The origin of ultra high energy cosmic rays

Pasquale Blasi

INAF/Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5 50125 Firenze (Italy)

E-mail: blasi@arcetri.astro.it

Abstract. We briefly discuss some open problems and recent developments in the investigation of the origin and propagation of ultra high energy cosmic rays (UHECRs).

1. Introduction

The detection of cosmic rays with energy in excess of $10^{20}$ eV puzzles the scientific community, mainly for two reasons: 1) most acceleration mechanisms need to be stretched to their extreme to allow for the generation of particles with this energy; 2) Energy losses of protons with energy high enough to suffer photopion production are such that, if the source distribution is homogeneous on scales larger than the loss length, a flux suppression should be expected in the spectrum, the so-called GZK feature [1]. It is not clear yet if this feature has been observed.

The importance of these two issues is here addressed in the context of the most recent findings in the investigation of particle acceleration at shock fronts, and in the light of the up-to-date measurements of the cosmic ray flux, anisotropy and chemical composition. A more extended discussion of these topics and their connection to the physics of lower energy cosmic rays can be found in two recent reviews [2, 3].

This review is organized as follows: we discuss some developments in the theory of particle acceleration at shock waves in Sec. 2. In Sec. 3 we address the important issue of identifying the energy region in which the transition from a galactic to an extragalactic origin of cosmic rays takes place. In Sec. 4 we discuss the current measurements of the spectrum and anisotropies of UHECRs. We conclude in Sec. 5.

2. Particle Acceleration at shock fronts

Diffusive particle acceleration at collisionless shock waves (hereafter Diffusive Shock Acceleration or DSA) remains one of the most promising acceleration mechanisms to energize charged particles to very high energies. Historically, the theory of DSA was first developed for the case of non relativistic shock fronts [4, 5, 6] and later for the case of relativistic shocks [24]. A full theory which describes particle acceleration at shocks of arbitrary speed and arbitrary scattering properties of the background medium was recently formulated [25, 26] and applied to a variety of cases [20, 27]. All these approaches are based on the assumption that the accelerated particles exert no dynamical reaction on the shock, the so-called test particle approximation (TPA).

Recent developments in this field are aimed at addressing the following issues: 1) Is the test particle approximation broken and if so, what are the implications? 2) What provides the scattering agents that allow particles to return to the shock front from the upstream fluid? This
question, as discussed below, is intrinsically related to the determination of the maximum energy of the accelerated particles.

The two questions above, as we will find, are not independent from each other. Regrettably, most investigations trying to address these issues have been carried out for the case of non-relativistic shocks, with a few exceptions.

The test particle approximation was first relaxed in the context of thermodynamical models, known as two-fluid models [11], in which the accelerated particles and the thermal plasma are described as two separate fluids interacting through the pressure exerted by the accelerated particles on the background shocked plasma. This class of models does not provide informations on the spectrum of the accelerated particles, but only on their general thermodynamical properties and their effect on the background plasma. The first attempts to gather information on the spectrum were carried out in [12, 13]. These models led to the modern kinetic models [14, 15, 16, 17, 18, 21] which provide also the spectrum of the accelerated particles. In this sense, kinetic models include two-fluid models. At the same time, several numerical approaches were developed [19]. A relatively recent up-to-date technical review of these subjects can be found in [20].

