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High-energy astroparticle physics

E. Lorenz*

ETH-Zurich and MPI for Physics, Munich, Germany

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Abstract

The current directions and main experiments in high-energy ($>10^6$ eV) astroparticle physics will be reviewed. Emphasis is put on the connection to the goals of this conference, e.g. to experiments which need good light sensors that can detect single photons.

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1. Introduction

High-energy astroparticle physics is a rapidly expanding field of fundamental physics research. It connects particle physics research with astronomy, astrophysics and cosmology. The sections of highest activity in high-energy astroparticle physics are:

(i) gamma-ray (γ) astronomy above $\approx$ few 10^{10} eV (very high-energy (VHE) γ-astronomy);
(ii) neutrino (ν) astronomy above a few MeV (HE ν-astronomy) and above a few 10^{10} eV (VHE ν-astronomy);
(iii) study of the chemical composition of cosmic rays (CR) above 10^{12}–10^{13} eV;
(iv) study of the highest energy ($>10^{19}$ eV) cosmic rays;
(v) dark matter searches;
(vi) nuclear astrophysics;
(vii) gravitational wave detection.

Obviously, the boundaries between the different sections are not sharply defined and are often even overlapping. Also, the definition of the specific energy ranges is somewhat arbitrary and changing. Here I will use 'high energy' astroparticle physics as a synonym for physics above 10^6 eV while using in connection with specific particles the abbreviation for high energy (HE) for the energy range from a few 10^6 to a few 10^9, very high energy (VHE) for the range from around $\approx 10^{10}$ to $\approx 10^{13}$ eV and extreme high energy (EE) for energies above 10^{18}, respectively 10^{19} eV. Not all of the leading experiments in the above-listed sections such as (iii), (v)–(vii) are in need of good photon detectors as key converters of photons into electrical signals, i.e. detectors that are sensitive to single photons and have the highest possible quantum efficiency, fast response and large detection areas or large number of pixels.

The experimental challenges in HE astroparticle physics are quite different to those in high-energy particle physics (HEP) at accelerators.

First of all, astroparticle physics is, like astronomy, an observational science. The laboratory is the universe and one has to live with what nature is 'willing' to reveal. Experiments are not always repeatable, e.g. an observation at a certain time is not in contradiction with a null observation at another time.

Secondly, one has no influence on the initial parameters such as the time, energy, particle nature and often the arrival direction of the cosmic particles. Good examples are gamma-ray bursts (GRB).

The fluxes of high-energy cosmic particles are, in general, very low; therefore one needs ultra large detectors. Some-

*Corresponding author. Max Planck Inst. Fuer Physik, Foehringer Ring 6, D80805 Muenchen, Germany. Tel.: +49 89 32354241; fax: +49 89 3226701.

E-mail address: e.lorenz@mac.com.

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times, absorbers of more than 10^9 tons are required. Obviously, this restricts absorbers to natural materials.

For the observation of high-energy particles one needs the calorimetric detection principle. The high-energy particles interact in some matter and normally produce a multitude of secondary particles, which, in turn, interact and again produce particles in a chain-like, often called avalanche-like multiplication process, thus generating extended showers. Most of the shower energy is eventually lost by ionisation, but a very small fraction of energy is transferred to Cherenkov light, or, in appropriate materials, to scintillation light. Ionisation can, in principle, be observed in media where charge carriers live long enough to be collected (no practical case in natural materials known), while the detection of photons requires transparent materials. The fraction of energy converted into Cherenkov light or scintillation light is in the range of 10^{-2}–10^{-5}. When talking about large volume detectors it is obvious that photons must be observable over large distances. This transmission requirement restricts calorimetric materials to the atmosphere, water or ice. The atmosphere, as the outer shell of the earth, is normally the absorber for high-energy γ's or CRs, while higher density materials, water or ice, are obviously the better suited materials for high-energy cosmic vs. In the atmosphere one can also detect, besides Cherenkov photons, very faint scintillation light, e.g. photons emitted by excited N_2 molecules.

Many HEP detectors rely on ionisation measurements for key components. As mentioned above, ionisation measurements are normally impossible in natural materials and therefore for astroparticle detection because of (a) conductivity problems, and (b) very limited lifetime of free charge carriers. Nevertheless it is often not possible to observe the full showers. Only a restricted number of shower particles escaping the boundaries of the calorimeter can be measured with detectors developed for HEP (scintillation counters, tracking detectors, etc.), but excessive costs necessary to cover very large areas are mostly forbidding their use. It should be mentioned further that there are some ongoing efforts to use semi-natural materials, such as ultra-pure liquid Argon or scintillating organic liquids (distilled from crude oil), which are available in sufficiently large volumes at low enough prices for special astroparticle physics detectors (e.g. neutrino detectors).

Another important difference in detecting cosmic particles compared to those in HEP experiments is caused by the earth rotation. Detectors for astroparticles need a large angular acceptance, and the absorber volume should either be viewed from all directions or must be constantly reoriented for the observation of specific sources in order to counteract the earth rotation.

Another aspect in astroparticle physics is the large distance at which cosmic events occur. In turn and as a consequence of the speed of light, one can look only 'backwards' in time, i.e. one can scan the development of the universe from cosmic events at different red shift. Also, another consequence of the large distances is that one can never go to places where cosmic events/reactions are taking place. Information about the relativistic (astronomers call it the non-thermal) universe is transmitted by 'messenger' particles. In the past only electromagnetic waves, respectively electromagnetic particles at higher energies were used as messenger particles. Only now one will explore also particles with mass as messengers. These particles must be long-living and relativistic in order to transmit information over cosmic distances.

Possible messenger particles are, in the order of their rest mass:

- gamma rays (γ) without mass;
- neutrinos; ν_e, ν_μ, ν_τ and their antiparticles;
- electrons, positrons;
- relativistic and ultra-relativistic charged baryons and heavy ions (p, pbar, He…Fe…), e.g. the classical cosmic rays;
- neutral baryons (neutron), if ultra-relativistic;
- possibly exotic particles (Wimps, Neutralinos …???), not yet discovered.

In principle, also low-energy electromagnetic waves (radio waves, infrared (IR) photons, visible photons, and X-rays) can transmit information about high-energy cosmic processes, but it is not always clear if they are produced in low- or high-energy reactions.

Nearly all leading high-energy astroparticle physics detectors are based on the observation of secondary photons in the spectral range between, say, 300 and 1000 nm. There are efforts to explore also acoustical or radio signals emitted by showers. While the observation of acoustical signals is not yet successful, the first successful detection of radio signals has been reported (radio).

Another general problem in high-energy astroparticle physics is the fact that the flux of particles has a strong dependence on the energy. Except for a few cases, fluxes drop according to power laws with coefficients below -2; thus detectors normally can span only 2–3 orders of magnitude in energy.

In the following I will discuss in some detail the physics issues and the leading techniques, which rely on photon detectors for the sub-areas of high-energy astroparticle physics.

2. VHE γ-astronomy

VHE γ-astronomy is currently one of the most active and successful fields of astroparticle physics. Only neutral particles can point back to the location of their origin. Charged cosmic rays, by many orders of magnitude more abundant than γ's, are deflected by the weak galactic, respectively ultra-weak extragalactic magnetic fields such that at least up to an energy of 10^{19} eV any information on the initial direction is lost. Other long-lived neutral