HIGH ENERGY ASTRONOMY FROM THE GROUND

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Summary

High Energy Astrophysics (HEA) is a modern interdisciplinary research field at the interface of astronomy, physics and cosmology, with the major objective to study extraterrestrial phenomena in their most energetic and extreme forms. HEA addresses a diversity of observational and theoretical topics related to the nonthermal Universe - acceleration, propagation and radiation of relativistic particles in different astronomical environments. Another important topic of HEA is the study of properties of compact relativistic sources as well as cosmological large scale structures through X-radiation of very hot thermal plasmas formed around or inside these objects. Currently, the main research areas that belong to *observational* HEA are (i) X-Ray Astronomy, (ii) Gamma-Ray Astronomy, (iii) Origin of Cosmic Rays, and (iv) an activity related to the design and construction of large-volume underwater/ice detectors of cosmic high energy neutrinos. This article is devoted to description of the status of the field in the very high energy domain ($E \geq 100$ GeV) covered by measurements with ground-based instruments.

1. Introduction

HEA is a fast developing branch of modern astrophysics. Historically, in the context of the traditional classification of astronomical disciplines based on the wavelength bands, HEA combines the last (highest) energy domains of cosmic electromagnetic radiation - X-rays and gamma-rays. Therefore HEA is generally treated as a nominal astronomical discipline which deals with high energy phenomena related to thermal or nonthermal plasmas formed in different astronomical environments. X-ray and gamma-ray astronomies “share” many common physical processes and astronomical objects. In this regard, their affinity is quite natural and their joint belonging to HEA is well justified. At the same time, the research interests and the coverage of scientific topics of HEA are not limited by X-ray and gamma-ray domains. For example, observations of nonthermal synchrotron radio emission produced by relativistic electrons accelerated, e.g. in supernova remnants, radiogalaxies, clusters of galaxies, *etc*, have direct links to HEA, although the radiation itself belongs to the lowest energy domain of the electromagnetic spectrum. Another example: diffuse galactic and extragalactic infrared/optical radiation components have thermal origin and formally do not associate with HEA. On the other hand, they play an important role in production and absorption of high energy gamma-rays through the inverse Compton scattering and photon-photon pair production processes. This determines the deep link of HEA to infrared and optical astronomies. In this regard, the multi-wavelength approach in studies of astronomical objects and phenomena is one of the distinct features of HEA. Moreover, HEA is unique in the sense of its *multi-messenger* approach. Namely, it is the only astronomical discipline which deals not only with electromagnetic waves (*photons*) but also with charged relativistic particles (electrons, protons, nuclei) called *cosmic rays*, as well as with *neutrinos* and *gravitational waves*. Finally, the phenomena relevant to HEA generally proceed under extreme physical conditions in environments characterized with huge gravitational, magnetic and electric fields, relativistic bulk motions and shock waves, highly excited (turbulent) media, very high temperature (sub-relativistic) thermal plasmas, *etc*. Consequently, any coherent description and interpretation of phenomena related to HEA requires deep knowledge of many *disciplines* of physics like nuclear and particle physics, quantum and classical electrodynamics, special and general relativity, plasma physics, magnetohydrodynamics, *etc*. Thus, HEA can be characterized as a *multi-discipline* research area with *multi-wavelength* and *multi-messenger* approach to the studies of highly energetic processes in the Universe. The huge energy coverage by HEA, from 10^3 eV (typical energy of X-ray photons) to 10^{20} eV (the highest energy particles detected in cosmic rays), is performed using different techniques and methods. While observations of X-rays and relatively low energy cosmic rays and gamma-rays can be performed using space-based telescopes, the very high energy domain of gamma-rays, cosmic rays and neutrinos are effectively conducted with ground-based detectors.

