the statistics at high energy, where the deflections are reduced and the horizon scale becomes smaller, so that only a few sources can significantly contribute. The fact that some anisotropy is already detectable gives strong confidence that the expected breakthrough is within reach of the next generation detectors, provided they can gather a statistics of the order of a few $10^5\,\mathrm{km}^2\,\mathrm{sr\,yr}$ or more(Olinto et al. 2009).

From the moment when the first few significant hot spots are observed in the UHECR sky, a new era will begin, with the study of individual sources. As indicated above, this should lead to key parameters such as the source power and spectral shape. The current statistics does not allow one to confirm whether the excess of events possibly seen around the location of Centaurus A is related to the first of such sources, but if it is the case, then the next generation of detectors should accumulate tens or even hundreds of events from that or similar sources.

4.6 Measurement of the chemical composition of the primaries

To interpret the information that we have on the energy spectrum and arrival direction pattern of ultra high-energy cosmic rays we need to know the charge, Z, of the particles, ideally on an event-by-event basis. Then, for example, if one had identified a point source, the bending of the particles from it as a function of energy could be used to distinguish between different models of the magnetic fields lying between the source and earth. However it is very difficult to be sure even of the atomic mass, A, as the only methods that are practical for estimating it require assumptions about the hadronic interactions at centre-of-mass energies well above what will be reached with the LHC.

The concept of the most promising method is to compare the average depth of shower maximum (called X_{max}) as a function of energy for protons, iron nuclei and photons with what is predicted for different hadronic models. The depth of maximum can be determined to $\sim (20 - -30)\,\mathrm{g/cm}^2$

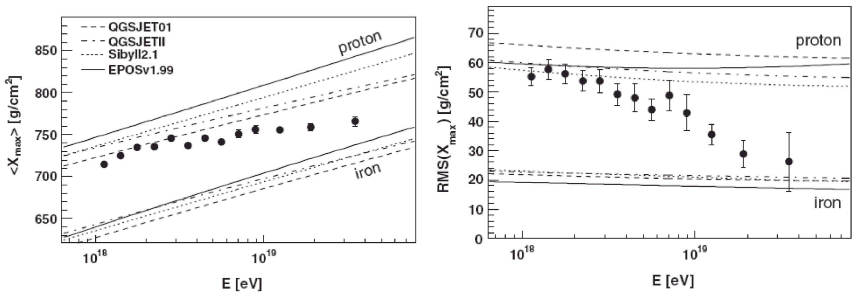

Fig. 9 Left: The average measurements of $X_{\max}$ as a function of energy reported by the Auger Collaboration based on 3754 events compared with the predictions of 4 different calculations (see Abraham et al. 2010, for details). Right: The measurements of the rms of $X_{\max}$ as a function of energy for the data of the figure on the left, compared with calculations (Abraham et al. 2010).

using the fluorescence technique. For a mass composition of a single species, $X_{\max}$ is expected to increase with energy as γ-rays from π^0 decay become more energetic and so the position of shower maximum is pushed deeper into the atmosphere. The average $X_{\max}$ for iron nuclei lies below that for protons because the energy per nucleon of an incoming primary is smaller for heavier nuclei at a given energy. The change of $X_{\max}$ with energy is known as the elongation rate. In addition to the elongation rate being a useful indicator of primary mass, a key parameter is the fluctuation in the depth of shower maximum at a particular energy. It is intuitively obvious that as an iron nucleus is larger than a proton, the cross-section for interaction will be greater. Thus fluctuations in the position of shower maximum also contain information about the primary mass. However, although these parameters can be measured rather accurately, the interpretation of the measurements must rely on models of shower development.

Work on this problem has recently been reported by the Auger Collaboration (Abraham et al. 2010) and by the HiRes Collaboration (Abbasi et al. 2010). With the Auger Observatory the depth of maximum has been determined for over 3700 events of energy $> 10^{18}$ eV. Each event has been reconstructed using the hybrid method: 2% of them are stereo events for which two independent estimates of $X_{\max}$ are made. Using stereo information it can be demonstrated that the accuracy of estimation of $X_{\max}$ in a non-stereo event is $\sim 20\,\mathrm{g/cm^{-2}}$ (about 200 m at the height of the maximum of a typical shower, $750\,\mathrm{g/cm^{-2}}$, or 2.5 km above sea-level in the vertical direction).

The Auger data on the depth and width of the fluctuation of shower maximum are shown in Fig. 9. The predictions for proton and iron nuclei of $X_{\max}$ and rms($X_{\max}$) are given for different models of the hadronic interactions (QGSJET01 etc). It is clear that if these models are approximately correct then the mean mass of the cosmic rays is becoming heavier as the energy increases. However the results from the HiRes collaboration seem to tell a different story. They conclude that their data, totaling 815 events, is entirely consistent with proton primaries from $\sim 3 \times 10^{18}$ eV. The reasons for the differences between the two measurements are not understood. The HiRes result is highly dependent on Monte Carlo calculations whereas the Auger measurement makes very little use of such calculations except, as is true for both measurements, when a comparison is made with the predictions. The Auger Collaboration have taken precautions in their analysis to test that the effects observed are not dependent on zenith angle, demonstrating that deeply penetrating events are not missed, and it is hard to see how distributions can be made too narrow as a consequence of the analysis procedures.

