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HIGH-ENERGY COSMIC RAYS: GALACTIC OR EXTRAGALACTIC?

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Abstract

The bulk of cosmic rays is assumed to be accelerated in our Milky Way, while the highest-energy particles in the Universe are attributed to extra-galactic sources. A transition is expected at energies around 10^{17} to 10^{18} eV. A new method is presented to measure the properties of cosmic rays in this energy region: the radio detection of air showers. And a comprehensive model is discussed to describe consistently the Galactic and extra-galactic components of cosmic rays from GeV energies up to $\sim 10^{20}$ eV.

1 Introduction

Cosmic rays (ionized atomic nuclei) impinge on the Earth with (kinetic) energies covering a wide range from MeV energies up to beyond 10^{20} eV. At

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[0] http://particle.astro.ru.nl

energies below $\sim$ 100 MeV they are accelerated in energetic outbursts of the Sun. At higher energies, the are assumed to originate in our Milky Way, being accelerated in Supernova remnants (e.g. [1, 2]). At energies exceeding 10^{18} eV it becomes increasinlgy difficult to magnetically bind the particles to our Galaxy. Thus, particles with energies above $\sim 10^{18}$ eV are usually considered to be of extra-galactic origin. A transition from a Galactic to an extra-galactic origin of cosmic rays is expected at energies around 10^{17} to 10^{18} eV [3, 4].

In this paper we will shed new light on the understanding of the origin of cosmic rays in the transition region ($10^{17} - 10^{18}$ eV). This necessitates a precise measurement of the properties of cosmic rays, namely their arrival direction (on the sky), their (kinetic) energy, and their particle type (atomic mass A).

The flux of cosmic rays is steeply falling, approximately following a power law $\propto E^{-3}$. In our region of interest, cosmic rays are only measured indirectly, using large ground-based detector installations. High-energy cosmic rays impinging on the atmosphere, initiate cascades of secondary particles, the extensive air showers. The challenge of the indirect measurements is to derive the properties of the incoming cosmic rays from air-shower observations. Most challenging is the measurement of the particle type, since the sensitivity of air shower measurements is only proportional to $\ln A$. Intrinsic shower fluctuations allow to divide the measured cosmic rays in up to five mass groups for the best experiments [5].

A (new) method to measure the properties of cosmic rays via the radio detection of air showers is described in Sect. 2. These measurements yield one of the key observables, the evolution of the mass composition of cosmic rays as a function of energy. These observations are the basis for a consistent model for the origin of Galactic and extra-galactic cosmic rays as outlined in Sect. 3, with particular emphasis on the transition region $10^{17} - 10^{18}$ eV.

2 Radio detection of air showers

Many secondary particles in extensive air showers are electrons and positrons. They emit radiation with frequencies of tens of MHz mainly due to interaction with the magnetic field of the Earth. Radio detection of air showers is suitable to measure the properties of cosmic rays with nearly 100% duty cycle [6, 7]. The LOFAR radio telescope [8, 9] is one of the leading installations for the radio measurements of air showers.

In the last years the radio technique has been established as a precise method to measure the mass composition of cosmic rays. The LOFAR measurements together with the predictions of the CoREAS [10] simulation package result in a complete understanding of the emission mechanisms. With LOFAR the properties of the radio emission have been measured with high accuracy [11, 12, 13] in the frequency range 30 – 80 MHz, which allows us to establish key features, such as the lateral density distribution of the radio signals [14, 15], the shape of the shower front [16] – important to reconstruct the arrival direction of the incoming cosmic ray, and the polarization of the radio signal [17]. These measurements help to understand the emission processes in the atmosphere and to quantify the contributions of the two mechanisms, being responsible for the radio emission of air showers – namely the geomagnetic effect (i.e. charge separation in the geomagnetic field) and the Askaryan effect (charge excess in the shower front). We obtained the first quantitative measurements in the frequency range 120 – 240 MHz [18]. We also recorded air showers during thunderstorm conditions [19, 20] and measured the structure of electric fields in the atmosphere.

The good agreement between the measurements and the predictions of the CoREAS code is essential to identify the type of incoming cosmic ray. This is inferred from the (atmospheric) depth of the shower maximum X_{max}, one of the standard measures to estimate $\ln A$. To measure X_{max} [22, 23] we analyse simultaneously measurements of the radio emission and the particle detectors, to determine X_{max} with an accuracy of ~ 20 g/cm^2 with the dense LOFAR core, thus, reaching the state of the art – the uncertainty of the Pierre Auger Observatory fluorescence detector. The measured values for the depth of the shower maximum X_{max} are used to derive the mean logarithmic mass of cosmic rays

$$\langle \ln A \rangle = \left(\frac{X_{\mathrm{max}} - X_{\mathrm{max}}^{\mathrm{p}}}{X_{\mathrm{max}}^{\mathrm{Fe}} - X_{\mathrm{max}}^{\mathrm{p}}} \right) \times \ln A_{\mathrm{Fe}}.$$

This necessiates predictions for the depth of the shower maximum for impinging protons and iron nuclei, $X_{\mathrm{max}}^{\mathrm{p}}$ and $X_{\mathrm{max}}^{\mathrm{Fe}}$, respectively. The resulting mean mass is depicted in Fig. 1 as a function of energy for the LOFAR results together with the world data set [21]. Two hadronic interaction models are used (EPOS and QGSJET) to interpret the data.

