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Gamma-ray astronomy / Astronomie des rayons gamma – Volume 2

Gamma rays as probes of the Universe

Les rayons gamma, sondes de l'Univers

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A B S T R A C T

The propagation of γ rays over very large distances provides new insights on the intergalactic medium and on fundamental physics. On their path to the Earth, γ rays can annihilate with diffuse infrared or optical photons of the intergalactic medium, producing e^+e^- pairs. The density of these photons is poorly determined by direct measurements due to significant galactic foregrounds. Studying the absorption of γ rays from extragalactic sources at different distances allows the density of low-energy diffuse photons to be measured. Gamma-ray propagation may also be affected by new phenomena predicted by extensions of the Standard Model of particle physics. Lorentz Invariance is violated in some models of Quantum Gravity, leading to an energy-dependent speed of light in vacuum. From differential time-of-flight measurements of the most distant γ-ray bursts and of flaring active galactic nuclei, lower bounds have been set on the energy scale of Quantum Gravity. Another effect that may alter γ-ray propagation is predicted by some models of String Theory, namely the mixing of the γ ray with a light fundamental boson called an "axion-like particle", which does not interact with low-energy photons. Such a mixing would make the Universe more transparent to γ rays than what would otherwise be, in a sense it decreases the amount of modification to the spectrum that comes from the extragalactic background light. The present status of the search for all these phenomena in γ-ray astronomy is reviewed.

R É S U M É

La propagation des photons γ sur de très grandes distances nous permet de sonder le milieu intergalactique et fournit des tests de physique fondamentale. Au cours de leur chemin vers la Terre, ceux-ci peuvent s'annihiler avec les photons infrarouges et optiques du milieu intergalactique, produisant ainsi des paires e^+e^-. L'absorption des photons γ émis par des sources extragalactiques à différentes distances permet de mesurer ce fond diffus, par ailleurs très mal connu par des mesures directes en raison des importants rayonnements d'avant-plan dus à la Galaxie. La propagation des photons γ peut aussi être affectée par de nouveaux phénomènes prédits par des extensions du modèle standard de la physique des particules. L'invariance de Lorentz est violée dans certains modèles de gravité

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quantique où la vitesse de la lumière dans le vide varie avec l'énergie du photon γ. Les mesures différentielles de temps de vol sur les sursauts γ et sur les éruptions de noyaux actifs de galaxie ont permis d'obtenir des bornes inférieures sur l'échelle d'énergie de la gravité quantique. Un autre effet pouvant affecter la propagation des photons γ est prédit par des modèles de la théorie des cordes. Il s'agit du mélange quantique entre le photon et une particule légère de type « axion », qui n'interagit pas avec les photons infrarouge et optiques. En diminuant dans les spectres l'empreinte de l'absorption par le fond diffus, ce mélange rendrait l'Univers plus transparent que prévu aux photons γ. L'article présente l'état actuel des recherches sur l'ensemble de ces phénomènes en astronomie γ

1. Introduction

Gamma rays are powerful and important messengers from cosmic accelerators. In addition, the propagation of γ rays over very large distances offers a number of opportunities to investigate the extragalactic medium and to discover or constrain new phenomena predicted by some extensions of the Standard Model of particle physics. In this review, we focus on the following aspects:

– diffuse photons in the intergalactic medium with which γ rays may annihilate producing e^+e^- pairs, including the well-known cosmic microwave background (CMB), which affects only the propagation of ultra-high energy γ rays (PeV range), and the diffuse background of optical and infrared photons – the extragalactic background light (EBL) – which is poorly known from direct measurements, due to important galactic foregrounds;
– the effects of a possible Lorentz-invariance violation (LIV), as predicted by models of Quantum Gravity (QG);
– the mixing of photons with light fundamental bosons ($m\,c^2 = \mathcal{O}(\text{neV})$) such as axion-like particles (ALPs), as predicted by models of String Theory, an effect sensitive to the magnetic field strength in extragalactic space.

Gamma rays propagating over very large distances are particularly good probes of the last two effects. Lorentz-invariance violation, leading to an energy-dependent dispersion of photons, would affect propagating photons with a large product of energy E and distance d. Gamma-ray sources at cosmological distances reach values of $E \cdot d \approx$ TeV Gpc, challenging high-precision measurements in the laboratory. The mixing of photons with ALPs depends on the product of the magnetic field strength B and the propagation distance as shown in section 4.2. The largest values of the product $B \cdot d$ provide the highest sensitivity to this effect. Even with extremely low intergalactic magnetic fields ($\sim 10^{-13}$ T) this product can reach $B \cdot d \approx 3 \times 10^{11}$ T m with very distant sources, a value which is currently not achievable in laboratory environments.

While the production of γ rays from self-annihilating massive dark matter probes fundamental physics at the mass scale of supersymmetric particles, i.e. close to the electro-weak symmetry-breaking scale [1], searches for axion-like particles are sensitive to new physics at intermediate energies of 10^{11} GeV and processes leading to Lorentz invariance violation are expected to be related to the Planck scale ($E_{\text{Pl}} = \sqrt{\hbar c^5/G} \approx 10^{19}$ GeV). Therefore, the propagation of γ rays from distant sources brings new insights on presently unexplored energy domains of particle physics.

In section 2, those γ-ray sources most commonly used in the search for LIV and for photon–ALP mixing are reviewed. Section 3 describes γ-ray propagation in the presence of extragalactic background light and of magnetic fields. The phenomenology of LIV and the relevant constraints from γ-ray observations are presented in section 4.1, whereas the current understanding of photon–ALP mixing (PAM) and corresponding constraints are discussed in section 4.2.

2. Sources of high-energy photons used in the study of propagation effects

High-energy (HE, $E > 100$ MeV) and very-high-energy (VHE, $E > 100$ GeV) photons are produced in the framework of the most violent events occurring in the Universe such as stellar explosions or accretion on supermassive black holes. The relevant acceleration and radiation processes in the three types of sources considered here are briefly described below:

(i) **Gamma-ray bursts (GRBs)**: bright and short flashes of γ-rays are produced following the collapse of a massive star or the coalescence of compact objects in a binary system. This catastrophic event results in a strongly collimated relativistic plasma outflow in which multiple shells travel at different velocities, producing internal shocks. Charged particles accelerated in these shocks further radiate HE photons [2]. Due to the relativistic bulk flow of the emitting plasma, photons are strongly beamed in the reference frame of the observer who also experiences an apparent rapid variability. The prompt emission of photons lasting from less than a second up to a few minutes is of interest for the studies of fundamental physics. It is characterized by high fluxes in the MeV–GeV energy range, with a variability in time of the order of tens of milliseconds. The prompt emission is followed by counterparts at longer wavelengths covering longer periods (up to months or years). So far, GRB emission has not been detected at VHE energies.

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