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Origin of high energy cosmic rays: A short review

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Abstract

I provide here a short review of some recent observational findings in the field of cosmic rays and of selected theoretical advancements in our understanding of acceleration and propagation of cosmic rays, from below the knee to the highest energies observed so far.

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1. Introduction

In the recent few years several new observational and theoretical findings have considerably contributed to improve our understanding of the origin and propagation of cosmic rays.

Direct measurements of cosmic ray fluxes have been extended to reach closer to the knee region. These measurements are now available for all nuclei from H to Fe, and accurate measurements of the abundances of nuclei heavier than Fe are being carried out. Some of these elements, such as Ge and Ga, can provide useful information on the characteristics of the environment where cosmic ray acceleration takes place. These direct measurements provide the best determination of the spectrum of nuclear species below the knee and seem to lead to approximately power law spectra for all species, with approximately the same slope, ~ 2.7. The spectrum of He, as provided by ATIC-2 and CREAM-I (see Ref. [1] for a review of the most recent results as presented at the 30th ICRC), seems to be slightly flatter than the proton spectrum, but a better statistics in the highest energy bins is needed to confirm this finding.

At energies around and above the knee, the KASCADE (and now the KASCADE-Grande) data and the data from the Tibet Array are basically the only ones that can shed light on the origin of the knee. Unfortunately there is no definite agreement between the data of KASCADE and Tibet Array (only preliminary data on the all-particle spectrum are available from KASCADE-Grande). The proton spectrum as measured by KASCADE shows a pronounced and well-defined knee at $\sim$few 10^{15} eV. The proton spectrum above the knee is rather steep and might even be a cutoff in the spectrum. The He spectrum also shows a similar behavior. The proton spectrum as measured by Tibet Array is somewhat steeper than the KASCADE spectrum and does not show a clear evidence for a knee. The He spectra measured by the two experiments are clearly different in shape and in relative normalizations.

The view that would arise from a simple extrapolation of the proton spectrum as measured by KASCADE is, however, impressively interesting. If the knees in the single chemical components are induced by a rigidity effect, possibly associated with the acceleration process, then the knee in the all-particle spectrum is likely to be interpreted as a superposition of the spectra of the different chemical

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elements. The most effective way to prove or disprove this picture would be to extend the direct measurements as close as possible to the knee or even across it, possibly using ultra-long duration balloon flights.

Both experiments, KASCADE and the Tibet Array, agree, however, on the presence of protons in the spectrum up to energies of $\sim 10^{15}$–10^{16} eV. This implies that the maximum energy of cosmic rays accelerated at the sources must be at least that high. If the KASCADE data are adopted, then the proton spectrum has a steepening or a cutoff at energies $\sim 3\times 10^{15}$ eV, which might be the first detection of the end of the galactic cosmic ray proton spectrum as it is generated at the sources, possibly supernova remnants (SNRs).

Another crucial implication of adopting the KASCADE results is that the galactic spectrum should end at energies of order $E_{\rm end}\approx Z_{\rm Fe}\times E^{\rm p}_{\rm knee}$, where $Z_{\rm Fe}=26$ is the charge of fully ionized Fe nuclei and $E^{\rm p}_{\rm knee}\approx 3\times 10^{15}$ is the position of the knee in the proton spectrum. This leads to $E_{\rm end}\sim 10^{17}$ eV, which clearly conflicts with the standard picture of the transition from galactic to extragalactic cosmic rays, as provided by the traditional ankle model (see the review paper by Hillas [2] and references therein), where the galactic cosmic ray spectrum need to extend above $\sim 10^{19}$ eV.

All these new data are contributing in a fundamental way to establishing an exciting new scenario for the origin of cosmic rays, partly based on some new theoretical insights and partly fueled by recent observations of SNRs at different wavelengths.

This review is organized as follows: in Section 2 I will summarize these new observations and the theoretical scenario that is emerging. In Section 3 I will discuss the implications of this scenario for the description of the transition from galactic to extragalactic cosmic rays. Some recent results on ultra-high energy cosmic rays (UHECRs) are discussed in Section 4. I summarize in Section 5.

2. A new supernova paradigm for the origin of cosmic rays

The supernova paradigm for the origin of cosmic rays is mainly based on an energetic argument: SNRs eject enough energy in the form of kinetic energy of the expanding ejecta that if a fraction $\sim$10–20% of it is converted to cosmic rays, the observed flux of cosmic rays can be accounted for. Clearly there are many more ingredients that add to this paradigm (the spatial distribution of SNRs, propagation in the Galaxy, the chemical composition of accelerated material and many others) but the basic picture remains unchanged.

The motion of the ejecta is supersonic and leads to the formation of a strong shock wave. Particle acceleration is expected to occur at this shock through the first order Fermi process. Since this scenario was first discussed [3–5], a problem was immediately recognized [6]: particle acceleration at energies comparable with that of the knee is possible only if substantial magnetic field amplification takes place at the shock location and particle scattering across the shock takes place at roughly the Bohm rate. For long time both these requirements have been the two assumptions of the problem.

A few years ago, high resolution X-ray observations of some SNRs led to the measurement of the thickness of the X-ray bright regions at the shock location (e.g. Ref. [7]). Most X-rays are non-thermal and are the result of synchrotron emission of high energy electrons. The thickness of the emission regions is related to the loss length of such electrons as due to synchrotron losses, so that it is possible to infer the strength of the magnetic field from measurements of the geometric thickness of the rims. In virtually all cases that have been investigated, the measured magnetic fields are of order 100–500 μG [8], a factor $\sim$100 larger than the typical interstellar medium (ISM) magnetic fields. This is the first convincing evidence of magnetic field amplification at SNR shocks.

The amplification is naturally achieved due to streaming instability [4,9]. The superalfvenic motion of the accelerated particles upstream of the shock leads to the development of an instability which results in amplification of perturbations in the magnetic field strength upstream of the shock. The amplified field is further enhanced by compression at the shock surface (this amplified and compressed downstream field is the one which is observed in the form of bright X-ray rims in SNRs).

Since the first order Fermi process is a stochastic diffusive mechanism, the acceleration time for particles of given momentum is the sum of the diffusive propagation times in the upstream and downstream sections. It is therefore important that the magnetic field is high in both regions, in order to make the acceleration time short and lead to efficient acceleration to high energies. Such a requirement is certainly satisfied by streaming instability. The modes which are unstable depend on the shock velocity and on the efficiency of particle acceleration. When particle acceleration occurs efficiently and the shock speed is high (the two things are not independent) non-resonant modes appear [9] which may grow faster than the resonant modes. This suggests that at different stages during the evolution of a SNR, different modes will be dominant and the maximum energy of the accelerated particles may be a non-trivial function of time [10,11].

If particle acceleration occurs efficiently, as requested for the SNR paradigm to hold up, the dynamical reaction of the accelerated particles on the shock is not negligible and leads to a variety of very interesting effects: (1) a precursor is formed upstream. This is a region in which the upstream fluid, as seen in the shock frame, slows down. This implies that the effective compression factor felt by particles may exceed the limit for a standard fluid shock, namely $r=4$. Moreover the velocity profile in the precursor makes the compression factor a function of the momentum of the particles, so that the expected spectrum of accelerated particles is not a power law. The predicted spectra are concave, being steeper than E^{-2} below 1–10 GeV and