Formally, the word ‘astronomy’ implies direct observations of extraterrestrial objects. While this definition is relevant to electromagnetic radiation and gravitational waves, as well as neutrinos – nearly massless, neutral and stable particles – in the case of cosmic rays the term ‘astronomy’ is used with a certain reservation. Because of deflections of electrically charged cosmic rays in the chaotic interstellar and intergalactic magnetic fields, the information about their original directions pointing to the sites of their production is lost. Instead, at the Earth we detect an (almost) isotropic flux of diffuse radiation contributed by huge number of galactic and extragalactic sources of different age and located at different distances. Moreover, these objects have different origin and are characterized by essentially different physical parameters – energy budget, time history, composition, acceleration mechanisms, *etc*. This makes extremely difficult the task of researchers trying to reveal the origin of cosmic ray sources based on the "smell" (chemical composition and energy spectra of particles) of the "soup" (isotropic flux of cosmic rays) cooked over cosmological timescales. At extremely high energies, $E \sim 10^{20}$ eV, the impact of galactic and extragalactic magnetic fields on the propagation of cosmic rays becomes less dramatic, which might lead to large and small scale anisotropies of cosmic ray fluxes. Thus, depending on the (highly unknown) intergalactic magnetic field, the highest energy domain of cosmic rays may offer us a new astronomical discipline – "cosmic-ray astronomy" (astronomy with charged particles) – with a potential to identify the extreme cosmic accelerators boosting the particles to energies $E \sim 10^{20}$ eV and beyond.

The main subject of study of HEA is the nonthermal Universe. The very fact of existence of cosmic rays, as well as detection of nonthermal electromagnetic radiation from radio to very high energies from objects representing almost all astronomical source populations implies that production of nonthermal relativistic particles in nature's machines - cosmic accelerators - takes place in wide diversity of forms and on different scales throughout the entire Universe: from galactic supernova remnants to clusters of galaxies, from solar mass black holes and pulsars to powerful radiogalaxies and quasars. In many cases we deal with almost ideally designed cosmic accelerators concerning both the high efficiency of transformation of the available thermal and bulk motion energy into nonthermal particles and the high rate of acceleration of individual particles.

The most common mechanism of particle acceleration most likely proceeds through collisions with "magnetic mirrors". If the magnetic clouds are moving randomly, the process is called *second order* Fermi acceleration. It has *stochastic* origin, because particles in such an environment can both gain and lose energy, depending on the collision with an approaching or receding cloud. Nevertheless, energy gain wins because on average the head-on collisions occur more often than the head-tail collisions. Generally, the acceleration becomes more effective in the case of non-random motion of scattering clouds. This is the so-called *first order* Fermi or diffusive shock acceleration which is realized most effectively in strong astrophysical shocks. A charged nonthermal particle ahead of the shock front can cross the shock (from upstream to downstream), and then be scattered by the magnetic field behind the shock allowing the reflected particle to cross the shock and appear again ahead of the shock, but with increased energy. Then particle, after being reflected by magnetic field upstream travels through the shock again, back to downstream. Since each shock crossing leads to a systematic gain of energy (proportional to the shock speed), the multiple repetition of the process allows an increase of the energy by many orders of magnitude.

The theory of the diffusive shock acceleration is comprehensively developed, in particular for fast expanding shells of young supernova remnants. Two principal requirements of the theory applied to effective particle accelerators are the high shock speed $v_{\rm sh}$ and diffusion of particles in the most effective regime called Bohm diffusion.

In this case the particle acceleration is inevitable and proceeds on timescales $\sim cR_{\rm L}/v_{\rm sh}^2$, where $R_{\rm L} = E/qB$ is the Larmor radius of a particle of charge q and energy E in random magnetic field of strength B, and c is the speed of light. The relativistic outflows, e.g. in the forms of pulsar winds or AGN jets, may operate as extreme accelerators with a rate close to the fundamental limit $\sim qBc$ determined by classical electrodynamics. Note that the maximum acceleration rate can be achieved also in strong electric fields, in particular in pulsar magnetospheres and in the proximity of rotating black holes.

2. Cosmic Rays

2.1 Brief History and Detection Methods

Cosmic rays are energetic nonthermal particles of extraterrestrial origin which continuously bombard the Earth's atmosphere from all directions. They consist of stable charged particles - protons (p), nuclei (A) and electrons (e), with a tiny fraction of neutral particles - photons (γ-rays), neutrinos (ν) and neutrons (n), as well as antiparticles - antiprotons ($\overline{p}$), antinuclei ($\overline{A}$), and positrons e^-. The energy of individual particles in cosmic rays span over 15 decades, from 10^6 eV to $\geq 10^{20}$ eV.

