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Introduction to high-energy gamma-ray astronomy

Introduction à l'astronomie gamma de haute énergie

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ABSTRACT

The present issue is the first of a two-volume review devoted to gamma-ray astronomy above 100 MeV, which has witnessed considerable progress over the last 20 years. The motivations for research in this area are explained, the follow-on articles of these two issues are introduced and a brief history of the field is given.

RÉSUMÉ

Le présent numéro est le premier de deux volumes consacrés à l'astronomie gamma de haute énergie au-dessus de 100 MeV, qui a considérablement progressé au cours des vingt dernières années. Cet article expose les motivations à la base de cette recherche, présente les articles de ces deux fascicules et fournit une brève introduction historique au domaine.

1. Motivations

1.1. The quest for cosmic accelerators

Present-day astronomy is still primarily concerned with the study of sources of photons and covers the electromagnetic spectrum from radio waves up to very-high-energy gamma rays. The gamma-ray domain corresponds to photons with energies greater than 0.5 MeV, and the most energetic cosmic photons presently detected reach about 100 TeV. The present review is focused on the high-energy part of the electromagnetic spectrum, above 100 MeV, which is related to the origin of cosmic rays. Low-energy γ-ray astronomy, which is based on specific techniques (collimators, coded masks, Compton telescopes), and essentially addresses different questions of astrophysics (e.g., nuclear γ-ray emission lines), is not covered in the present review, except for gamma-ray bursts, some of which have a high-energy component.

Cosmic rays, discovered in 1912 by Victor Hess [1], are, for the most part, high-energy protons and nuclei whose spectrum extends over eleven orders of magnitude [2], from a few times 10^9 eV up to about 10^{20} eV. Their energy distribution is well described by a power law ($\propto E^{-\gamma_{cr}}$), whose exponent or "spectral index" γ_{cr} is equal to 2.7 up to about 4×10^{15} eV, then to 3 up to 4×10^{18} eV, where γ_{cr} is again slightly lower. The first spectral break in the 10^{15} eV (or PeV) region is

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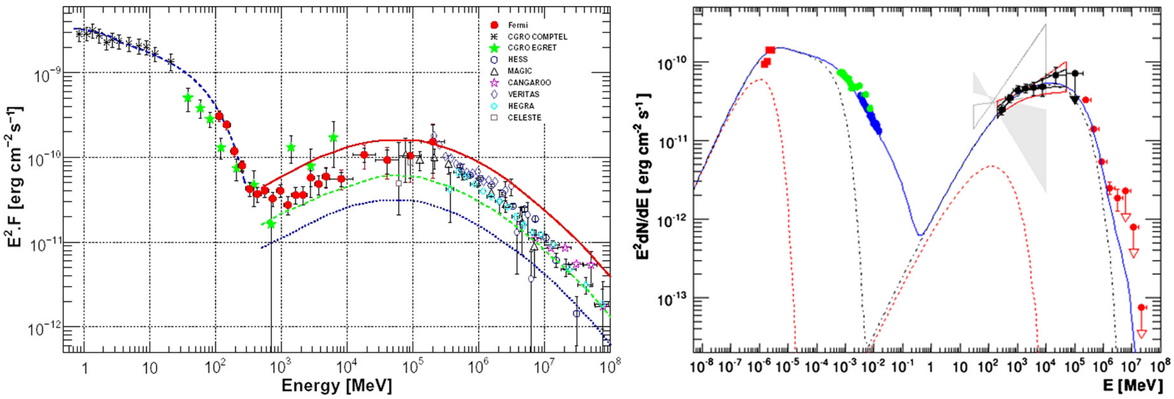

