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Cosmic Ray Origins: An Introduction

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Abstract

Physicists have pondered the origin of cosmic rays for over a hundred years. However the last few years have seen an upsurge in the observation, progress in the theory and a genuine increase in the importance attached to the topic due to its intimate connection to the indirect detection of evidence for dark matter. The intent of this talk is to set the stage for the meeting by reviewing some of the basic features of the entire cosmic ray spectrum from GeV to ZeV energy and some of the models that have been developed. The connection will also be made to recent developments in understanding general astrophysical particle acceleration in pulsar wind nebulae, relativistic jets and gamma ray bursts. The prospects for future discoveries, which may elucidate the origin of cosmic rays, are bright.

Keywords: cosmic rays, dark matter, particle acceleration, pulsar wind nebulae, relativistic jets, gamma ray bursts

1. The Accelerating Universe

1.1. Direct Measurements

The observed cosmic ray spectrum extends from $\sim$ MeV to $\sim$ ZeV[1] energy — fifteen decades in total (Figure 1). The lowest energy particles derive from the sun, the solar wind and the planets and provide (thankfully) small scale illustrations of general mechanisms that operate in the interstellar and intergalactic media. In particular, the two faithful Voyager spacecraft have traversed the solar wind termination shocks, and one of them appears to have crossed the heliopause and is now sampling interstellar cosmic rays directly [1, 2]. The $\sim$ GeV – $\sim$ 100 TeV particles, mostly come form Galactic supernova remnants (e.g., [3, 4, 5]). Recent advances include the consistent measurement of their age at low energy and the measurement of subtle features in their energy spectra by experiments like CREAM [6]. The particles between the "knee(s)" and the "ankle" have a changing composition and may be the heavy counterparts of the highest rigidity protons (e.g., [7]; and [8] for a review). Larger shocks than those associated with individual supernova remnants, perhaps supershells or a Galactic wind termination shock are suggested. Alternatively, neutron stars in the form of pulsars (and their surrounding wind nebulae) are credible sources. The highest energy particles — Ultra High Energy Cosmic Rays (UHECR) — appear to manifest the "GZK" cutoff due to photo-pion production on the microwave background and seem to have a composition that is changing from hydrogen to iron as shown in Figure 2 [9, 10, 11], perhaps for the same reason as the $\sim$ PeV particles. Proposed sources include Active Galactic Nuclei (AGN, e.g., [12]), Gamma Ray Bursts (GRB, e.g., [13]), spinning magnetars (e.g., [14]), and intergalactic shock fronts (e.g. [15]).

1.2. Indirect Observations

Of course most of what we know about putative cosmic ray sources derives from electromagnetic observations throughout the $\sim$ 70 octaves open to astronomical observations. The Chandra X-ray Observatory (CXO) has nearly matched the resolution of radio maps of SuperNova Remnants (SNR) and exhibited electron synchrotron emission from the bounding shock fronts (Figure 3). They have also produced compelling evidence

[1] Almost the energy of a Marchisio goal, but the momentum of a snail!

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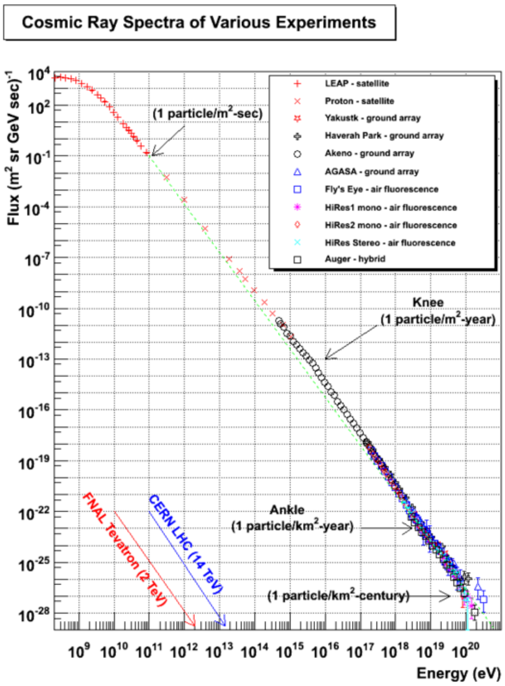

Figure 1: Overall energy spectra of cosmic rays from various experiments. (Courtesy of Dr William Hanlon.)

that high Mach number shocks stretch and amplify magnetic field as well as accelerate cosmic ray electrons with energy up to ~ 100 TeV [16]. While, it was hard to doubt that this was accompanied by proton acceleration, direct evidence has only been presented recently by *Fermi* and AGILE observations which exhibit the predicted "pion bump" in the γ-ray observations in middle-aged supernova remnants expanding into dense molecular gas [17, 18] (Figure 4). No less dramatic have been the observations by Atmospheric Cerenkov Telescopes (ACTs) of TeV γ-rays which show evidence for efficient acceleration beyond ~ 100 TeV (e.g., [19, 20]).

CXO and XMM-Newton observations of clusters of galaxies have demonstrated that the entropy of gas in the outskirts of rich clusters of galaxies is extremely high [21] and is strongly suggestive of the presence of high Mach number accretion shocks[2] as had been predicted on the basis of cosmological simulations [22]. A second development is the measurement of the iron abundance which can be as high as one third solar [23]. These two observations support the intergalactic shock explanation

[2]Radio features that have been identified with giant shocks may not have high enough Mach numbers to be efficient particle accelerators

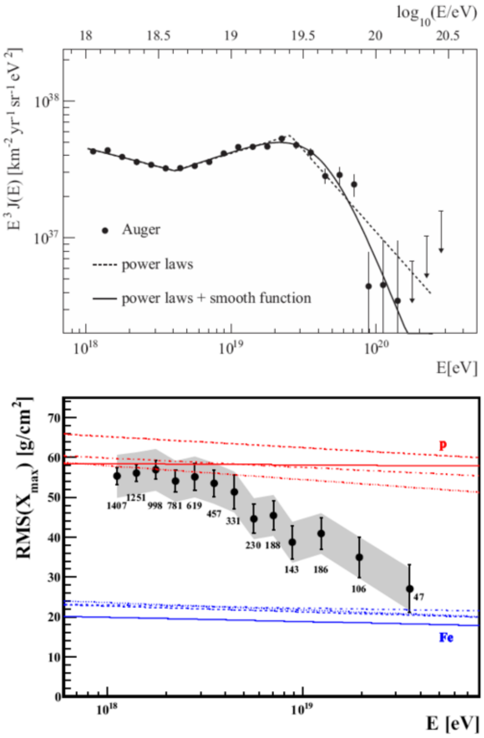

Figure 2: Spectrum of UHECR (top panel) and fluctuation of the atmospheric depth X_{max} around its mean value $RMS(X_{max})$ as a function of energy (bottom panel) measured by Pierre Auger Observatory (from [10]).

of UHECR.

Part of the reason for a resurgence of interest in cosmic ray astrophysics is the race to identify dark matter. As is well known, the most compelling candidate is one or more new "Weakly Interacting Massive Particles" (WIMPs) that have been postulated to be the supersymmetric partners to the particles of the standard model. Exquisite experiments below ground (in mines, e.g. [24]), on ground (at the Large Hadron Collider [25, 26]) and above ground (using *Fermi* and other γ-ray telescopes [27]) have each furnished impressive constraints on the properties of the presumptive particles. Cosmic ray physics is the mother of particle physics and having produced the first detections of positrons, pions, muons and kaons could be the first to detect another radically new class. However, no such claim should ever be accepted ahead of a confident understanding of the more prosaic and conventional cosmic ray foregrounds and backgrounds.