Cosmic rays have been discovered in 1912 thanks to the balloon experiments of Victor Hess aimed at measurements of ionization of the air at very high altitudes. These measurements revealed that the ionization rate increases with altitude, just contrary to the expectations based on the belief that the source of the ionization of the air was radioactive elements of local origin. The conclusion of Victor Hess was straightforward - the ionization is caused by radiation of unknown origin arriving "from above" which he called *cosmic rays*. Now we know that indeed the reason of the ionization is due to particles of extraterrestrial origin, although not directly but through the *"atmospheric"* cosmic rays, i.e. secondary particles produced at interactions of *"astrophysical"* cosmic rays with the Earth's atmosphere.

Remarkably, many elementary particles, in particular such fundamental ones as the positrons, μ- and π-mesons, have been discovered in cosmic rays. In this regard, cosmic rays played a great role in the development of *Particle Physics*, at least up to the 1960s when the man-made accelerators became the main tools for studies of properties of elementary particles. Moreover, the atmospheric cosmic rays continue to provide the only available channel of information about interactions of elementary particles at energies above 10^{17} eV.

All primary cosmic rays, except for neutrinos, are effectively absorbed in the Earth's atmosphere. Therefore an ideal detector of cosmic rays would be an instrument located above the Earth's atmosphere which measures the direction, energy, and the charge/mass of the primary particle. In this regard, the most detailed and unambiguous information about cosmic rays can be obtained with space- and/or balloon-based detectors. However, the flux of cosmic rays falls rapidly with energy (see Figure 1); around 10^{15} eV the integral flux does not exceed 1 particle per m^2 per $year$. This reduces the potential of direct studies of cosmic rays with space-based instruments. Fortunately, measurements of cosmic rays to energies 10^{15} eV is possible from ground, by detecting the secondary products, i.e. atmospheric cosmic rays, either directly or through their electromagnetic (Cherenkov or fluorescence) radiation. Presently several complementary methods are developed for study of very high energy cosmic rays covering a huge energy range from approximately 10^{13} eV to 10^{21} eV, and using different ground-based experimental techniques, in particular scintillator or water Cherenkov detectors for registration of electrons, gamma-rays and muons, calorimeters for detection of hadronic component of air showers (nucleons, pion, kaons), as well as optical devices for detection of the Cherenkov or fluorescence radiation of air showers. Different methods based on the study of properties of lateral and longitudinal distributions of air showers using the so-called “fast-timing”, “density-sampling“ and ”calorimetric“ techniques allow quite precise determination of the arrival direction (with an accuracy as good as 1 degree) and energy (with 20 to 40% accuracy) of primary cosmic rays on an event-by-event basis. Depending on configuration of ground-based detectors, the combination of these techniques is successfully used both at relatively low ($\leq 10^{15}$ eV) and highest ($\geq 10^{20}$ eV) energy domains. A major problem of the ground-based technique is related to the recognition of the type (protons, nucleus or a photon?) of arriving particles. This is partly related to the lack of experimental information about the interaction features (cross-sections) at energies which are not measured by particle accelerators but rather extrapolated to highest energies based on reasonable, but yet model-dependent assumptions. However, even in the case of perfect knowledge of interaction cross-sections, the identification of the type of a primary particle is quite limited because of intrinsic fluctuations characterizing these interactions.

