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Recent developments in cosmic ray physics

P. Blasi

INAF/Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5 50125 Firenze, Italy
Gran Sasso Science Institute (INFN), Viale F. Crispi 6, 60100 L'Aquila, Italy

Abstract

The search for a theory of the origin of cosmic rays that may be considered as a standard, agreeable model is still ongoing. On one hand, much circumstantial evidence exists of the fact that supernovae in our Galaxy play a crucial role in producing the bulk of cosmic rays observed on Earth. On the other hand, important questions about their ability to accelerate particles up to the knee remain unanswered. The common interpretation of the knee as a feature coinciding with the maximum energy of the light component of cosmic rays and a transition to a gradually heavier mass composition is mainly based on KASCADE results. Some recent data appear to question this finding: YAC1 - Tibet Array and ARGO-YBJ find a flux reduction in the light component at $\sim$ 700 TeV, appreciably below the knee. Whether the maximum energy of light nuclei is as high as 3000 TeV or rather as low as a few hundred TeV has very important consequences on the supernova remnant paradigm for the origin of cosmic rays, as well on the crucial issue of the transition from Galactic to extragalactic cosmic rays. In such a complex phenomenological situation, it is important to have a clear picture of what is really known and what is not. Here I will discuss some solid and less solid aspects of the theory (or theories) for the origin of cosmic rays and the implications for future searches in this field.

1. Introduction

In the long search for the origin of cosmic rays (CRs), the current period appears particularly rich with new data as well as with both old and new unanswered questions. Larger, better experiments allowed us to collect an impressively large wealth of data on spectra, mass composition and, although to a lesser extent, anisotropy, so much so that the main limitation to using such data is imposed in most cases by systematic errors and systematic uncertainties rather than statistics. The spectral breaks measured by PAMELA [1] in the proton and helium spectra and not confirmed by the preliminary results of AMS-02, presented at the 33^{rd} ICRC, might be instances of this situation.

For many years, one of the main observational pillars in the search for the origin of CRs has been the measurement of a knee in the light cosmic ray component at about the same energy as the knee in the all-particle spectrum [2]. This finding has driven much of the recent theoretical investigation on the highest energies achievable in supernova remnants, in that reaching the knee, even in the presence of rapidly growing plasma instabilities, appears to be rather problematic. As a confirmation on how potentially severe systematic uncertainties may affect our findings, YAC1 - Tibet Array [1], and independently ARGO-YBJ [2] have measured the spectrum of the light component in CRs, and claimed that a knee may be identified at energy $\sim$ 700 TeV, appreciably below the all-particle spectrum knee. ARGO-YBJ also managed to measure the all-particle spectrum, confirming the detection of the standard knee at $\sim 3\times10^{15}$ eV. Interestingly, we are still rather uncertain as to whether

[1]Results presented at the 33^{rd} ICRC in Rio de Janeiro, Brazil, 2013.

[2]Results presented by I. De Mitri at Frontier Research in Astrophysics, May 26-31, 2014, Mondello, Italy

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the proton spectrum steepens at ~ 400 TeV or ~ 3000 TeV. The implications of this data-driven ambiguity on both the modelling of acceleration in Galactic sources and on the end of the Galactic CR spectrum and transition to extragalactic CRs are rather severe.

From the theoretical point of view, the basic model for the origin of Galactic cosmic rays is based on two pillars: *a)* CRs are assumed to be accelerated with power law spectra, $N(E) \sim E^{-\gamma}$ in Galactic sources, such as supernova remnants (SNRs). *b)* CRs propagate diffusively throughout the Galaxy with a diffusion coefficient that, at energies above a few GeV, is assumed to be $D(E) \sim E^{\delta}$. The basic combination of these phenomena, acceleration and propagation in the Galaxy, leads to an equilibrium spectrum $n(E) \sim N(E)/D(E) \propto E^{-(\gamma+\delta)}$, that reflects the balance between injection of newly accelerated CRs and escape of CRs from the confinement volume on time scales $\tau_d = H^2/D(E)$, where H is the height of the galactic halo. This simple estimate also leads to the powerful prediction that the ratio of fluxes of secondary and primary nuclei should be a decreasing function of energy, $\sim E^{-\delta}$ at high energy, so that the measurement of such ratios (such as the Boron to Carbon ratio) would allow us to measure the energy dependence of the diffusion coefficient.

Both pillars listed above, acceleration and propagation, acquire a physical meaning only after a derivation from some basic physical principles. When one tries to do so, it is easy to show that several subtleties can change the simple predictions discussed above in ways that are potentially subject to observational scrutiny. Here I will briefly discuss several of these effects, while a more complete discussion can be found in recent reviews such as those in Refs. [3, 4, 5].

The paper is organized as follows: in §2 I discuss some simple modifications of the standard diffusion scenario that lead to important changes in predicted CR spectra and secondary to primary ratios. In §3 I introduce some of the most important non-linear effects that are at the very basis of the mechanism of diffusive shock acceleration in SNRs. In §4 I comment on the implications of the SNR paradigm for the end of the Galactic CR spectrum and the transition to extragalactic CRs. I summarize in §5.

2. CR transport in the Galaxy

Current models of CR propagation mainly focus on two scenarios: 1) *pure diffusion model*, with $D(E) \propto E^{0.6}$ and a flattening below a few GeV, and injection spectrum $N(E) \sim E^{-2.1}$; 2) *reacceleration model*, with $D(E) \propto E^{1/3}$ and no low energy break, and an injection spectrum $N(E) \propto E^{-2.4}$ with a low energy break below ~ 2 GeV. In fact there is a third class of propagation models that postulate the presence of a Galactic wind that leads to advection dominated CR transport at low enough energies, but the implications of these models for the high energy behaviour of the relevant quantities is not very different from that of the two classes of models listed above. In all these models the breaks in either the diffusion coefficient and/or the injection spectrum are required in order to fit the data and do not derive from fundamental physical arguments. Moreover, both pure diffusion models and reacceleration models are based on the assumptions of spatially homogeneous and isotropic diffusion.

In the following I will discuss the implications of relaxing some of these assumptions in a minimal way.

2.1. Anisotropic Diffusion

In the presence of a large scale magnetic field, such as the spiral shaped one in the Galaxy, diffusion parallel to the large scale field is bound to be faster than diffusion perpendicular to the field lines. This is true even in the presence of fluctuations with $\delta B/B \sim 1$, as discussed for instance in [6, 7]. Observations of diffuse backgrounds of radio and gamma ray emissions require a significant diffusion of CRs perpendicular to the Galactic disc, which reflects in the need to have substantial random walk of magnetic field lines. In all existing models of CR propagation in the Galaxy this very important effect is not taken into account, although some recent calculations [8] have renewed the interest in this line of research.

2.2. Inhomogeneous diffusion coefficient

Even retaining the approximation of isotropic diffusion, the minimal generalization of the diffusion model consists in assuming that the diffusion coefficient may be larger in the halo of the Galaxy and smaller close to the Galactic disc, and possibly with different slopes, E^{δ_1} close to the disc and E^{δ_2} ($\delta_2 > \delta_1$) farther away. This simple generalization of the diffusion model leads to equilibrium spectra of CRs that are no longer pure power laws, but broken power laws. The slope of the CR spectrum measured in the disc is $E^{-(\gamma+\delta_2)}$ at low energies and $E^{-(\gamma+\delta_1)}$ at high energy, where the boundary between low and high energies is set at some critical value E_* determined by the absolute normalizations of the diffusion coefficients and by the spatial size of the regions 1 and 2 with different diffusion properties. This type of two zones diffusion has been recently studied [9]