Ultra High Energy Cosmic Rays

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Abstract

The origin of the particles in the highest energy end of the cosmic ray spectrum is discussed in the context of the wider problem of the origin of the whole cosmic radiation as observed at the Earth. In particular we focus our attention on the acceleration problem and on the transition from galactic to extragalactic cosmic rays.

1 Introduction

There are mainly two reasons for the attention shown by the community for the origin of the highest energy cosmic ray spectrum, say above $10^{19}$ eV: on the one hand most acceleration processes need to be pushed to their extreme (or beyond) in the attempt to reach such energies. On the other hand, even in the presence of numerous nearby sources, the spectrum is expected to show a suppression, known as the GZK feature (Greisen 1966; Zatsepin & Kuzmin 1966) above the threshold for photopion production on the photons of the cosmic microwave background (CMB). The suppression should become evident around $\sim 10^{20}$ eV. Here we review some recent ideas put forward to address both points mentioned above.

The acceleration of cosmic rays to the observed energies is a problem even in supernova remnants, as possible sources of galactic cosmic rays, therefore it is natural to try and learn from that instance. As for the presence of the GZK feature we summarize the results of current experiments and try to address the issue of what future experiments could be expected to observe. However, in order to understand the origin of extragalactic cosmic rays and
more specifically of UHECRs, it is crucial to understand which cosmic rays are in fact extragalactic. The two main lines of thought in this respect will be summarized and discussed: in the so-called ankle scenario (Hillas 2005; Wibig & wolfendale 2005) the transition takes place around $10^{19}$ eV where a steep galactic spectrum encounters the flat spectrum of extragalactic cosmic rays. In the dip scenario (Berezinsky et al. 2002, 2005) the transition takes place at energies roughly one order of magnitude lower. The case of a mixed chemical composition of extragalactic cosmic rays (Allard et al. 2005a; Allard et al. 2005b) will also be discussed.

The paper is structured as follows: in §2 we discuss the problem of acceleration and some recent findings on magnetic field amplification in the acceleration region. In §3 we discuss the current ideas on the transition between galactic and extragalactic cosmic rays. In §4 we describe the current status of the observations of the end of the cosmic ray spectrum and of the anisotropies in such energy range. We conclude in §5.

2 Recent ideas on acceleration of Cosmic Rays

While it is often argued that the known acceleration mechanisms have serious problems in achieving energies in excess of $10^{20}$ eV, it is sometimes not recognized that supernova remnants (SNRs), the most serious candidates as accelerators of galactic CRs, have the same problems in accelerating particles above the knee ($\sim 10^{15}$ eV). Here we start from this analogy to gather information on the source of the problem and try to assess its possible solutions.

In the case of SNRs, acceleration is assumed to take place at the shock front associated with the supersonic motion of the expanding shell. Particles are energized through diffusive acceleration a la Fermi. The acceleration time is given by the well known expression $\tau_{acc} = \frac{3}{u_1 - u_2} \left[ \frac{D_1}{u_1} + \frac{D_2}{u_2} \right]$, where the subscripts 1 and 2 refer to the upstream and downstream region respectively. For a strong shock $u_1/u_2 \approx 4$ and if we assume that the diffusion coefficient is not changed dramatically at the shock ($D_1 \approx D_2$), the acceleration time can be written as:

