C. R. Physique 15 (2014) 329–338

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Ultra-high-energy cosmic rays / Rayons cosmiques d'ultra-haute énergie

Origin of very high- and ultra-high-energy cosmic rays

Origine des rayons cosmiques de très haute et ultra-haute énergie

Pasquale Blasi [a,b,*]

[a] *INAF/Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5, 50125 Firenze, Italy*
[b] *Gran Sasso Science Institute (INFN), viale F. Crispi 7, 67100 L'Aquila, Italy*

ARTICLE INFO

Article history:
Available online 21 March 2014

Keywords:
VHECR
UHECR
Knee
Acceleration
Galactic–extragalactic

Mots-clés :
VHECR
UHECR
Genoux
Accélération
Galactique–extragalactique

ABSTRACT

While there is some level of consensus on a Galactic origin of cosmic rays up to the knee ($E_k \sim 3 \times 10^{15}$ eV) and on an extragalactic origin of cosmic rays with energy above $\sim 10^{19}$ eV, the debate on the genesis of cosmic rays in the intermediate energy region has received much less attention, mainly because of the ambiguity intrinsic in defining such a region. The energy range between 10^{17} eV and $\sim 10^{19}$ eV is likely to be the place where the transition from Galactic to extragalactic cosmic rays takes place. Hence the origin of these particles, though being of the highest importance from the physics point of view, it is also one of the most difficult aspects to investigate. Here I will illustrate some ideas concerning the sites of acceleration of these particles and the questions that their investigation may help answer, including the origin of *ultra*-high-energy cosmic rays.

RÉSUMÉ

Alors qu'il existe un certain niveau de consensus sur l'origine galactique des rayons cosmiques jusqu'au genou ($E_k \sim 3 \times 10^{15}$ eV) et sur leur origine extragalactique au-delà de $\sim 10^{19}$ eV, le débat sur la genèse de ces rayons dans la région intermédiaire a reçu beaucoup moins d'attention, en particulier du fait de l'ambiguïté intrinsèque à la définition même de cette zone. L'intervalle d'énergie de 10^{17} eV à $\sim 10^{19}$ eV est probablement celui où la transition galactique–extragalactique a lieu. Par conséquent, l'origine des rayons cosmiques dans cet intervalle, bien que revêtant une importance toute particulière du point de vue de la physique, est aussi particulièrement difficile à étudier. J'illustre ici quelques idées concernant les sites d'accélération de ces particules et les questions auxquelles leur étude peut répondre, y compris concernant l'origine des rayons cosmique d'ultra-haute énergie.

* Correspondence to: INAF/Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5, 50125 Firenze, Italy.
E-mail address: blasi@arcetri.astro.it.

http://dx.doi.org/10.1016/j.crhy.2014.02.008
1631-0705/

1. Introduction

The bulk of cosmic rays (CRs) reaching the Earth is most likely accelerated in Galactic sources, and based on energetic arguments, supernova remnants (SNRs) are the most likely sources (see [1] for a review of the positive and critical aspects of this scenario). The greatest challenge to this so-called SNR paradigm is represented by the maximum energy that can be achieved: even in the presence of efficient magnetic field amplification at the SNR shock, reaching proton energies in the $\sim$ PeV range appears to be very challenging, so much so that new avenues are being pursued. For instance the perspective of acceleration in the early (fastest) phases of the supernova explosion is insistingly been investigated [2–4], though this version of the SNR paradigm is also not problem free. Many arguments conspire to suggest that SNRs can hardly accelerate CRs to rigidities in excess of 1–10 PeV. This would imply that the proton spectrum extends to about the knee region, while heavier nuclei with electric charge Ze get accelerated to energies Z times larger. This qualitative picture seems to be confirmed by the fact that the chemical composition at the knee shows a transition from light to heavy [5]. In this scenario it would be natural to expect that Galactic CRs would end with an iron-dominated composition at $\sim 10^{17}$ eV. Yet no appreciable drop in the CR flux is observed at such energies, indicating that either there are Galactic sources able to accelerate to much higher energies than we are able to account for at present, or that there is a substantial flux of extragalactic CRs already at $E \gtrsim 10^{17}$ eV. These two possibilities have very different implications in terms of chemical composition and anisotropy of very high-energy (VHE) and ultra-high-energy (UHE) CRs (see [6] for a recent review on UHECRs).