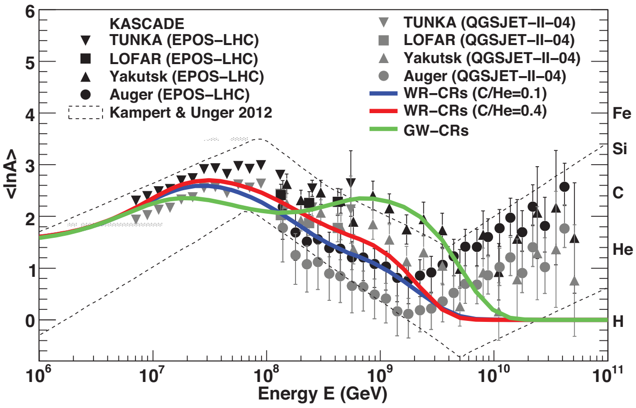

Figure 1: Mean logarithmic mass $\ln A$ as measured by various experiments, interpreted with two hadronic interaction models. In addition, predictions are shown for three different models of the additional Galactic component: cosmic rays from Wolf-Rayet stars (C/He = 0.1 and C/He = 0.4), and cosmic rays being re-accelerated by the Galactic wind. See [21] for further details.

3 The transition from Galactic to extra-glactic cosmic rays

To understand the implications of the LOFAR measurements and the available world data set from direct and indirect measurements a model has been developed to consistently describe the observed energy spectrum and mass composition of cosmic rays with energies up to about 10^{18} eV [21]. We assume that the bulk of Galactic cosmic rays is accelerated by strong Supernova remnant shock waves [24]. After acceleration, cosmic rays undergo diffusive propagation through the Galaxy. During the propagation, cosmic rays may again encounter expanding Supernova remnant shock waves, and get re-accelerated. As the probability of encountering old Supernova remnants is expected to be larger than the younger remnants because of their bigger sizes, re-acceleration is expected to be produced mainly by weaker shocks. Since weaker shocks generate a softer particle spectrum, the resulting re-accelerated component will have a spectrum steeper than the initial cosmic-ray source spectrum produced by strong shocks. For a reasonable set of model parameters, it is shown that the re-accelerated component can dominate the GeV energy region while the nonre-accelerated component dominates at higher energies, thereby explaining the (recently) observed GeV-TeV spectral anomaly.

We assume a source spectrum for the individual cosmic-ray components at the sources proportional to a power law in total momentum p with an exponential cut-off, which can be written in terms of momentum/nucleon as

$$Q(p) = AQ_0(ap)^{-q} \exp\left(-\frac{Ap}{Zp_c}\right),$$

where Q_0 is a normalization constant, q is the spectral index, and p_c is the cut-off momentum for protons. We assume that the maximum energy of cosmic rays attained during the acceleration process is proportional to the nuclear charge number Z: $E_c = Z \cdot 4.5 \cdot 10^6$ GeV. With these assumptions the energy spectra for individual elements in cosmic rays are perfectly described from the lowest energies (direct measurements at ~ 1 GeV) up to about 10^{16} eV.

Our study shows that a single Galactic component with rigidity-dependent energy cut-offs in the individual spectra of different elements cannot explain the observed all-particle spectrum at energies exceeding $\sim 2 \cdot 10^{16}$ eV. Similar findings have already been obtained earlier 25). We discuss two approaches for a second component of Galactic cosmic rays: re-acceleration at a Galactic wind termination shock and Supernova explosions of Wolf-Rayet stars.

Galactic winds can lead to the production of an additional component of cosmic rays which can dominate at high energies. Galactic winds, which start at a typical velocity of about few km/s near the disk, reach supersonic speeds at distances of a few tens of kpc away from the disk. At about a hundred kpc distance, the wind flow terminates resulting into the formation of termination shocks. These shocks can encounter cosmic rays escaping from the disk into the Galactic halo, and re-accelerate them via the diffusive shock acceleration process. The re-accelerated cosmic rays can return to the disk through diffusive propagation against the Galactic wind outflow. For an energy dependent diffusion process, only the high-energy particles may be effectively able to reach the disk. In order to describe the observed all-particle spectrum around 10^{16} to 10^{18} eV we assume an injection efficiency of 14.5% and a cut-off energy for protons of $9.5 \cdot 10^7$ GeV.