$$\tau_{acc}(E) = \frac{20}{3} \frac{D_1(E)}{u_1^2}. \tag{1}$$

If the supernova shell is expanding in the interstellar medium, it is reasonable to take as a diffusion coefficient a form that is often used to describe the propagation of cosmic rays in the Galaxy, $D(E) = AE^\alpha$ with $A = 3 \times$
$10^{27} \text{cm}^2 \text{s}^{-1}$ ($A = 3 \times 10^{29} \text{cm}^2 \text{s}^{-1}$) for $\alpha = 0.6$ ($\alpha = 0.3$) and $E$ is the particle energy in units of GeV. The maximum energy of the accelerated particles can be estimated by comparing the acceleration time with the age of the remnant. For both choices of the diffusion coefficient given above, the maximum energy turns out to be of in the GeV range for a remnant of $\sim 1000$ years: the magnetic scattering provided by the ISM is insufficient to warrant the acceleration of cosmic rays to the observed energies. This conclusion is not appreciably changed by taking into account the mild compression of the perpendicular components of the magnetic field at the shock front. A crucial consequence of this finding is that the mechanism of diffusive particle acceleration at supernova shocks is efficient only if additional scattering exists close to the shock, either because the circumstellar material provides it, or because the accelerated particles generate a larger magnetic field $\delta B$ from the background field $B$, through streaming instability. The possibility of magnetic field amplification was already discussed in (Bell 1978; Lagage & Cesarsky 1983a,b), where its consequences on the maximum achievable energy were also evaluated. The conclusion of Lagage & Cesarsky (1983a,b) was that shocks in SNRs could accelerate cosmic rays up to $\sim 10^4$ GeV, below the knee, if the amplification results in $\delta B/B \sim 1$ (on all spatial scales) and the diffusion coefficient has the form of the Bohm diffusion, $D(E) = 10^{23} E(\text{GeV}) \delta B_\mu^{-1} \text{cm}^2 \text{s}^{-1}$, where $\delta B_\mu$ is the amplified magnetic field in $\mu \text{G}$. Using this diffusion coefficient, the maximum energy evaluated as above turns out to be $E_{\text{max}} \sim (1 - 4) \times 10^4 \text{ GeV}$ for $u_1 = 5000 - 10000 \text{ kms}^{-1}$, $\delta B_\mu = 1$ and a supernova age of 1000 years. Slightly larger (or smaller) values of $E_{\text{max}}$ can be obtained for slightly different values of the parameters.

There are two main issues of physical relevance here, whose validity goes well beyond the specific case of SNRs: 1) the nature of the instabilities that lead to the magnetic field amplification and 2) the saturation of the amplified magnetic field. Both affect the maximum energy of the particles with respect to the values quoted above.

The streaming of the accelerated particles upstream of the shock at super-Alfvenic speed leads to streaming instability, as already discussed by Bell (1978) (see also references therein). The maximum values of the amplified magnetic field $\delta B$ is however not limited by the value of the background field, but by the value

$$\delta B = B \left[ 2M_A \frac{P_{CR}}{\rho u^2} \right]^{1/2},$$

(2)

where $\rho u^2$ is the ram pressure of the inflowing fluid in the upstream region, $P_{CR}$ is the pressure in the form of accelerated particles, and $M_A = u \sqrt{4\pi \rho}/B$
is the Alfvenic Mach number of the upstream fluid. All these results are obtained in the context of the quasi-linear theory and should in principle been used only for $\delta B/B \ll 1$, while they predict $\delta B/B \gg 1$, therefore these conclusions should be used with much care. The waves that turn nonlinear within this approach are Alfven waves.

Recently Bell and Lucek (2000) have presented evidence for magnetic fields much larger than those given by Eq. 2. The interpretation of this result appears in (Bell 2004) where a new non-alfvenic purely growing mode is identified. Quasi-linear theory suggests that the saturation of the growth of these waves should take place at

$$\delta B = B_{MA} \sqrt{\frac{u P_{CR}}{c \rho u^2}}$$

where the symbols have the same meaning as above. This saturation level seems to be confirmed by hybrid simulations presented in (Bell 2004). For typical parameters of a SNR and assuming that an appreciable fraction of the kinetic pressure is transformed into cosmic rays ($\rho u^2 \approx P_{CR}$), one can predict $\delta B/B \sim 500$ (versus $\delta B/B \sim 20$ in the previous case). If one assumes Bohm diffusion, this translates to correspondingly higher values of the maximum energy of accelerated particles: for $\delta B/B \sim 500$ one has $E_{max} \sim (0.5 - 2) \times 10^7$ GeV (assuming Bohm diffusion).