5 Some conclusions and perspectives

Magnetic fields play a key role in the acceleration, propagation and radiation of galactic cosmic rays. Current generation of X-ray *Chandra*, *XMM-Newton* and *Suzaku* and gamma ray telescopes *H.E.S.S.*, *MAGIC*, *MILAGRO*, *VERITAS* and *Fermi* have provided conclusive evidences for CR particle acceleration up to the energies at least about 100 TeV in young supernova remnants, starburst regions, radio galaxies and AGNs. With the coming generation of the focusing hard X-ray telescopes *Astro-H* (Takahashi et al. 2010) and *NuSTAR* (Harrison et al. 2010) new possibilities will be opened to study in details hard X-rays images and spectra that of cosmic ray sources providing unique information on both particle spectra and fluctuating magnetic fields in the sources. A project of very large X-ray telescope *IXO* that is currently under discussion in addition to the unprecedent sensitivity will be likely supplied with X-ray imaging polarimetry (Barcons et al. 2011). Imaging polarimetry is sensitive to details of magnetic field amplification mechanism in the particle acceleration sources like supernova remnants and radio galaxies (Bykov et al. 2009). The Cherenkov Telescope Array *CTA* project under development is the next generation ground-based gamma-ray instrument, which is supposed to provide at least 5 times better sensitivity in the current energy domain of about 100 GeV to about 10 TeV and an extension of the accessible energy range well below 100 GeV and to above 100 TeV.

At extremely high energies, $E \sim 10^{20}$ eV, the impact of galactic and extragalactic magnetic fields on the propagation of cosmic rays becomes less dramatic, which should result in large and small scale anisotropies of the cosmic rays. Although the corresponding fluxes are very low, considerable progress has been made in the recent years, with the detection of the giant cascades (so-called extensive air showers) induced by these cosmic rays in the atmosphere, by large detectors consisting of ground arrays (AGASA), fluorescence telescopes (HiRes) or hybrid detectors (Auger, currently in operation).

The extension of cosmic ray studies up to energies of the order of 10^{20} eV is likely to give rise to what is referred to as “proton astronomy” (or more generally “charged particle astronomy”), where charged cosmic rays are used as astronomical messengers pointing roughly back to their sources, because of the reduced deflections in the intervening magnetic fields. Another key aspect of the cosmic rays phenomenology in this energy range is the existence of a physical horizon, associated with the energy losses suffered by the cosmic rays as they interact with the background radiation fields (notably the cosmological microwave background).

Whether protons or heavier nuclei, particles of such high energies can arrive only from relatively nearby accelerators, say within 100 Mpc, which decreases dramatically the number of potential sources capable of accelerating cosmic rays up to $\geq 10^{20}$eV and contributing to the observed flux. In principle, many weak sources may be at work, which may prevent one from detecting them individually, by the accumulation of events in a given direction. However, even with large source densities, a few most nearby and brightest sources may be expected to contribute a significant fraction of the total flux, in a similar way as what is observed at all photon wavelengths, where a few sources dominate the sky. Alternatively, there may be only a few sources within the horizon, especially if one considers the tough requirements associated with 10^{20} eV proton accelerators (Aharonian et al. 2002). This excludes, in particular, astrophysical objects like ordinary galaxies, unless these galaxies accelerate the highest energy cosmic rays through transient events related to compact objects like Gamma Ray Bursts. Whether we can identify the accelerators of extragalactic cosmic rays using the highest energy protons is a question which largely depends on the strength and structure of the large scale IGMF. However, if the latter are not too large, as seems to indicate the current UHECR data showing anisotropy above 55 EeV or so, the cosmic rays from identified sources may be used in turn to probe the intergalactic magnetic fields in the nearby universe, as well as the structure and strength of the galactic magnetic field, from the observed (energy- and charge-dependent) deflections.

The identification of the first cosmic ray sources by astronomical means, i.e. through hot spots or elongated multiplets with a characteristic rigidity ordering, may be provided by the next generation detectors, either on the ground, with the Northern site of the Pierre Auger Observatory (Blümer and the Pierre Auger Collaboration 2010), proposed for construction over 20,000 km^2, with the proven technique of Auger South and similar performance, or in space, with the *JEM-EUSO* mission (Ebisuzaki et al. 2010), proposed to be installed on the Japanese module of the International Space Station, for an even larger aperture at the highest energies. This is expected to lead to a new era of cosmic ray studies, where nearby sources may be studied individually, and particle acceleration may be explored in the most challenging regime, up to above 10^{20}eV.

Finally, we stress that the strong coupling between cosmic ray studies and the understanding of the magnetic field generation, amplification and structure in the universe calls for an increased exchange of knowledge between the different communities involved. Important progress is expected in both fields in the coming years, and any progress in one of the various aspects of the problem will benefit to the others, and to the whole field of high-energy astrophysics, where energetic particles are responsible for non-thermal emission at all energies, as well as to the physics of the interstellar medium in general, in which the magnetic field is a key component.

Acknowledgements We thank the referee for the constructive comments. A.M.B. was supported in part by RBRF grants 09-02-12080, 11-02-00429 by the RAS Presidium Programm, and the Russian government grant 11.G34.31.0001 to Sankt-Petersburg State Politechnical University. He performed some of the simulations at the Joint Supercomputing Centre (JSCC RAS) and the Supercomputing Centre at Ioffe Institute, St. Petersburg. V.S.P. was supported by RFBR grant 10-02-00110.