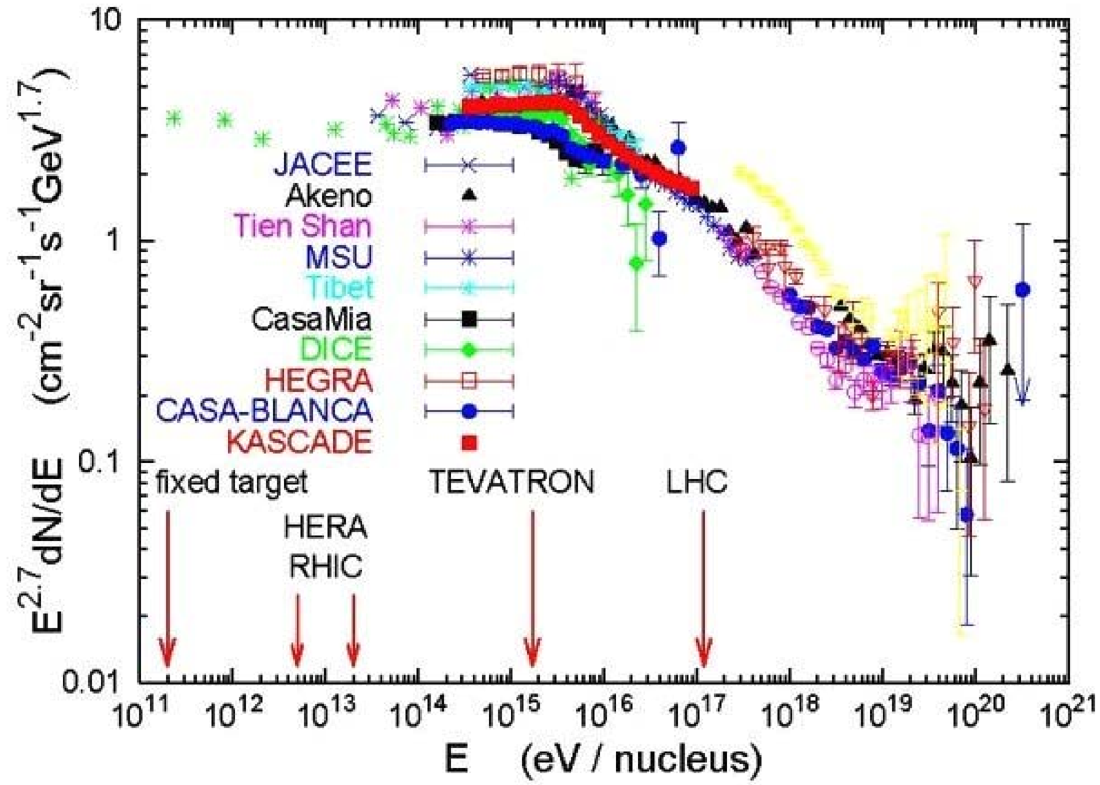

Figure 1. Summary of ground-based measurements of fluxes of cosmic rays. Energies achievable in human-made accelerators (TEVATRON, LHC) are indicated for reference. Source: T. Gaiser 2001, AIP Conf. Proc.

This introduces significant uncertainties in the measurements of the primary composition of cosmic rays. The combination of different detection techniques allows significant reduction, but unfortunately not full removal of these uncertainties. This approach is effectively used, in particular, in the KASKADE (Karlsruhe, Germany) and the Pierre Auger Observatory (Mendoza province, Argentina) arrays – currently the two most sensitive ground-based cosmic ray detectors operating in the PeV ($1\text{PeV} = 10^{15}\text{eV}$) and EeV ($1\text{EeV} = 10^{18}\text{eV}$) energy regions.

The second major concern in studies of cosmic rays is related to the statistics of detected events. This is especially important at extremely high energies when the flux of cosmic rays at 10^{20}eV is reduced to a level of 1 particle per km^2 per century (see Figure 1). To a certain extent, this problem is overcame by the giant array of water Cherenkov detectors of the Pierre Auger Observatory which covers 3000km^2 area. The additional four wide-angle optical telescopes of the atmospheric fluorescence light (produced at excitation of nitrogen molecules by air shower particles) give an important information about the location of the shower maximum and provide a ”calorimetric“ measurement of the energy of primary particle with a 20% accuracy. The adequate statistics coupled with good energy and angular resolutions, and with a reasonable capability of identification of showers induced by protons and heavy nuclei, should allow the Pierre Auger Observatory to perform a robust test of distinct spectral features theoretically predicted at energies between 10^{18}eV and 10^{20}eV, as well as to search for statistically-significant fluctuations of cosmic ray flux over the isotropically distributed background. If the intergalactic magnetic fields are very weak ($\sim 10^{-10}\,\mathrm{G}$ or less) the Pierre Auger array at highest energies may open new astronomical discipline – “cosmic-ray astronomy”.