The condition $\rho u^2 \approx P_{CR}$ is typically found to be a consequence of the nonlinear effects in particle acceleration, namely the effects due to the dynamical reaction of the accelerated particles (see Malkov & Drury (2001) and Blasi (these proceedings) for a review). This reaction, which leads to the so-called cosmic ray modification of shocks, has three important phenomenological consequences: 1) creation of a cosmic ray precursor which is also responsible for a concave energy spectrum (non power law); 2) large efficiency for particle acceleration; 3) suppression of the plasma heating in cosmic ray modified shocks.

A unified picture of nonlinear particle acceleration at shocks with self-generation of scattering has recently been presented by Amato & Blasi (2005, 2006). An important effect of the shock modification is that while the amplification of the magnetic field leads to an increase of the maximum achievable momentum, the precursor (slowing down of the upstream fluid and spatial variation of the magnetic field) lead to a somewhat lower value of the maximum energy (Blasi, Amato & Caprioli 2006).

The observational picture provided by the KASCADE data is extremely important to identify the sources of cosmic rays in the Galaxy. In Fig.
Figure 1: Spectrum of protons

We plot the spectrum of protons as measured by KASCADE and other experiments (Hoerandel 2005). The proton knee is clearly visible, while the spectrum extends up to at least $10^7$ GeV, although it is not clear whether the steepening above the knee is a cutoff due to an approaching $E_{\text{max}}$ or rather a slope change either due to acceleration or to propagation in the Galaxy.

The spectrum of helium nuclei appears to extend to slightly higher energies, as it could be expected in a rigidity dependent model of acceleration. In this picture the knee in the iron component would be expected to be at energy $E_{\text{Fe}}^{k} = ZE_{p}^{k} \approx 8 \times 10^{16}$ eV, while the spectrum would probably extend up to $E_{\text{Fe}}^{\text{max}} = ZE_{p}^{\text{max}} \approx 2 \times 10^{17}$ eV. The spectrum of iron nuclei is however not observed in a reliable way at this time, therefore this should be considered as a phenomenological conclusion. But a very important one: in fact it is difficult to imagine more energetic particles above the maximum energy of iron nuclei, being originated inside the Galaxy. Therefore, current observations, together with the most recent theoretical understanding of the acceleration processes at shock fronts hint to the fact that the galactic component of cosmic rays should end around $\sim 2 \times 10^{17}$ eV.

These observational findings clearly indicate that if SNRs are in fact the sources of galactic cosmic rays, then substantial magnetic field amplification should take place at the shock. Independent evidences for such amplification comes from Chandra X-ray observations of the X-ray rim of several SNRs, produced as synchrotron emission of relativistic electrons accelerated at the shock front. It has been pointed out that the spatial extension of these
regions is compatible with magnetic fields of the order of $\sim 100 - 300 \mu G$ and not with the typical fields in the interstellar medium (Warren et al. 2005).

The example of SNRs illustrated above shows that in order to assess the ability for a class of sources to accelerate particles to a given energy it is absolutely crucial to take into account the nonlinear processes which in fact make the acceleration possible and efficient. This applies equally well to the putative sources of UHECRs, such as active galactic nuclei (AGNs) or gamma ray bursts (GRBs) could be. Unfortunately, in both these cases the acceleration is likely to involve relativistic plasma motions, for which the investigation of the shock acceleration process has mostly been studied in the linear regime. An extension of the nonlinear theory to these cases is of the highest importance.

The most valuable lesson that can be probably learned from the case of SNRs is that in estimating the maximum energy achievable in a cosmic accelerator, the value of the local ambient magnetic field might not be the physically relevant quantity. The self-generated amplified magnetic field in the vicinity of the source can in fact wildly exceed the ambient field, thereby enhancing the maximum energy as inferred from Hillas-like plots. The topology of the turbulent field is also extremely important: the same rms field leads to different diffusion properties of cosmic rays for different topologies. For self-generated fields, the topology is determined by the particles which are being accelerated, which makes it extremely difficult to carry out realistic self-consistent calculations.