References

Abbasi RU, Abu-Zayyad T, Al-Seady M, Allen M, et al. (2009) Measurement of the flux of ultra high energy cosmic rays by the stereo technique. Astroparticle Physics 32:53–60, Arxive0904.4500

Abbasi RU, Abu-Zayyad T, Al-Seady M, Allen M, et al. (2010) Indications of Proton-Dominated Cosmic-Ray Composition above 1.6 EeV. Physical Review Letters 104(16):161 101–+, Arxive0910.4184

Abbasi RU, Abu-Zayyad T, Allen M, Amman JF, et al. (2008a) First Observation of the Greisen-Zatsepin-Kuzmin Suppression. Physical Review Letters 100(10):101 101–+, ArxivearXiv:astro-ph/0703099

Abbasi RU, Abu-Zayyad T, Allen M, Amman JF, et al. (2008b) Search for correlations between HiRes stereo events and active galactic nuclei. Astroparticle Physics 30:175–179, Arxive0804.0382

Abraham J, Abreu P, Aglietta M, Aguirre C, et al. (2007) Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects. Science 318:938–, Arxive0711.2256

Abraham J, Abreu P, Aglietta M, Aguirre C, et al. (2008) Correlation of the highest-energy cosmic rays with the positions of nearby active galactic nuclei. Astroparticle Physics 29:188–204, Arxive0712.2843

Abraham J, Abreu P, Aglietta M, Ahn EJ, et al. (2010) Measurement of the Depth of Maximum of Extensive Air Showers above 10^{18} eV. Physical Review Letters 104(9):091 101–+, Arxive1002.0699

Abraham J, Aglietta M, Aguirre IC, Albrow M, et al. (2004) Properties and performance of the prototype instrument for the Pierre Auger Observatory. Nuclear Instruments and Methods in Physics Research A 523:50–95

Abreu P, Aglietta M, Ahn EJ, Allard D, et al. (2010) Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter. ArXiv e-prints Arxive1009.1855

Acciari VA, Aliu E, Arlen T, Aune T, et al. (2009) A connection between star formation activity and cosmic rays in the starburst galaxy M82. Nature 462:770–772, Arxive0911.0873

Acero F, Aharonian F, Akhperjanian AG, Anton G, et al. (2009) Detection of Gamma Rays from a Starburst Galaxy. Science 326:1080–, Arxive0909.4651

Aharonian F, Akhperjanian AG, Bazer-Bachi AR, Beilicke M, et al. (2007a) Detection of extended very-high-energy γ-ray emission towards the young stellar cluster Westerlund 2. Astron. Astrophys. 467:1075–1080, ArxivearXiv:astro-ph/0703427

Aharonian F, Akhperjanian AG, Bazer-Bachi AR, Beilicke M, et al. (2007b) Primary particle acceleration above 100 TeV in the shell-type supernova remnant ¡ASTROBJ¿RX J1713.7-3946¡/ASTROBJ¿ with deep HESS observations. Astron. Astrophys. 464:235–243, ArxivearXiv:astro-ph/0611813

Aharonian F, Buckley J, Kifune T, Sinnis G (2008) High energy astrophysics with ground-based gamma ray detectors. Reports on Progress in Physics 71(9):096 901–+

Aharonian FA, Belyanin AA, Derishev EV, Kocharovsky VV, et al. (2002) Constraints on the extremely high-energy cosmic ray accelerators from classical electrodynamics. Phys. Rev. D 66(2):023 005–+, ArxivearXiv:astro-ph/0202229

Aharonian FA, Drury LO, Voelk HJ (1994) GeV/TeV gamma-ray emission from dense molecular clouds overtaken by supernova shells. Astron. Astrophys. 285:645–647

Aharonian FA, Kelner SR, Prosekin AY (2010) Angular, spectral, and time distributions of highest energy protons and associated secondary gamma rays and neu-

trinos propagating through extragalactic magnetic and radiation fields. Phys. Rev. D 82(4):043 002–+, Arxive1006.1045
Ahn HS, Allison PS, Bagliesi MG, Beatty JJ, et al. (2008) Measurements of cosmic-ray secondary nuclei at high energies with the first flight of the CREAM balloon-borne experiment. Astroparticle Physics 30:133–141, Arxive0808.1718
Allard D, Ave M, Busca N, Malkan MA, et al. (2006) Cosmogenic neutrinos from the propagation of ultrahigh energy nuclei. JCAP 9:5–+, ArxivearXiv:astro-ph/0605327
Allard D, Parizot E, Olinto AV (2007) On the transition from galactic to extragalactic cosmic-rays: Spectral and composition features from two opposite scenarios. Astroparticle Physics 27:61–75, ArxivearXiv:astro-ph/0512345
Allard D, Parizot E, Olinto AV, Khan E, et al. (2005) UHE nuclei propagation and the interpretation of the ankle in the cosmic-ray spectrum. Astron. Astrophys. 443:L29–L32, ArxivearXiv:astro-ph/0505566
Aloisio R, Berezinsky V, Blasi P, Gazizov A, et al. (2007) A dip in the UHECR spectrum and the transition from galactic to extragalactic cosmic rays. Astroparticle Physics 27:76–91, ArxivearXiv:astro-ph/0608219
Aloisio R, Berezinsky VS (2005) Anti-GZK Effect in Ultra-High-Energy Cosmic Ray Diffusive Propagation. Astrophys. J. 625:249–255, ArxivearXiv:astro-ph/0412578
Armstrong JW, Rickett BJ, Spangler SR (1995) Electron density power spectrum in the local interstellar medium. Astrophys. J. 443:209–221
Aublin J, Parizot E (2006) On the viability of holistic cosmic-ray source models. Astron. Astrophys. 452:L19–L22, ArxivearXiv:astro-ph/0605046
Axford WI (1994) The origins of high-energy cosmic rays. Astrophys. J. Suppl. 90:937–944
Bamba A, Ueno M, Nakajima H, Koyama K (2004) Thermal and Nonthermal X-Rays from the Large Magellanic Cloud Superbubble 30 Doradus C. Astrophys. J. 602:257–263, ArxivearXiv:astro-ph/0310713
Barbosa HMJ, Catalani F, Chinellato JA, Dobrigkeit C (2004) Determination of the calorimetric energy in extensive air showers. Astroparticle Physics 22:159–166, ArxivearXiv:astro-ph/0310234
Barcons X, Barret D, Bautz M, Bookbinder J, et al. (2011) International X-ray Observatory (IXO) Assessment Study Report for the ESA Cosmic Vision 2015-2025. ArXiv e-prints Arxive1102.2845
Beck R (2008) Galactic and Extragalactic Magnetic Fields. In: American Institute of Physics Conference Series (ed. F A Aharonian, W Hofmann, & F Rieger), vol. 1085 of *American Institute of Physics Conference Series*, pp. 83–96, Arxive0810.2923
Bell AR (1978) The acceleration of cosmic rays in shock fronts. I. Mon. Not. Royal Astron. Soc. 182:147–156
Bell AR (2004) Turbulent amplification of magnetic field and diffusive shock acceleration of cosmic rays. MNRAS 353:550–558
Berezinskii VS, Bulanov SV, Dogiel VA, Ginzburg VL, et al. (1990) Astrophysics of cosmic rays
Berezinskii VS, Grigor'eva SI (1988) A bump in the ultra-high energy cosmic ray spectrum. Astron. Astrophys. 199:1–12
Berezinsky V (2009) Ultra High Energy Cosmic Ray Protons: Signatures and Observations. Nuclear Physics B Proceedings Supplements 188:227–232, Arxive0901.0254
Berezinsky V, Gazizov A, Grigorieva S (2004) Propagation and Signatures of Ultra High Energy Cosmic Rays. Nuclear Physics B Proceedings Supplements 136:147–158, ArxivearXiv:astro-ph/0410650
Bhattacharjee P, Sigl G (2000) Origin and propagation of extremely high energy cosmic rays. Phys Rep 327:109–247, ArxivearXiv:astro-ph/9811011
Binns WR, Wiedenbeck ME, Arnould M, Cummings AC, et al. (2007) OB Associations, Wolf Rayet Stars, and the Origin of Galactic Cosmic Rays. Space Sci. Rev. 130:439–449, Arxive0707.4645
Blandford R, Eichler D (1987) Particle Acceleration at Astrophysical Shocks - a