Fig. 1. (Color online.) Spectral energy distributions $E^2 \mathrm{d}^3 N_\gamma/(\mathrm{d}E\,\mathrm{d}t\,\mathrm{d}S)$ of two different non-thermal sources emitting photons from radio waves to very-high-energy gamma rays: on the left, a galactic source, the Crab nebula [4]; on the right, an extra-galactic source, the active galactic nucleus PKS 2155-304 [5]. Note that 1 erg·cm^{-2}·s^{-1} $= 10^{-3}$ W·m^{-2}.

called the "knee". Cosmic rays with energies below the knee are essentially originating from our Galaxy. Above the knee, their origin (galactic vs. extra-galactic) remains controversial. Therefore, identifying cosmic accelerators in which particles can reach at least the PeV energy range (or "pevatrons") is an important challenge today. About 2% of the cosmic rays are electrons and positrons with a much steeper energy spectrum [2]. Unfortunately, all these particles are charged, and thus continuously deviated by turbulent magnetic fields embedded in interstellar and intergalactic plasmas, so that their direction when they reach the Earth is almost completely uncorrelated with that of their source, except perhaps at extreme energies where fluxes are extremely low [3]. Thus, the quest for cosmic accelerators as well as for acceleration mechanisms mostly relies on photons that propagate along a straight line. The presence of high-energy electrons and positrons can also be indirectly detected by their synchrotron radiation from radio waves to X rays, but the most energetic photons produced by cosmic-ray interactions with radiation fields or matter provide a complementary and more direct insight into both the accelerators and the targets (e.g., molecular clouds).

1.2. Gamma-ray production mechanisms

Gamma rays can be produced by two different processes.

- High-energy electrons and positrons interact with radiation fields. In magnetic fields, they produce synchrotron photons whose energies can at most reach the domain of low-energy gamma rays. But they can also interact with ambient low-energy photons (from stellar or synchrotron origin) and boost them to very high energies. This last mechanism is just the Compton effect, albeit observed from a Lorentz frame quite different from that of the electron at rest, used in nuclear physics; it is therefore referred to as the "Inverse Compton effect". The two preceding processes, induced by electrons and positrons, are said to be "leptonic".
- In denser regions of the interstellar medium, high-energy protons and nuclei interact with matter through nuclear interactions, often producing neutral mesons, mainly π^0's, which decay into γ rays and whose mass m_0 is 135 MeV/c^2. These processes involving nucleons and mesons are said to be "hadronic". The kinematics of the decay $\pi^0 \to \gamma + \gamma$ shows that, whatever the spectrum of the incident particle, the γ-ray energy spectrum reaches a maximum at $m_0 c^2/2 \approx 68$ MeV, just above the threshold of the production reaction, then decreases smoothly, according to a power law whose spectral index is close to that of the incident particle.[1] This is the main reason why this review is limited to γ rays above 100 MeV.

Many of the sources detected above 100 MeV also emit non-thermal photons over the whole electromagnetic spectrum. Since γ-ray differential fluxes $\mathrm{d}^3 N_\gamma/(\mathrm{d}E\,\mathrm{d}t\,\mathrm{d}S)$ decrease very rapidly with energy, it is convenient to consider the "spectral energy distribution" (or SED), i.e. the distribution of the quantity[2]:

$$E^2 \frac{\mathrm{d}^3 N_\gamma}{\mathrm{d}E\,\mathrm{d}t\,\mathrm{d}S} = E \frac{\mathrm{d}^3 N_\gamma}{\mathrm{d}\ln E\,\mathrm{d}t\,\mathrm{d}S} \qquad (1)$$

which represents the power received by unit area by unit of $\ln E$. The spectral energy distribution provides a useful representation of the non-thermal emission of an astrophysical object from radio waves to the highest energies. Fig. 1 shows

[1] Note that γ rays can also undergo hadronic interactions, e.g., $\gamma + \mathrm{p} \to \pi^0 + \mathrm{p}$.

[2] In the notation of radio-astronomy, the SED takes the form $\nu F(\nu)$, in which ν is the photon frequency and $F(\nu)$ is the power received per unit area and frequency.