3 The transition from galactic to extragalactic cosmic rays

It has long been thought that the ankle, at $\sim (0.5 - 1) \times 10^{19}$ eV is a feature arising from the intersection of a steeply falling galactic spectrum of cosmic rays with a flatter spectrum of extragalactic cosmic rays. This view implies that the galactic cosmic ray spectrum should extend to energies in excess of $\sim 10^{19}$ eV. However the arguments illustrated in Sec. 2 suggest an early end of the galactic component, between $10^{17}$ and $10^{18}$ eV, although as we stressed, this inference is not purely based on observations. Where does the transition actually take place? As pointed out by Berezinsky et al. (2002, 2005), a dip appears in the spectrum of extragalactic cosmic rays at energy $\sim 3 \times 10^{18}$ eV, as due to the combination of adiabatic losses (expansion of the universe) and $e^\pm$ pair production. This dip was shown to fit very well the
observed spectra for all the relevant experiments, as also shown in Fig. 2. A very important point to make is that the position of the dip is independent of astrophysical details, and is fixed by the rates of adiabatic losses and pair production. The low energy part of the dip fits what is currently named the second knee. Below the second knee the predicted spectrum flattens and drops below the flux of galactic cosmic rays. This low energy part depends to some extent on the mean distance between sources and on the magnetic field value and topology in the intergalactic medium (Aloisio & Berezinsky 2005; Lemoine 2005). In this scenario the transition between galactic and extragalactic cosmic rays takes place somewhere between $10^{17}$ eV and $10^{18}$ eV, but it remains true that in the transition region a steep galactic spectrum encounters a flatter extragalactic spectrum (Berezinsky et al. 2006), as in the ankle scenario.
Both possibilities are currently viable and have positive and negative aspects. The injection spectrum required to fit the data in the ankle scenario is as flat as \( E^{-\alpha} \), with \( \alpha \sim 2 - 2.4 \), which is tantalizingly close to the results expected for shock acceleration, while in the dip scenario the injection spectrum has \( \alpha = 2.6 - 2.7 \). However, it was pointed out in (Kachelriess & Semikoz 2005) that the superposition of flat spectra with different maximum energies naturally provides a good fit to the data without requiring a steep injection spectrum. In any case one should always keep in mind that \( \alpha \sim 2 \) is more likely a number we got used to rather than a value than Nature prefers, as discussed by Berezinsky et al. (2006): many physical situations contribute to steepen the spectrum with respect to the canonical case \( \alpha \sim 2 \).

From the point of view of the chemical composition the two models differ the most: in the ankle scenario (Wibig & Wolfendale 2005), the galactic cosmic rays extend to \( > 10^{19} \) eV and are mainly iron nuclei, while the dip scenario requires that CRs with energy above \( \sim 10^{19} \) eV are mostly protons (with no more than \( \sim 15\% \) contamination of helium) and that the proton dominated extragalactic component is important down to energies around \( \sim 10^{18} \) eV. The dip scenario would naturally account for the \( \sim 10\% \) proton abundance observed by Akeno at \( 10^{17} \) eV. The difference in the prediction of the chemical composition of CRs also represents the most striking prediction of the models and the tool to possibly discriminate between them.

An important aspect of the dip scenario is that it provides a description of the transition from galactic to extragalactic cosmic rays which is consistent with the KASCADE observations. On the other hand, the ankle scenario requires that galactic sources should be able to accelerate cosmic rays up to \( \sim 10^{19} \) eV, which appears rather challenging on the basis of current knowledge of acceleration processes in galactic sources.