Theory of Cosmic-Ray Origin. Phys Rep 154:1–+
Blasi P (2006) The origin of ultra high energy cosmic rays. Journal of Physics Conference Series 39:372–378, ArxivearXiv:astro-ph/0512438
Blasi P, Epstein RI, Olinto AV (2000) Ultra-High-Energy Cosmic Rays from Young Neutron Star Winds. Astrophys. J. 533:L123–L126, ArxivearXiv:astro-ph/9912240
Bloemen JBGM, Dogiel VA, Dorman VL, Ptuskin VS (1993) Galactic diffusion and wind models of cosmic-ray transport. I - Insight from CR composition studies and gamma-ray observations. Astron. Astrophys. 267:372–387
Blumenthal GR (1970) Energy Loss of High-Energy Cosmic Rays in Pair-Producing Collisions with Ambient Photons. Phys. Rev. D 1:1596–1602
Blümer J, the Pierre Auger Collaboration (2010) The northern site of the Pierre Auger Observatory. New Journal of Physics 12(3):035 001–+
Boyer JH, Knapp BC, Mannel EJ, Seman M (2002) FADC-based DAQ for HiRes Fly's Eye. Nuclear Instruments and Methods in Physics Research A 482:457–474
Breitschwerdt D, McKenzie JF, Voelk HJ (1991) Galactic winds. I - Cosmic ray and wave-driven winds from the Galaxy. Astron. Astrophys. 245:79–98
Bykov AM (2001) Particle Acceleration and Nonthermal Phenomena in Superbubbles. Space Science Reviews 99:317–326
Bykov AM, Dolag K, Durret F (2008) Cosmological Shock Waves. Space Sci. Rev. 134:119–140, Arxive0801.0995
Bykov AM, Fleishman GD (1992) On non-thermal particle generation in superbubbles. Mon. Not. Royal Astron. Soc. 255:269–275
Bykov AM, Osipov SM, Ellison DC (2011) Cosmic ray current driven turbulence in shocks with efficient particle acceleration: the oblique, long-wavelength mode instability. Mon. Not. Royal Astron. Soc. 410:39–52, Arxive1010.0408
Bykov AM, Toptygin IN (1987) Effect of shocks on interstellar turbulence and cosmic-ray dynamics. Astroph. Sp. Sci. 138:341–354
Bykov AM, Toptygin IN (1993) Particle Kinetics in Highly Turbulent Plasmas (Renormalization and Self-consistent Field Methods). Physics-Uspekhi 36:1020–1052
Bykov AM, Toptygin IN (2001) A Model of Particle Acceleration to High Energies by Multiple Supernova Explosions in OB Associations. Astronomy Letters 27:625–633
Bykov AM, Uvarov YA, Bloemen JBGM, den Herder JW, et al. (2009) A model of polarized X-ray emission from twinkling synchrotron supernova shells. Mon. Not. Royal Astron. Soc. 399:1119–1125, Arxive0907.2521
Calvez A, Kusenko A, Nagataki S (2010) Role of Galactic Sources and Magnetic Fields in Forming the Observed Energy-Dependent Composition of Ultrahigh-Energy Cosmic Rays. Physical Review Letters 105(9):091 101–+, Arxive1004.2535
Casse F, Lemoine M, Pelletier G (2002) Transport of cosmic rays in chaotic magnetic fields. Phys. Rev. D 65(2):023 002–+, ArxivearXiv:astro-ph/0109223
Casse M, Paul JA (1982) On the stellar origin of the Ne-22 excess in cosmic rays. Astrophys. J. 258:860–863
Cesarsky CJ (1980) Cosmic-ray confinement in the galaxy. Ann. Rev. Astron. Astrophys. 18:289–319
Cesarsky CJ, Montmerle TM (1982) Cosmic rays from OB associations and supernovae - Anti-protons and the origin of local cosmic rays. In: International Cosmic Ray Conference, vol. 9 of *International Cosmic Ray Conference*, pp. 207–210
Cho J, Lazarian A (2002) Compressible Sub-Alfvénic MHD Turbulence in Low-β Plasmas. Physical Review Letters 88(24):245 001–+, ArxivearXiv:astro-ph/0205282
Davis AJ, Mewaldt RA, Binns WR, Christian ER, et al. (2000) On the low energy decrease in galactic cosmic ray secondary/primary ratios. In: Acceleration and Transport of Energetic Particles Observed in the Heliosphere (ed. R A Mewaldt, J R Jokipii, M A Lee, E Möbius, & T H Zurbuchen), vol. 528 of *American*