2.2. Basic Facts

Cosmic rays consist mainly of “primary” i.e. directly accelerated particles - protons, nuclei and electrons. At the same time, a major fraction of some species of cosmic rays, in particular the nuclei of the light element group (Li, Be, B), as well as the antiparticles (positron and antiprotons) have a *secondary* origin. They are produced by *primary* cosmic rays interacting with the ambient interstellar and intergalactic media, and partly with thermal gas and low-frequency radiation fields *inside* the accelerators. Note that a fraction of the detected positron and antiprotons can be of primary, although *non-acceleration*, origin. Namely, antiparticles can be produced in certain “exotic” processes like evaporation of primordial black holes or annihilation of non-barionic Dark Matter.

The flux and the energy spectrum of cosmic rays is known quite well. The spectrum of hadronic component of cosmic rays extends to extremely high energies, $E \sim 10^{20}\,\mathrm{eV}$, while the energy spectrum of electrons is measured up to $\simeq 2\mathrm{TeV}$. The chemical composition of directly accelerated particles and the secondary-to-primary ratio of cosmic rays depend significantly on the energy band. In the best studied energy interval between 1 GeV and 1 TeV, the protons, nuclei and electrons contribute to the observed flux of cosmic rays in a ratio of approximately 100:10:1. At 1 TeV the content of electrons in cosmic rays does not exceed 10^{-3}.

The cosmic ray spectrum has two distinct features - the so-called *knee* around $10^{15}\,\mathrm{eV}$ and the *ankle* around $10^{18}\,\mathrm{eV}$ (see Figure 1). It is believed that all particles below the knee are of galactic origin, and that the extremely high energy cosmic rays above the ankle are produced/accelerated outside the Galactic disk - in powerful extragalactic objects like active galaxies or clusters of galaxies. The extragalactic origin of low energy cosmic rays below the knee is excluded because the arrival time of these particles from objects located well beyond our Galaxy would exceed, due to their slow diffusion in the intergalactic magnetic fields, the maximum available (Hubble) time - the age of the Universe $t_{\mathrm{H}} = 1/H_0 \sim 10^{10}\,\mathrm{yrs}$. On the other hand, the particles of energy $E \geq 10^{19}$ eV cannot be produced in the Galactic disk, otherwise significant anisotropies would then be expected, in contrast to observations. Some models associate these particles with the halo of our Galaxy, in particular within the so-called “top-down” scenarios, in which the observed particles are not result of classical acceleration (the “bottom-up” scenario), but may originate from decays of relic topological defects or super-massive particles clustered in the Galactic halo. These models have an unmistakable signature - they predict very high gamma-to-proton ratio, $\gamma/p \sim 1$. Thus the photon-to-proton ratio can be used as a powerful diagnostic tool for the “top-down” model of highest energy cosmic rays.

The smooth transition of the cosmic ray spectrum from the “sub-knee” to the “above the knee” region, which over 3 decades up to $10^{18}\,\mathrm{eV}$ is described by a steep differential power-law index $\alpha \sim 3$, favors a galactic origin for this part of the spectrum as well, although alternative (extragalactic) models are not excluded. Presently the region between the knee and ankle remains the most controversial energy interval as long as this concerns the simple “galactic or extragalactic?” question.

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Biographical Sketch

Felix Aharonian was born in 1952 in Armenia, obtained his Master degree and PhD in Moscow Engineering-Physics Institute. In 1987-1991 he was the head of the “Gamma-Ray Astronomy” group in Yerevan Physics Institute in Armenia. Since 1993 his scientific career is connected with Heidelberg (Germany). Prof. Aharonian is currently a group leader of High Energy Astrophysics Theory Group of MPIK Heidelberg, and a member of The Astronomy & Astrophysics Section of the Dublin Institute for Advanced Studies. He is the author of 400 scientific papers, currently one of the leaders of the HESS experiment.