It is qualitatively easy to explain why the breaking of the TPA may play a very important role for particle acceleration: the typical spectrum of accelerated particles at a strong shock (very large Mach number) within the TPA is $f(p) \propto p^{-4}$, which contains a divergent amount of energy when integrated over momentum, unless a high momentum cutoff, $p_{\text{max}}$ is imposed. Since $p_{\text{max}}$ is determined by environmental parameters (e.g. magnetic field, size or age of the accelerator), even with a given $p_{\text{max}}$ and at fixed number of particles accelerated to suprathermal energies, it may happen that the pressure in the form of accelerated particles, $P_{\text{CR}} = \int_0^{p_{\text{max}}} dp 4\pi p^3 v(p) f(p)$, exceeds the total kinetic pressure $\rho u^2$ crossing the shock front. This is clearly unphysical and suggests that the reaction of the particles on the shock may become important. Moving towards the shock front from upstream infinity, the pressure of the accelerated particles increases, and the fluid is slowed down to form a shock precursor. The reaction of the accelerated particles implies that the total compression factor between upstream infinity and downstream can vastly exceed 4, while the compression factor at the subshock remains bound to be $\leq 4$. The kinetic models have convincingly demonstrated that this situation corresponds to non-power-law concave spectra of the accelerated particles: the spectrum is harder than $p^{-4}$ at low momenta and harder than $p^{-4}$ for high momenta. As a consequence, most pressure is exerted by the highest energy particles and this implies that the few particles with $p \sim p_{\text{max}}$ that can escape to upstream infinity carry enough energy to make the shock radiative and thereby more compressible, namely the spectrum tends to get harder at high energies. Moreover, if a sufficiently large amount of energy is accumulated in the accelerated particles, the adiabatic index of the fluid tends to $4/3$ instead of $5/3$, and again this makes the shock more compressible. This set of phenomena all point in the direction of contributing to the shock modification and to an enhancement of the acceleration efficiency. In the absence of Alfvén heating or other processes that heat up the upstream fluid in a non-adiabatic way, very high efficiencies of acceleration can be achieved (e.g. [21]).

All the calculations developed so far assume that the diffusion coefficient that determines the efficiency of the scattering of particles in the upstream and downstream plasmas is an input to the problem. It is well known that at least for the case of supernova remnants in the interstellar medium (ISM), the level of magnetic turbulence is insufficient to allow for energization of the particles to energies of astrophysical interest. The general picture of DSA admits that local magnetic scattering is self-generated in the shock vicinity due to streaming instability [6]. The amount of turbulence that can be generated in this way determines the maximum momentum of the accelerated particles (see [7] for the case of supernova remnants). If stationarity of the acceleration process and of the generation of Alfvén waves is assumed, the maximum level of
turbulence can be shown to be [8]:

\[ \frac{\delta B^2}{B^2} = 2M_A \frac{P_{CR}}{\rho u^2}, \]  

(1)

where \( M_A \) is the Alfvén Mach number. If \( P_{CR} \sim \rho u^2 \), the amplification of the magnetic field with respect to the background undisturbed field can be as high as \( \sim M_A^{1/2} \). Several processes can reduce the effective magnetic field to values much lower than those found through Eq. (1). On the other hand, Eq. (1) immediately shows that the linear theory that it is based upon is easily broken in the description of efficient particle acceleration at shocks (namely if \( P_{CR} \sim \rho u^2 \)).

In a series of recent investigations [22, 23] the possibility was advanced that the saturation level of the turbulent magnetic field may be even higher than what found through Eq. (1). In [23], Bell discussed in detail the generation and growth of non-resonant, non-alfvenic waves induced by cosmic rays in the shock vicinity: in the reference frame of the upstream plasma, the shock moves toward the observer and carries a current of positively charged particles \( \vec{J}_{CR} \) (the accelerated particles). Due to the condition of charge neutrality, a return current \( \vec{J}_{ret} \) is established in the upstream plasma. In the frame of the upstream plasma, the plasma itself is subject to a force \( \vec{J}_{ret} \times \vec{B} \). This force vanishes at the zero order in the case of a parallel shock, but after taking into account the perturbations of the equation of motion and of Maxwell equations, this term remains in the form of a forcing term. The dispersion relation of the waves can be shown to develop a branch of non-alfvenic modes with a dominant imaginary part of the frequency, which are therefore almost purely growing. In [23] the non-linear part of the evolution of the perturbations was followed through a hybrid numerical simulation. The author of Ref. [23] reaches the conclusion that the saturation level of the unstable modes is well described by

\[ \frac{\delta B^2}{B^2} = M_A^2 \frac{u}{c} \frac{P_{CR}}{\rho u^2}. \]  

(2)

Whether the saturation level is correctly described by this expression or is rather determined by one of the several effects that could not be included in the calculations of [23] is still to be seen. However, if Eq. (2) is in fact correct, then the magnetic field can be amplified in the proximity of a shock to very large values \( \delta B/B \sim M_A^{1/2} \rho u^2 \), thereby opening the possibility that acceleration to very high energies may be achieved.