Institute of Physics Conference Series, pp. 421–424
Dawson BR, for the Auger Collaboration (2008) Hybrid Performance of the Pierre Auger Observatory. In: International Cosmic Ray Conference, vol. 4 of *International Cosmic Ray Conference*, pp. 425–428, Arxive0706.1105
Deligny O, Letessier-Selvon A, Parizot E (2004) Magnetic horizons of UHECR sources and the GZK feature. Astroparticle Physics 21:609–615, ArxivearXiv:astro-ph/0303624
Dolag K, Bykov AM, Diaferio A (2008) Non-Thermal Processes in Cosmological Simulations. Space Sci. Rev. 134:311–335, Arxive0801.1048
Dolag K, Grasso D, Springel V, Tkachev I (2005) Constrained simulations of the magnetic field in the local Universe and the propagation of ultrahigh energy cosmic rays. J. Cosmol. Astropart. Phys. 1:9–+, ArxivearXiv:astro-ph/0410419
Drury LO, Aharonian FA, Voelk HJ (1994) The gamma-ray visibility of supernova remnants. A test of cosmic ray origin. Astron. Astrophys. 287:959–971, ArxivearXiv:astro-ph/9305037
Drury LO, Ellison DE, Aharonian FA, Berezhko E, et al. (2001) Test of galactic cosmic-ray source models - Working Group Report. Space Sci. Rev. 99:329–352
Duric N, Gordon SM, Goss WM, Viallefond F, et al. (1995) The relativistic ISM in M33: Role of the supernova remnants. Astrophys. J. 445:173–181
Duvernois MA, Garcia-Munoz M, Pyle KR, Simpson JA, et al. (1996a) The Isotopic Composition of Galactic Cosmic-Ray Elements from Carbon to Silicon: The Combined Release and Radiation Effects Satellite Investigation. Astrophys. J. 466:457–+
Duvernois MA, Simpson JA, Thayer MR (1996b) Interstellar propagation of cosmic rays: analysis of the ULYSSES primary and secondary elemental abundances. Astron. Astrophys. 316:555–563
Ebisuzaki T, Takahashi Y, Kajino F, Mase H, et al. (2010) The JEM-EUSO Mission to Explore the Extreme Universe. In: American Institute of Physics Conference Series (ed. H Susa, M Arnould, S Gales, T Motobayashi, C Scheidenberger, & H Utsunomiya), vol. 1238 of *American Institute of Physics Conference Series*, pp. 369–376
Ellison DC, Drury LO, Meyer J (1997) Galactic Cosmic Rays from Supernova Remnants. II. Shock Acceleration of Gas and Dust. Astrophys. J. 487:197–+, ArxivearXiv:astro-ph/9704293
Ellison DC, Patnaude DJ, Slane P, Raymond J (2010) Efficient Cosmic Ray Acceleration, Hydrodynamics, and Self-Consistent Thermal X-Ray Emission Applied to Supernova Remnant RX J1713.7-3946. Astrophys. J. 712:287–293, Arxive1001.1932
Elmegreen BG, Scalo J (2004) Interstellar Turbulence I: Observations and Processes. Ann. Rev. Astron. Astrophys. 42:211–273, ArxivearXiv:astro-ph/0404451
Engelmann JJ, Ferrando P, Soutoul A, Goret P, et al. (1990) Charge composition and energy spectra of cosmic-ray nuclei for elements from Be to NI - Results from HEAO-3-C2. Astron. Astrophys. 233:96–111
Everett JE, Zweibel EG, Benjamin RA, McCammon D, et al. (2007) Does the Milky Way launch a large-scale wind? Astroph. Sp. Sci. 311:105–110
Everett JE, Zweibel EG, Benjamin RA, McCammon D, et al. (2008) The Milky Way's Kiloparsec-Scale Wind: A Hybrid Cosmic-Ray and Thermally Driven Outflow. Astrophys. J. 674:258–270, Arxive0710.3712
Farmer AJ, Goldreich P (2004) Wave Damping by Magnetohydrodynamic Turbulence and Its Effect on Cosmic-Ray Propagation in the Interstellar Medium. Astrophys. J. 604:671–674, ArxivearXiv:astro-ph/0311400
Ferrari C, Govoni F, Schindler S, Bykov AM, et al. (2008) Observations of Extended Radio Emission in Clusters. Space Sci. Rev. 134:93–118, Arxive0801.0985
Ferrière KM (2001) The interstellar environment of our galaxy. Reviews of Modern Physics 73:1031–1066, ArxivearXiv:astro-ph/0106359
Galtier S, Nazarenko SV, Newell AC, Pouquet A (2000) A weak turbulence theory for incompressible magnetohydrodynamics. Journal of Plasma Physics 63:447–488, ArxivearXiv:astro-ph/0008148