In addition to the two scenarios discussed above, there is a third one, based on the possibility that the chemical composition at the source is contaminated by nuclei heavier than hydrogen (Allard et al. 2005a; Allard et al. 2005b). The propagation of these elements and their fragmentation in the cosmic photon background determine a rather complex energy dependent chemical composition at the Earth, which depends somewhat on the assumptions on the injection spectra and relative abundancies in the sources. In this model the transition between galactic and extragalactic cosmic rays takes place at \( \sim 2 \times 10^{18} \) eV, not very different from but slightly higher than the prediction of the dip scenario. As a consequence, this model also appears to agree with the fact that the galactic spectrum should end at energies \( 10^{17} - 10^{18} \) eV. However, the mixed composition model requires a rather flat injection spectrum and predicts that the chemical composition
in the transition region has a strong iron and helium contamination. In (Allard et al. 2005b) the authors argue that the model is in good agreement with the elongation rate observed by different experiments. This conclusion is reached by adopting a specific recipe for the chemical abundance in the accelerator and then studying the dependence of the results on the initial assumptions. Unfortunately the data on the chemical composition as derived from the elongation rate (or any other method so far) are rather heavily affected by uncertainties in the interaction models and a final confirmation of one or the other of these models will require dedicated measurements of the chemical composition in the transition region and possibly a better understanding of the physics entering the description of the interactions in the atmosphere in this energy region.

4 Spectrum and anisotropies of UHECRs

The discussion on the spectrum of UHECRs is often concentrated on the presence or absence of the GZK feature, a flux suppression at energies in excess of $10^{20}$ eV resulting from photopion production interactions of protons with the cosmic microwave background. The theoretical prediction of this part of the spectrum is extremely uncertain, being dependent on the injection spectrum, the distribution and spatial density of the sources and the strength and topology of the intergalactic magnetic field. The search for this feature has given inconclusive results so far, mainly due to the very low statistics of detected events. From the statistical point of view, the most significant data are those collected by AGASA, HiRes and the Pierre Auger Observatory. AGASA and HiRes, with comparable exposures, have results which are discrepant in the highest energy part: the spectrum of AGASA does not show the GZK suppression, while HiRes spectrum has a pronounced GZK feature. The numerical simulations of De Marco, Blasi & Olinto (2003) showed however that, given the small number of collected events, the discrepancy is in fact at $\sim 2 - 3\sigma$ level, being further reduced if the offset in the overall normalization of the spectra is attributed to a systematic error in the energy determination. A systematic error of $\sim 30\%$ would in fact make the experiments to reasonably agree with each other. It is important to stress that the simulation of the propagation of UHECRs was carried out by De Marco, Blasi & Olinto (2003) in the case of a truly continuous distribution of the sources (no point sources with finite density).

The most recent measurement of the spectrum by the Pierre Auger Observatory (Sommers et al., 2005) is in closer agreement with the HiRes re-
results, although again no conclusive evidence for the absence of the GZK feature can be claimed so far.

An important piece of information on the sources of UHECRs and indirectly even on their injection spectrum, can be inferred from small scale anisotropies (SSA), that signal for the presence of point sources. The SSA can be measured through the effect they have on the two point correlation function of the arrival directions of the detected events, and clearly they provide information on point sources only if the magnetic field in the propagation volume is not significant (Blasi & De Marco, 2003). The two point correlation function of the AGASA data, when compared with the simulated events provides an estimate of the source number density of \( \sim 10^{-5}\text{Mpc}^{-3} \) (Blasi & De Marco, 2003), with a very large uncertainty (about one order of magnitude on both sides) that results from the limited statistics of events above \( 4 \times 10^{19} \text{eV} \), where the analysis should be carried out in order to avoid (or limit) the effects of the galactic magnetic field.