While the majority of the Supernova explosions in the Galaxy occur in the interstellar medium, a small fraction is expected to occur in the winds of massive progenitors like Wolf-Rayet stars. Magnetic fields in the winds of

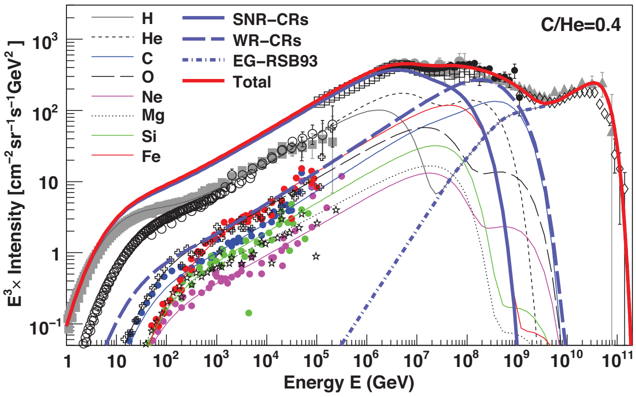

Figure 2: Model prediction for the all-particle spectrum using the Wolf-Rayet star model with a ratio C/He = 0.4. The thick solid blue line represents the total cosmic-rays flux from Supernova remnants, the thick dashed line represents the cosmic rays from Wolf-Rayet stars, the thick dotted-dashed line represents extra-galactic cosmic rays, according to [26], and the thick solid red line represents the total all-particle spectrum. The thin lines represent spectra for the individual elements. For the Supernovae cosmic rays, an exponential energy cut-off for protons at $E_c = 4.1 \cdot 10^6$ GeV is assumed. See [21] for further details.

Wolf-Rayet stars can reach of the order of 100 G, and it has been argued that a strong Supernova shock in such a field can lead to particle acceleration up to energies of $\sim 10^9$ eV [27]. We estimate a frequency of ∼ 1 Wolf-Rayet explosion every 210 years. This corresponds to ∼ 1 Wolf-Rayet explosion for every 7 Supernova explosions occurring in the Galaxy. The source indices of the different cosmic-ray species and the propagation parameters for the Wolf-Rayet cosmic rays are taken to be the same as for the 'regular' component from Supernova remnants. Different elemental compositions of the Wolf-Rayet winds are discussed in the literature: a carbon-to-helium (C/He) ratio of 0.1 and 0.4. The latter scenario can explain almost all observed features in the all-particle spectrum and the mass composition of cosmic rays up to $\sim 10^{18}$ eV, when combined with a canonical extra-galactic spectrum as expected from strong radio galaxies or a source population with similar cosmological evolution. The resulting spectrum is shown in Fig. 2. In this two-component Galactic cosmic-ray model, the 'knee' at $\sim 4 \cdot 10^{15}$ eV and the 'second knee' at $\sim 4 \cdot 10^{17}$ eV in the all-particle spectrum are due to the cut-offs of the first and second Galactic cosmic-ray components, respectively.

Finally, at energies above 10^{18} eV several assumptions for an extra-galactic component have been investigated: from a minimal contribution to scenarios with a significant component below the 'ankle' (at $\sim 4 \times 10^{18}$ eV). It has been found that extra-galactic contributions in excess of regular source evolution are neither indicated nor in conflict with the existing data. We find that an extra-galactic contribution is unlikely to dominate at or below the second knee. The main result is that the second Galactic component predicts a composition of Galactic cosmic rays at and above the second knee that largely consists of helium or a mixture of helium and CNO nuclei, with a weak or essentially vanishing iron fraction, in contrast to most common assumptions. This prediction is in agreement with new measurements from LOFAR and the Pierre Auger Observatory which indicate a strong light component and a rather low iron fraction between $\sim 10^{17}$ and $\sim 10^{18}$ eV.

4 Summary

The radio detection of extensive air showers enables us to measure the properties of cosmic rays (arrival direction, energy, and particle type) above energies exceeding 10^{17} eV with high precision.

We developed a model to consistently describe the observed energy spectrum and mass composition of cosmic rays from GeV energies up to 10^{20} eV. We adopt a three component model: 'regular' cosmic rays being accelerated in Supernova remnants up to $\sim 10^{17}$ eV, a second Galactic component, dominating the all-particle flux between $\sim 10^{17}$ and $\sim 10^{18}$ eV from cosmic rays being accelerated by exploding Wolf-Rayet stars, yielding a strong contribution of He and CNO elements, and, finally, an extra-galactic contribution at energies above $\sim 10^{18}$ eV.

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