Ginzburg VL (1965) Cosmic Rays and Plasma Phenomena in the Galaxy and Metagalaxy. Sov Astron 9:877–+
Globus N, Allard D, Parizot E (2008) Propagation of high-energy cosmic rays in extragalactic turbulent magnetic fields: resulting energy spectrum and composition. Astron. Astrophys. 479:97–110, Arxive0709.1541
Goldreich P, Sridhar S (1995) Toward a theory of interstellar turbulence. 2: Strong alfvenic turbulence. Astrophys. J. 438:763–775
Goldreich P, Sridhar S (1997) Magnetohydrodynamic Turbulence Revisited. Astrophys. J. 485:680–+, ArxivearXiv:astro-ph/9612243
Greisen K (1966) End to the Cosmic-Ray Spectrum? Physical Review Letters 16:748–750
Hanasz M, Kowal G, Otmianowska-Mazur K, Lesch H (2004) Amplification of Galactic Magnetic Fields by the Cosmic-Ray-driven Dynamo. Astrophys. J. 605:L33–L36, ArxivearXiv:astro-ph/0402662
Hanasz M, Otmianowska-Mazur K, Kowal G, Lesch H (2006) Cosmic ray driven dynamo in galactic disks: effects of resistivity, SN rate and spiral arms. Astronomische Nachrichten 327:469–+
Harrison FA, Boggs S, Christensen F, Craig W, et al. (2010) The Nuclear Spectroscopic Telescope Array (NuSTAR). In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 7732 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Arxive1008.1362
Higdon JC, Lingenfelter RE, Ramaty R (1998) Cosmic-Ray Acceleration from Supernova Ejecta in Superbubbles. Astrophys. J. 509:L33–L36
Hillas AM (1984) The Origin of Ultra-High-Energy Cosmic Rays. Ann. Rev. Astron. Astrophys. 22:425–444
Hillas AM (2005) TOPICAL REVIEW: Can diffusive shock acceleration in supernova remnants account for high-energy galactic cosmic rays? Journal of Physics G Nuclear Physics 31:95–+
Hörandel JR, Kalmykov NN, Timokhin AV (2007) Propagation of super-high-energy cosmic rays in the Galaxy. Astroparticle Physics 27:119–126, ArxivearXiv:astro-ph/0609490
Ipavich FM (1975) Galactic winds driven by cosmic rays. Astrophys. J. 196:107–120
Iroshnikov PS (1964) Turbulence of a Conducting Fluid in a Strong Magnetic Field. Sov. Astron. 7:566–+
Jones FC, Lukasiak A, Ptuskin V, Webber W (2001) The Modified Weighted Slab Technique: Models and Results. Astrophys. J. 547:264–271, ArxivearXiv:astro-ph/0007293
Jones TJ, Rudnick L, DeLaney T, Bowden J (2003) The Identification of Infrared Synchrotron Radiation from Cassiopeia A. Astrophys. J. 587:227–234, ArxivearXiv:astro-ph/0212544
Kang H, Ryu D, Cen R, Song D (2005) Shock-heated Gas in the Large-Scale Structure of the Universe. Astrophys. J. 620:21–30, ArxivearXiv:astro-ph/0410477
Kawai H, Nunomura T, Sakurai N, Yoshida S, et al. (2005) Telescope Array; Progress of Surface Array. In: International Cosmic Ray Conference, vol. 8 of *International Cosmic Ray Conference*, pp. 181–+
Kennel CF, Engelmann F (1966) Velocity Space Diffusion from Weak Plasma Turbulence in a Magnetic Field. Physics of Fluids 9:2377–2388
Khan E, Goriely S, Allard D, Parizot E, et al. (2005) Photodisintegration of ultra-high-energy cosmic rays revisited. Astroparticle Physics 23:191–201, ArxivearXiv:astro-ph/0412109
Kotera K, Allard D, Olinto AV (2010) Cosmogenic Neutrinos: parameter space and detectabilty from PeV to ZeV. ArXiv e-prints Arxive1009.1382
Kotera K, Lemoine M (2008a) Inhomogeneous extragalactic magnetic fields and the second knee in the cosmic ray spectrum. Phys. Rev. D 77(2):023 005–+, Arxive0706.1891
Kotera K, Lemoine M (2008b) Inhomogeneous extragalactic magnetic fields and the second knee in the cosmic ray spectrum. Phys. Rev. D 77(2):023 005–+, Arxive0706.1891
Kotera K, Lemoine M (2008c) Optical depth of the Universe to ultrahigh energy