An extra component of CRs accelerated in the Galaxy was already advocated in [7], where the extragalactic CR flux was assumed to follow the dip model [8] (pure protons). Both possibilities of a Galactic and extragalactic additional component were investigated in [9] in the case in which the extragalactic CR flux has a mixed composition tuned to fit the Pierre Auger Observatory (Auger) observed spectrum and chemical composition. Indeed, the spectra and chemical composition of UHECRs (with energy $\gtrsim 10^{18}$ eV) as measured by Auger [10,11] suggest that CRs are injected with a mixed composition and, somewhat surprisingly, with a rather hard spectrum.

At energies between the knee and $\sim 10^{18}$ eV the measurement of spectrum and chemical composition is of the utmost importance to understand the origin of VHECRs. Recent measurements carried out with KASCADE-Grande [12,13] reveal an interesting structure in the spectrum and composition of CRs between 10^{16} and 10^{18} eV: the collaboration managed to separate the showers in electron-rich (a proxy for light chemical composition) and electron-poor (a proxy for heavy composition) showers and showed that the light component (presumably protons and He, with some contamination from CNO) has an ankle like structure at 10^{17} eV. The authors suggest that this feature signals the transition from Galactic to extragalactic CRs. The spectrum of Fe-like CRs continues up to energies of $\sim 10^{18}$ eV, where the flux of Fe and the flux of light nuclei are comparable. Similar results were recently put forward by the ICETOP collaboration [14]. This finding does not seem in obvious agreement with the results of the Pierre Auger Observatory [11], HiRes [15,16] and Telescope Array [17,18], which show a chemical composition at 10^{18} eV that is dominated by the light component.

Given the complexity of the situation as currently suggested by data, here we will keep the discussion as general as possible. In Section 2 we will summarize the arguments that lead to require a Galactic or an extragalactic extra CR component; in Section 3 we will discuss some sources of Galactic CRs that may be able to accelerate protons to energies of $\sim 10^{17}$ eV, with special attention for pulsars and powerful supernova explosions. In Section 4 we will extend the discussion on particle acceleration to extragalactic sources and their potential as sources of UHECRs. We will summarize in Section 5.

2. Galactic versus extragalactic CRs: where is the transition?

A reasonable understanding of the CR spectrum up to energies of order 10^{16} eV can be achieved by assuming that sources inject a power law spectrum into the interstellar medium (ISM) and that diffusion adds an energy dependence, which reflects in the high-energy behavior of the secondary to primary ratios, such as B/C. One such description can be found in [19], where the all-particle spectrum is fitted reasonably well with a diffusion coefficient $D(E) \propto E^{1/3}$, qualitatively compatible with the observed anisotropy [20]. The maximum energy of protons was assumed to be $\sim 5 \times 10^{15}$ eV. This situation is illustrated in the left panel of Fig. 1: the different lines show ten different realizations of the spatial distribution of SNRs in the Galaxy, while the step-function shows the average flux of the ten realizations. The data points with error bars represent the average all-particle spectrum as provided in Ref. [21]. The spread in the theoretical predictions provides an estimate of the role of fluctuations on the all-particle spectrum. The high-energy part of the all-particle spectrum is dominated by the iron component, with a spectrum that dives starting at $\sim 10^{16}$ eV. Fig. 1 (left panel) shows the predicted all-particle spectrum departing from the observed one at energies above $\sim 10^{16}$ eV.

At energies $\gtrsim 10^{16}$ eV, a substantial contribution to the all-particle spectrum must come either from an additional class of Galactic sources or from extragalactic CRs. For instance in the right panel of Fig. 1 we plot the all-particle spectrum obtained by summing the SNR contribution (again, ten realizations of their distribution are shown) and a basic dip model [8] for the extragalactic component. A low energy exponential cutoff in the extragalactic CR flux has been imposed by hand at 10^7 GeV, in order to mimic the possible effect of extragalactic magnetic fields. The normalization of the predicted extragalactic CR flux was chosen so as to fit the all-particle spectrum as measured by HiRes [22].

The perspective provided by Auger on UHECRs is rather different from that of HiRes and more recently of Telescope Array: the mean depth of shower maximum, $X_{\max}(E)$, and its dispersion $\sigma(E)$ as measured by Auger suggest that at en-