If we use the best fit for the source density \( n_s \sim 10^{-5}\text{Mpc}^{-3} \) (Blasi & De Marco, 2003) and determine the simulated spectrum of UHECRs at the Earth, we can see that AGASA small scale anisotropies appear to be inconsistent with the spectrum measured by the same experiment at the level of \( \sim 5\sigma \) (De Marco, Blasi & Olinto 2006a). Given the large error in the determination of \( n_s \) this result cannot be taken too seriously, but it certainly hints to the possibility that the SSA observed by AGASA may be a statistical fluctuation. Its statistical significance has in fact been shown to be rather weak (Finley & Westerhoff 2004) and dependent upon the choice of the binning angle for the arrival directions (Finley & Westerhoff 2004; De Marco, Blasi & Olinto 2006a). Moreover, the technique of a combined study of the SSA and spectrum of UHECRs appears to be promising in the perspective of the wealth of data that the Pierre Auger Observatory will provide us with.

The investigation of the SSA through the two point correlation function is however likely to be difficult even with the results that will come out of the Auger South observatory. In (De Marco, Blasi & Olinto 2006b) the simulations of propagation from point sources were repeated for the expected Auger statistics of events: the results suggest that although it will be easy to distinguish the case of point sources from the case of a purely homogeneous distribution, it will not be easy to achieve a good resolving power between different values of the source density \( n_s \). Accounting for the galactic magnetic field and luminosity function of the sources contributes to emphasize this difficulty. On the other hand, the SSA should also result in the appearance of hot spots in the UHECR sky, so that the search for the
sources can proceed though alternative routes, such as the identification of counterparts or the cross-correlation of arrival directions with the positions of sources in given catalogs. The power of these analyses is expected to be much larger when both Auger South and Auger North will be available.

5 Conclusions

We discussed three of the crucial issues in the investigation of the origin of UHECRs: 1) Particle acceleration in astrophysical sources; 2) the transition from galactic to extragalactic cosmic rays; 3) the spectrum and anisotropies of UHECRs.

The theoretical investigation of particle acceleration at shock fronts is recently experiencing a boost, due to some interesting calculations of the nonlinear effects of particle acceleration (e.g. dynamical reaction of the accelerated particles and self-generation of scattering) and some observational results on the spectra of single chemical components (e.g. measurements from KASCADE). These lines of investigation are leading to some consensus on the fact that protons may be accelerated by sources in the Galaxy up to energies \( \sim 10^{16} \) eV. A rigidity dependent argument would imply that the spectrum of iron extends to energy \( \sim 3 \times 10^{17} \) eV. The flux of galactic cosmic rays should rapidly decay above this energy, so that a transition to extragalactic cosmic rays is expected to take place at energy \( \sim 10^{18} \) eV. This conclusion is at odds with the traditional interpretation of the ankle (Wibig and Wolfendale 2005) as the transition feature, while it appears to agree with the prediction of the dip scenario (Berezinsky et al. 2006). A similar energy for the transition energy is however inferred in the case of a mixed composition of extragalactic cosmic rays, as discussed in (Allard et al. 2005a; Allard et al. 2005b). Whether the dip or the mixed composition scenario best describes the observations will most likely be decided when an accurate measurement of the chemical composition between \( 10^{17} \) and \( 10^{19} \) eV will become available.

At larger energies, a crucial issue is represented by the measurement of the spectrum at energies around \( 10^{20} \) eV, where the GZK suppression has long been searched and missed. AGASA and HiRes spectra are in a mild contradiction which may well be due to statistical fluctuations and a systematic error in the energy determination with the two different techniques used. The Pierre Auger Observatory should soon settle this issue.

At sufficiently high energies the magnetic field of the Galaxy is not expected to bend the trajectories of high energy particles by more than the
angular resolution of the operating cosmic ray experiments. This may lead to the identification of small scale anisotropies, flagging the presence of discrete sources of UHECRs. A signal of this type was found by AGASA, though its statistical significance was later questioned (Finley & Westerhoff 2004; De Marco, Blasi & Olinto 2006b). The level of SSA detected by AGASA would correspond to a source density $\sim 10^{-5}\text{Mpc}^{-3}$ (Blasi and De Marco 2004). This density would roughly correspond to the density of active galactic nuclei. This has inspired numerous searches for correlations between the directions of arrival of UHECRs and the locations of AGNs. Despite several claims of positive correlations, a definite answer is still missing.

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