cosmic ray scattering in the magnetized large scale structure. Phys. Rev. D 77(12):123 003–+, Arxive0801.1450
Kraichnan RH (1965) Inertial-Range Spectrum of Hydromagnetic Turbulence. Physics of Fluids 8:1385–1387
Kulsrud RM (2005) Plasma physics for astrophysics. Princeton University Press
Kulsrud RM, Zweibel EG (2008) On the origin of cosmic magnetic fields. Reports on Progress in Physics 71(4):046 901–+, Arxive0707.2783
Kushnir D, Katz B, Waxman E (2009) Magnetic fields and cosmic rays in clusters of galaxies. J. Cosmol. Astropart. Phys. 9:24–+, Arxive0903.2275
Kuwabara T, Nakamura K, Ko CM (2004) Nonlinear Parker Instability with the Effect of Cosmic-Ray Diffusion. Astrophys. J. 607:828–839, ArxivearXiv:astro-ph/0402350
Lemoine M (2005) Extragalactic magnetic fields and the second knee in the cosmic-ray spectrum. Phys. Rev. D 71(8):083 007–+, ArxivearXiv:astro-ph/0411173
Lemoine M, Waxman E (2009) Anisotropy vs chemical composition at ultra-high energies. JCAP 11:9–+, Arxive0907.1354
Lingenfelter RE, Ramaty R, Kozlovsky B (1998) Supernova Grains: The Source of Cosmic-Ray Metals. Astrophys. J. 500:L153+
Lithwick Y, Goldreich P (2001) Compressible Magnetohydrodynamic Turbulence in Interstellar Plasmas. Astrophys. J. 562:279–296, ArxivearXiv:astro-ph/0106425
Longair MS (2010) High Energy Astrophysics
Lozinskaya TA (1992) Supernovae and stellar wind in the interstellar medium
Lukasiak A (1999) Voyager Measurements of the Charge and Isotopic Composition of Cosmic Ray Li, Be and B Nuclei and Implications for Their Production in the Galaxy. In: International Cosmic Ray Conference, vol. 3 of *International Cosmic Ray Conference*, pp. 41–+
Malkov MA, Drury L (2001) Nonlinear theory of diffusive acceleration of particles by shock waves. Reports on Progress in Physics 64:429–481
Marcowith A, Casse F (2010) Postshock turbulence and diffusive shock acceleration in young supernova remnants. Astron. Astrophys. 515:A90+, Arxive1001.2111
Mészáros P (2006) Gamma-ray bursts. Reports on Progress in Physics 69:2259–2321, ArxivearXiv:astro-ph/0605208
Mewaldt RA (1999) The Time Delay between Nucleosynthesis and Acceleration Based on ACE Measurements of Primary Electron-Capture Nuclides. In: International Cosmic Ray Conference, vol. 3 of *International Cosmic Ray Conference*, pp. 1–+
Meyer J, Drury LO, Ellison DC (1997) Galactic Cosmic Rays from Supernova Remnants. I. A Cosmic-Ray Composition Controlled by Volatility and Mass-to-Charge Ratio. Astrophys. J. 487:182–+, ArxivearXiv:astro-ph/9704267
Milgrom M, Usov V (1995) Possible Association of Ultra–High-Energy Cosmic-Ray Events with Strong Gamma-Ray Bursts. Astrophys. J. 449:L37+, ArxivearXiv:astro-ph/9505009
Morlino G, Blasi P, Amato E (2009) Gamma rays and neutrinos from SNR RX J1713.7-3946. Astroparticle Physics 31:376–382, Arxive0903.4565
Nagano M, Watson AA (2000) Observations and implications of the ultrahigh-energy cosmic rays. Reviews of Modern Physics 72:689–732
Norman CA, Melrose DB, Achterberg A (1995) The Origin of Cosmic Rays above 10 18.5 eV. Astrophys. J. 454:60–+
Olinto AV, Adams JH, Dermer CD, Krizmanic JF, et al. (2009) White Paper on Ultra-High Energy Cosmic Rays. In: astro2010: The Astronomy and Astrophysics Decadal Survey, vol. 2010 of *ArXiv Astrophysics e-prints*, pp. 225–+, Arxive0903.0205
Parizot E (2004) GZK horizon and magnetic fields. Nuclear Physics B Proceedings Supplements 136:169–178, ArxivearXiv:astro-ph/0409191
Parker EN (1966) The Dynamical State of the Interstellar Gas and Field. Astrophys. J. 145:811–+
Parker EN (1992) Fast dynamos, cosmic rays, and the Galactic magnetic field. Astrophys. J. 401:137–145
Pierre Auger Collaboration, Abraham J, Abreu P, Aglietta M, et al. (2010a) Mea-

surement of the energy spectrum of cosmic rays above 10^{18} eV using the Pierre Auger Observatory. Physics Letters B 685:239–246, Arxive1002.1975

Pierre Auger Collaboration, Abraham J, Abreu P, Aglietta M, et al. (2010b) Measurement of the energy spectrum of cosmic rays above 10^{18} eV using the Pierre Auger Observatory. Physics Letters B 685:239–246, Arxive1002.1975

Profumo S (2008) Dissecting cosmic-ray electron-positron data with Occam's Razor: the role of known Pulsars. ArXiv e-prints Arxive0812.4457

Ptuskin V, Zirakashvili V, Seo E (2010) Spectrum of Galactic Cosmic Rays Accelerated in Supernova Remnants. Astrophys. J. 718:31–36, Arxive1006.0034

Ptuskin VS, Moskalenko IV, Jones FC, Strong AW, et al. (2006) Dissipation of Magnetohydrodynamic Waves on Energetic Particles: Impact on Interstellar Turbulence and Cosmic-Ray Transport. Astrophys. J. 642:902–916, ArxivearXiv:astro-ph/0510335

Ptuskin VS, Voelk HJ, Zirakashvili VN, Breitschwerdt D (1997) Transport of relativistic nucleons in a galactic wind driven by cosmic rays. Astron. Astrophys. 321:434–443

Ptuskin VS, Zirakashvili VN, Plesser AA (2008) Non-linear diffusion of cosmic rays. Advances in Space Research 42:486–490

Puget JL, Stecker FW, Bredekamp JH (1976) Photonuclear interactions of ultrahigh energy cosmic rays and their astrophysical consequences. Astrophys. J. 205:638–654

Reynolds SP (2008) Supernova Remnants at High Energy. Ann. Rev. Astron. Astrophys. 46:89–126

Ryu D, Kim J, Hong SS, Jones TW (2003) The Effect of Cosmic-Ray Diffusion on the Parker Instability. Astrophys. J. 589:338–346, ArxivearXiv:astro-ph/0301625

Scalo J, Elmegreen BG (2004) Interstellar Turbulence II: Implications and Effects. Ann. Rev. Astron. Astrophys. 42:275–316, ArxivearXiv:astro-ph/0404452

