Astroparticle Physics 60 (2015) 54–71

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Review

Atmospheric effects in astroparticle physics experiments and the challenge of ever greater precision in measurements

Karim Louedec *

Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Grenoble-Alpes, CNRS/IN2P3, 38026 Grenoble cedex, France

ARTICLE INFO

Article history:
Received 12 March 2014
Received in revised form 9 May 2014
Accepted 18 May 2014
Available online 2 June 2014

Keywords:
Cosmic ray
Gamma ray
Extensive air shower
Astronomical survey
Atmospheric effects
Systematic errors

ABSTRACT

Astroparticle physics and cosmology allow us to scan the universe through multiple messengers. It is the combination of these probes that improves our understanding of the universe, both in its composition and its dynamics. Unlike other areas in science, research in astroparticle physics has a real originality in detection techniques, in infrastructure locations, and in the observed physical phenomenon that is not created directly by humans. It is these features that make the minimisation of statistical and systematic errors a perpetual challenge. In all these projects, the environment is turned into a detector medium or a target. The atmosphere is probably the environment component the most common in astroparticle physics and requires a continuous monitoring of its properties to minimise as much as possible the systematic uncertainties associated. This paper introduces the different atmospheric effects to take into account in astroparticle physics measurements and provides a non-exhaustive list of techniques and instruments to monitor the different elements composing the atmosphere. A discussion on the close link between astroparticle physics and Earth sciences ends this paper.

Contents

* Tel.: +33 670982771.
E-mail address: karim.louedec@gmail.com

http://dx.doi.org/10.1016/j.astropartphys.2014.05.011
0927-6505/

1. Introduction

Recent years have seen the development of major infrastructure around the Earth in order to increase considerably the performances of experiments in astroparticle physics and cosmology. Unlike other fields in science where measurements are made on a physical phenomenon created in laboratory, research in astroparticle physics has originality in detection techniques and infrastructure locations. Experiments are operated over large desert areas as the Cherenkov Telescope Array (CTA) [1], the Pierre Auger Observatory [2] or very soon the LSST telescope [3], in oceans or ice with ANTARES [4] and IceCube [5], respectively, or even in space with projects as the AMS-02 experiment [6] or soon the JEM-EUSO telescope [7]. In all these projects, and more than any other experience in subatomic physics, minimising statistical and systematic errors is a challenge because the physical phenomenon observed is not produced by man himself: scientists are just observers. Thus, scientists build ever larger detectors to go further in the knowledge. However, owning a large detector is not a necessary and sufficient requirement to push the limits of our knowledge: the systematic error still lurks and demands from scientists an excellent understanding of their detector. The temptation to increase the duty cycle of the detector in order to reduce still more the statistical error should not obscure the need to control the associated increase in systematic error. Therefore there is a point where these two errors become inseparable and where the optimisation of detector performance can be tricky.

In all these projects, the environment is turned into a detector medium or a target. The atmosphere is probably the environment component the most common in astroparticle physics, usually used as a giant calorimeter in cosmic ray experiments or as an irreducible detection volume in the case of ground-based astrophysics surveys. To minimise as much as possible the systematic errors associated to the atmosphere evolution in time, its properties have to be continuously monitored. It is to this end that extensive atmospheric monitoring programs have been developed by different collaborations in astroparticle physics. Section 2 will list briefly the different experiments where the atmosphere is a part of the detector. In all cases, at some point, photons propagate into the atmosphere and they are affected by the medium before being detected. Section 3 will describe the different physics phenomena affecting photon propagation in the atmosphere in order to remove their effect in measurements. Then, in Section 4, the main instruments used to monitor the atmospheric properties or the atmosphere components will be presented. Astroparticle physics experiments, equipped with such infrastructures and located in unusual places, provide an opportunity to develop interdisciplinary activities, especially in atmospheric science: this will be the purpose of the conclusion.

2. Astroparticle physics experiments and the atmosphere as part of the detector

Astroparticle physics is a research field at the intersection of particle physics, astrophysics and cosmology. The term "astro" refers to the messengers from the universe and arriving on Earth. This area has the particularity to express the relationship increasingly close between the infinitely large (such as astrophysical objects in the universe) and the infinitely small (such as the study of the structure of matter). Origins of the field bring us back one century ago with the discovery in 1912 by Victor Hess (Nobel Prize in Physics in 1936, [8]) of cosmic rays, opening at that time a new window for particle physics. The main messenger used to probe the universe is the photon. Other messengers from universe can also be detected as cosmic rays or neutrinos: in some cases, photons produced by the interaction of these primaries with the atmosphere are recorded to evaluate indirectly the messenger properties. Whether it is direct or indirect messenger detection, photon propagation in the atmosphere is of principal interest in astroparticle physics. This section presents briefly the actual and future experiments using the atmosphere as part of their detector.

2.1. Very-high energy gamma rays and ultra-high energy cosmic rays: a detection via extensive air showers

The flux of ultra-high energy (UHE, $E \geqslant 10^{18}$ eV) cosmic rays and very-high energy (VHE, $E \geqslant 10^{11}$ eV) gamma rays is very low on Earth. To enlarge the detection area of these messengers from the universe, telescopes are directly installed on the ground and the Earth's atmosphere acts as the calorimeter of the detector. When cosmic rays or gamma rays enter the atmosphere, they induce extensive air showers composed of secondary particles. Among these particles, photons are emitted: their properties provide a direct way to probe the characteristics of the primaries. In the following, we describe the main experiments and their techniques employed to detect ultra-high energy cosmic rays or very-high energy gamma rays.

2.1.1. Ultra-high energy cosmic rays and fluorescence telescopes

The cosmic ray energy spectrum observed on Earth extends from below 1 GeV to beyond 10^{20} eV, more than eleven orders of magnitude. This energy spectrum drops rapidly with energy. For the so-called ultra-high energy cosmic rays corresponding to the right-hand limit of the spectrum, fundamental properties such as their origin, their chemical composition and their acceleration mechanisms are still a mystery (see [9–12] for more details). At energies greater than 10^{18} eV, their flux is lower than one particle per century and per square kilometre. This makes these events only detectable indirectly through extensive air showers. Charged particles composing the air shower excite atmospheric nitrogen molecules, and these molecules then emit fluorescence light isotropically in the 300–420 nm range [13,14]. Detection of ultra-high energy cosmic rays using nitrogen fluorescence emission is a well established technique [15], used in the past in the Fly's Eye [16] and HiRes [17] experiments, currently at the Pierre Auger Observatory [18,19] and Telescope Array [20,21], and in the future by the JEM-EUSO telescope [22]. The energy and the geometry of extensive air showers can be calculated from information on the amount and the arrival time of recorded light signals at the fluorescence detectors (FD). After more than thirty years of development having led to a better understanding of this technique, the current "hybrid" observatories set their energy scale using fluorescence measurements [23,24]. Also, the air-fluorescence technique allows the determination of the depth of maximum of the extensive air shower $X_{\max}$ in a direct way, providing an estimation of the UHECR composition [25,26]. During the development of an extensive air