The implications of this result for galactic cosmic rays have been discussed in [2, 3]. It is easy to extend those conclusions to astrophysical scenarios where DSA is at work and can possibly lead to the generation of UHECRs, though at present no systematic investigation has been carried out. Due to the many physical processes involved (generation, growth and damping of non-alfvenic perturbations) the role of this mechanism of magnetic field amplification should be studied on the case-by-case basis.

### 3. The transition from galactic to extragalactic origin

The first step towards unveiling the origin of UHECRs is to understand at which energies cosmic rays become of extragalactic origin. The transition from galactic to extragalactic cosmic rays has historically been identified with the ankle and interpreted as the intersection of a rapidly falling galactic spectral component and a flat spectrum of extragalactic cosmic rays. In [28, 29] it was pointed out that the combination of pair production energy losses and adiabatic energy losses due to the expansion of the universe generates a second knee and a dip in the spectrum of extragalactic cosmic rays, consistent with the observations (see Fig. 6 for predictions obtained following the calculations of [30, 28, 29]).

In this model the transition from galactic to extragalactic cosmic rays takes place at energies below \( \sim 10^{18} \) eV, where the galactic cosmic ray component would be cut off. In its basic form,
this scenario implies that cosmic rays are injected at extragalactic sources with an injection spectrum $E^{-2.7}$ and no luminosity evolution (solid line in Fig. 1). Although it is a worse fit, also the case of sources with luminosity evolving with redshift as $L(z) \propto (1 + z)^4$ and with injection spectrum $E^{-2.4}$ shows a dip-like feature (dashed line in Fig. 1). In both cases, even small levels of magnetization of the intergalactic medium would induce a low energy suppression of the flux, which might in fact improve the fit to the all-particle spectrum \cite{31,32}. The contributions of many sources with different values of the maximum energy $E_{\text{max}}$ was shown in \cite{33} to mimick a steeper injection spectrum, though requiring much less energy injection as compared with the case of an injection spectrum $E^{-2.7}$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Spectrum of cosmic rays of extragalactic origin for an injection spectrum $\propto E^{-2.7}$ and no luminosity evolution (solid line) and for injection spectrum $\propto E^{-2.4}$ and luminosity evolution $L(z) \propto (1 + z)^4$ (dashed line). The data are from Akeno and AGASA.}
\end{figure}

A clear prediction of this model is that the Galactic component of cosmic rays should be vanishing at energies $\leq 10^{18}$ eV. The KASCADE data \cite{10} show that above the knee the chemical composition of cosmic rays becomes increasingly more dominated by heavy elements. Moreover, these data suggest that rigidity dependent knees in the single chemical components appear, and that cosmic rays in the energy region around $10^{17} - 10^{18}$ eV are expected to be mainly iron nuclei. At these energies the flux is also expected to vanish, if the rigidity dependent knees observed for protons and helium nuclei \cite{8} are assumed to be present for heavier elements as well. This observational scenario appears to provide circumstantial evidence that the spectrum of galactic cosmic rays may be terminated at $10^{17} - 10^{18}$ eV.

A more serious concern for the model of \cite{28,29} is related to the chemical composition: the dip is in fact likely to disappear if a small contamination (with solar-like abundance) of nuclei heavier than hydrogen is present at the source \cite{29,33}. Magnetic horizon effects related with nuclei with different charge to mass ratio might somewhat mitigate the relevance of this issue \cite{35}. An accurate measurement of the chemical composition of cosmic rays in the transition region appears to be of crucial importance.