Schlickeiser R (2002) Cosmic Ray Astrophysics

Seo ES, Ptuskin VS (1994) Stochastic reacceleration of cosmic rays in the interstellar medium. Astrophys. J. 431:705–714

Sigl G (2009) Time structure and multi-messenger signatures of ultra-high energy cosmic ray sources. New Journal of Physics 11(6):065 014–+

Simon M, Heinrich W, Mathis KD (1986) Propagation of injected cosmic rays under distributed reacceleration. Astrophys. J. 300:32–40

Skilling J (1975a) Cosmic ray streaming. I - Effect of Alfven waves on particles. Mon. Not. Royal Astron. Soc. 172:557–566

Skilling J (1975b) Cosmic ray streaming. III - Self-consistent solutions. Mon. Not. Royal Astron. Soc. 173:255–269

Stephens SA, Streitmatter RE (1998) Cosmic-Ray Propagation in the Galaxy: Techniques and the Mean Matter Traversal. Astrophys. J. 505:266–277

Strong AW, Moskalenko IV (1998) Propagation of Cosmic-Ray Nucleons in the Galaxy. Astrophys. J. 509:212–228, ArxivearXiv:astro-ph/9807150

Strong AW, Moskalenko IV, Ptuskin VS (2007) Cosmic-Ray Propagation and Interactions in the Galaxy. Annual Review of Nuclear and Particle Science 57:285–327, ArxivearXiv:astro-ph/0701517

Takahashi T, Mitsuda K, Kelley R, Aharonian F, et al. (2010) The ASTRO-H Mission. In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 7732 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Arxive1010.4972

Taylor AM, Vovk I, Neronov A (2011) EGMF Constraints from Simultaneous GeV-TeV Observations of Blazars. ArXiv e-prints Arxive1101.0932

Toptygin IN (1985) Cosmic rays in interplanetary magnetic fields

Torres DF, Anchordoqui LA (2004) Astrophysical origins of ultrahigh energy cosmic rays. Reports on Progress in Physics 67:1663–1730, ArxivearXiv:astro-ph/0402371

Vannoni G, Aharonian FA, Gabici S, Kelner SR, et al. (2009) Acceleration and radiation of ultra-high energy protons in galaxy clusters. ArXiv e-prints Arxive0910.5715

Véron-Cetty M, Véron P (2006) A catalogue of quasars and active nuclei: 12th edition. Astron. Astrophys. 455:773–777
Vietri M (1995) The Acceleration of Ultra–High-Energy Cosmic Rays in Gamma-Ray Bursts. Astrophys. J. 453:883–+, ArxivearXiv:astro-ph/9506081
Vink J (2008) Multiwavelength Signatures of Cosmic Ray Acceleration by Young Supernova Remnants. In: American Institute of Physics Conference Series (ed. F A Aharonian, W Hofmann, & F Rieger), vol. 1085 of *American Institute of Physics Conference Series*, pp. 169–180
Vissani F, Aharonian F, Sahakyan N (2011) On the Detectability of High-Energy Galactic Neutrino Sources. ArXiv e-prints Arxive1101.4842
Waxman E (1995) Cosmological Gamma-Ray Bursts and the Highest Energy Cosmic Rays. Physical Review Letters 75:386–389, ArxivearXiv:astro-ph/9505082
Waxman E (2004) High-Energy Cosmic Rays from Gamma-Ray Burst Sources: A Stronger Case. Astrophys. J. 606:988–993, ArxivearXiv:astro-ph/0210638
Webb GM, Kaghashvili EK, le Roux JA, Shalchi A, et al. (2009) Compound and perpendicular diffusion of cosmic rays and random walk of the field lines: II. Non-parallel particle transport and drifts. Journal of Physics A Mathematical General 42(23):235 502–+
Wentzel DG (1974) Cosmic-ray propagation in the Galaxy - Collective effects. Ann. Rev. Astron. Astrophys. 12:71–96
Wiedenbeck ME, Yanasak NE, Cummings AC, Davis AJ, et al. (2001) The Origin of Primary Cosmic Rays: Constraints from ACE Elemental and Isotopic Composition Observations. Space Sci. Rev. 99:15–26
Yanasak NE, Wiedenbeck ME, Mewaldt RA, Davis AJ, et al. (2001) Measurement of the Secondary Radionuclides and Implications for the Galactic Cosmic-Ray Age. Astrophys. J. 563:768–792
Zatsepin GT, Kuzmin VA (1966) Upper limit of the spectrum of cosmic rays. Sov Phys JETP Lett 4:78–80
Zhou Y, Matthaeus WH, Dmitruk P (2004) Colloquium: Magnetohydrodynamic turbulence and time scales in astrophysical and space plasmas. Reviews of Modern Physics 76:1015–1035
Zirakashvili VN, Aharonian FA (2010) Nonthermal Radiation of Young Supernova Remnants: The Case of RX J1713.7-3946. Astrophys. J. 708:965–980, Arxive0909.2285
Zirakashvili VN, Breitschwerdt D, Ptuskin VS, Voelk HJ (1996) Magnetohydrodynamic wind driven by cosmic rays in a rotating galaxy. Astron. Astrophys. 311:113–126
Zirakashvili VN, Pochepkin DN, Ptuskin VS, Rogovaya SI (1998) Propagation of ultra-high-energy cosmic rays in Galactic magnetic fields. Astronomy Letters 24:139–143
Zirakashvili VN, Ptuskin VS (2008) Diffusive Shock Acceleration with Magnetic Amplification by Nonresonant Streaming Instability in Supernova Remnants. Astrophys. J. 678:939–949, Arxive0801.4488
Zweibel EG (2003) Cosmic-Ray History and Its Implications for Galactic Magnetic Fields. Astrophys. J. 587:625–637, ArxivearXiv:astro-ph/0212559