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The future of gamma-ray astronomy

L'avenir de l'astronomie gamma

Jürgen Knödlseder

IRAP, 9, avenue du Colonel-Roche, 31028 Toulouse cedex 4, France

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ABSTRACT

The field of gamma-ray astronomy has experienced impressive progress over the last decade. Thanks to the advent of a new generation of imaging air Cherenkov telescopes (H.E.S.S., MAGIC, VERITAS) and thanks to the launch of the Fermi-LAT satellite, several thousand gamma-ray sources are known today, revealing an unexpected ubiquity of particle acceleration processes in the Universe. Major scientific challenges are still ahead, such as the identification of the nature of Dark Matter, the discovery and understanding of the sources of cosmic rays, or the comprehension of the particle acceleration processes that are at work in the various objects. This paper presents some of the instruments and mission concepts that will address these challenges over the next decades.

RÉSUMÉ

Le domaine de l'astronomie gamma a connu des progrès impressionnants au cours de la dernière décennie. Grâce à l'avènement d'une nouvelle génération de télescopes Tcherenkov (H.E.S.S., MAGIC, VERITAS) et grâce au lancement du satellite Fermi-LAT, plusieurs milliers de sources de rayons gamma sont connues aujourd'hui, révélant une ubiquité inattendue des processus d'accélération de particules dans l'Univers. Toutefois, des questions scientifiques majeures restent en suspens, telles que l'identification de la nature de la matière sombre, la découverte et la compréhension des sources de rayons cosmiques, ou la compréhension des processus d'accélération de particules qui sont à l'œuvre dans les différents astres. Cet article présente quelques-uns des instruments et des concepts de mission qui vont relever ces défis au cours des prochaines décennies.

1. Introduction

Gamma-ray astronomy covers observations of photons with energies above a few 100 keV, with current instruments reaching up to about 100 TeV. Formally, there is no upper energy limit to gamma rays, yet pair-production on background

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E-mail address: jknodlseder@irap.omp.eu.

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photons will effectively set a horizon to the explorable Universe. For photon energies above ~ 1 PeV this horizon is of the size of our Galaxy [1]. Gamma rays interact with the Earth's atmosphere, hence their direct detection from the terrestrial surface is not possible. Gamma rays are thus either observed directly from space using detectors aboard satellites or stratospheric balloons, or indirectly from the ground by detecting the electromagnetic cascades that are generated by gamma-ray induced pair production in the Earth atmosphere. Gamma-ray instruments comprise coded-mask telescopes for the low-energy range (e.g., INTEGRAL [2]), Compton telescopes for the medium-energy range (e.g., COMPTEL [3]), pair creation telescopes for the high-energy range (e.g., Fermi [4], AGILE [5]), Cherenkov telescopes for the very-high-energy range (e.g., H.E.S.S. [6], MAGIC [7], VERITAS [8], MILAGRO [9]), and charged particle detectors or integrating non-imaging Cherenkov detectors for the ultra-high-energy range (e.g., AIROBICC [10]). For a review of these detection techniques, see [11,12] and references therein.

Detection of the first celestial gamma-ray sources has been achieved in the late 1950s in the low-energy domain [13], in the early 1960s in the medium-energy [14] and high-energy domains [15], and in the late 1980s in the very-high-energy domain [16]. Since then, improvements in instrumental performance have differed between domains, with the most spectacular results achieved so far in the high-energy range that today has an inventory of over 3000 steady sources of gamma rays [17]. Progress has also been impressive in the very-high-energy domain, with well over 100 confirmed sources. The low- and medium-energy gamma-ray domains have so far not experienced a comparable development, the number of few 100 keV and MeV steady sources being of the order of several tens. No gamma-ray source has so far been detected in the ultra-high-energy range, in the domain above ~ 100 TeV.

The common feature of all gamma-ray sources is the non-thermal nature of the underlying emission processes. As opposed to thermal radiation that originates from the random movements of particles in matter with temperature above absolute zero, non-thermal radiation may have a variety of origins: the decay or de-excitation of atomic nuclei, the decay of particles or their annihilation with antiparticles, and the interaction of non-thermal particle populations with photons and matter. These processes may either lead to emission of mono-energetic photons or to emission of a broad-band continuum spectrum of photons, covering eventually the full electromagnetic spectrum from the radio band to the gamma-ray domain. Within that spectrum, the gamma-ray band is unique since it is free from concurrent thermal radiation that dilutes the non-thermal radiation at lower energies. In other words, gamma rays provide the clearest window onto the non-thermal physics in our Universe, and for decay, de-excitation and annihilation processes they often provide the only view.

Gamma-ray astronomy is thus the astronomy of the non-thermal Universe. Since its advent about 50 years ago it has revealed an unexpected variety of objects that release a significant, sometimes even dominant fraction of their energy through non-thermal processes, including amongst others neutron stars, black holes, stellar explosions and their remnants. The exploratory phase is certainly concluded for the high-energy and very-high-energy range, which now will turn into mature fields of contemporary astronomy that will deepen our understanding of the underlying physics. For the low- and medium-energy domains, exploration has only started, and an important step needs to be taken to bring the non-thermal phenomenologies into light. The ultra-high-energy domain is still terra incognita, but instruments exist that could soon reveal first sources, provided that some exist within the accessible Universe [18].

This review aims to depict the evolution of the field of gamma-ray astronomy in the foreseeable future, based on recent achievements, open science questions, and ongoing instrument developments. The review will concentrate on the high-energy and very-high-energy range, which currently are the most vital domains. Specifically, the review will discuss future instruments (or instrument concepts) that are able to detect gamma rays in the 100 MeV to 100 TeV energy range, although some of the discussed instruments will explore the sky beyond this band.

2. Scientific challenges

2.1. Dark matter

The nature of dark matter is certainly one of the most fundamental problems of modern science. Evidenced as apparently missing mass at scales of galaxies, galaxy clusters, but also the entire Universe, it inevitably points us to a flaw in our understanding of nature. Proposed solutions to this mystery comprise modifications to the fundamental laws of physics, as well as the introduction of new, weakly interacting particles that so far escaped detection. The most popular candidate for the latter are weakly interacting massive particles (WIMP) that arise in extensions to the standard model of particle physics [19]. Direct searches for WIMPs are currently performed in underground laboratories and using the Large Hadron Collider, while indirect searches rely on the detection of annihilation and decay products that may lead to observable signatures in the gamma-ray domain [20]. Less popular but not less interesting candidates comprise the axion that may leave an imprint on gamma-ray spectra of distant sources [21].

Annihilation or decay of dark matter particles is expected to lead to gamma-ray continuum and line emission in the GeV–TeV domain [19]. The most stringent limits today come from the Fermi-LAT telescope which has ruled out the existence of WIMPs with masses <30 GeV [22]. These measurements are corroborated by recent upper limits obtained with the Planck satellite on the maximum WIMP annihilation cross section in the early Universe [23]. At higher energies, existing upper limits are less constraining, and current measurements cannot exclude the existence of WIMPs with masses above a few 10 GeV. Next generation very-high-energy telescopes will be decisive to probe WIMPs with higher masses. Any detection would mark a historical scientific breakthrough, while an upper limit would put scientific constraints that will question the

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