4. Spectrum and small scale anisotropies of UHECRs
UHECRs present us with at least two questions. The first one is related to the search for an acceleration process and an acceleration site at which these particles win against energy losses or finite size of the accelerator and succeed in becoming UHECRs. The second is related to their propagation: for sources distributed homogeneously in the universe, particles for which the reaction of photopion production is kinematically allowed suffer rapid energy losses, with
a loss length of $\sim 20$ Mpc at $10^{20}$ eV. This results in a suppression of the flux at the Earth, the so-called GZK feature [1]. The shape of this feature is extremely model dependent: local overdensities of sources, the injection spectrum, local magnetic fields and source evolution all play a role in changing the shape of the GZK feature.

In this section we deal with the second point, namely the detection of the GZK feature and the role that small scale anisotropies in the directions of arrival can play in unveiling the sources of UHECRs.

The very low fluxes expected at energies around and above $10^{20}$ eV makes the detection of the GZK feature very problematic. Experiments that have operated so far have not been successful in either detecting the GZK feature or proving its absence with a sufficiently high statistical significance. The spectra of AGASA, HiRes and the newly released data from the Pierre Auger telescope [38] are plotted in Fig. 2 (left panel). In the right panel of the same figure we show the spectra when the AGASA energies have been shifted downwards by 25%.

![Figure 2. Left Panel) Spectrum of AGASA, HiRes and Auger. Right Panel) Spectrum of AGASA, HiRes and Auger with a correction of the AGASA energy for a possible systematic error in the energy determination by $-25\%$.](image)

It is rather remarkable that all experiments are in substantial agreement, and that the few differences can be interpreted in terms of rather small systematic energy shifts in one or more of the experiments. Several Monte Carlo simulations (see [39, 40]) have convincingly showed that the differences in the high energy parts of these spectra have a rather low statistical significance, of the order of $2-3\sigma$. This means that for a given statistics of events above $10^{19}$ eV, the number of events with energy above $10^{20}$ eV is low enough that is affected by statistical fluctuations.

These statistical considerations are the result of averages over large samples of realizations of source distributions, therefore one might wonder whether the individual spectra of those realizations which have a large number of events at ultra high energies are similar to the AGASA spectrum or not. In Fig. 3 (from [40]) we show the spectra of UHECRs obtained in some of the realizations that showed 11 or more events above $10^{20}$ eV (the error bars here are just poissonian, namely they have the same meaning as in Fig. 2). These spectra closely resemble the AGASA spectrum, namely they do not show any GZK suppression, despite the fact that in the lower energy region they all fit the data quite well. This shows that an AGASA-like spectrum is not that improbable, even if the average cosmic ray spectrum can be expected to show a GZK feature [40].

The spectrum of cosmic rays by itself does not contain enough information to determine the type of sources of UHECRs. A first hint at the type of sources can come from the identification of small clusters of events with arrival directions which differ little. Such a signal of small scale
Figure 3. Some of the simulated realizations with number of events equal to or larger than the actual number detected by AGASA [40].

anisotropies (SSA) was first claimed by the AGASA collaboration [41]. The signal was however shown to have a low statistical significance [42]. No evidence of SSA has been found so far in the HiRes data [45].

On the other hand, if astrophysical point sources are believed to accelerate UHECRs, then SSA are to be expected. It was shown in [43] that, if the AGASA results were confirmed, the number density of sources could be estimated to be around $10^{-5}$ Mpc$^{-3}$, with a quite large uncertainty due to the very limited statistics of events available (see [44] for other estimates). In [40] the authors show that the spectrum of AGASA appears to be not fully consistent with the detection of the SSA by the same experiment. The possibility of coupling the information on the spectrum and SSA to gather better information on the number of sources will probably prove useful with the upcoming data from the Pierre Auger Collaboration.

5. Summary
We briefly discussed three issues related to the origin and propagation of ultra-high energy cosmic rays. In particular we summarized some recent developments in the investigation of particle acceleration at non-relativistic shock fronts, including the non linear dynamical reaction of the accelerated particles on the shock and the generation of waves by the accelerated particles. We also addressed the important issue of the transition from galactic to extragalactic origin of the observed cosmic rays. Finally we discussed the status of the measurements of spectrum and anisotropies of UHECRs.

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