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Gamma Ray Astronomy: Implications for Fundamental Physics

J. Rico[*]
Institució Catalana de Recerca i Estudis Avançats (ICREA)
&
Institut de Física d'Altes Energies (IFAE), Bellaterra (Barcelona), 08193, Spain
E-mail: `jrico@ifae.es`

Gamma Ray Astronomy studies cosmic accelerators through their electromagnetic radiation in the energy range between ∼100 MeV and ∼100 TeV. The present most sensitive observations in this energy band are performed, from space, by the Large Area Telescope onboard the Fermi satellite and, from Earth, by the Imaging Air Cherenkov Telescopes MAGIC, H.E.S.S. and VERITAS. These instruments have revolutionized the field of Gamma Ray Astronomy, discovering different populations of gamma ray emitters and studying in detail the non-thermal astrophysical processes producing this high-energy radiation. The scientific objectives of these observatories include also questions of fundamental physics. With gamma ray instruments we study the origin of Galactic cosmic rays, testing the hypothesis of whether they are mainly produced in supernova explosions. Also, we obtain the most sensitive measurement of the cosmic electron/positron spectrum between 20 GeV and 5 TeV. By observing the gamma ray emission from sources at cosmological distances, we learn about the intensity and evolution of the extragalactic background light, and perform tests of Lorentz Invariance. Moreover, we can search for dark matter by looking for gamma ray signals produced by its annihilation or decay in over-density sites. In this paper, we review the most recent results produced with the current generation of gamma ray instruments in these fields of research.

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[*] Speaker.

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1. INTRODUCTION

Gamma rays are the most energetic form of electromagnetic radiation. They are produced in the non-thermal processes happening in the most violent cosmic environments. The main production mechanisms are radiation and interaction of accelerated charged particles, either electrons or protons. Therefore, by studying gamma rays we learn about cosmic particle accelerators (for a recent review see, e.g., Ref. [1]). In addition, Gamma Ray Astronomy can shed light on fundamental questions of Physics: the origin of cosmic rays (CRs), the spectrum of cosmic electron-positrons, the extragalactic background light (EBL), Lorentz Invariance or dark matter (DM). In this paper we present the most recent results produced by the current gamma ray observatories on these questions. In Section 2 we briefly describe the present generation of gamma ray instruments, and then address each of the above-mentioned topics from Sections 3 to 6 (DM topic is discussed elsewhere in these proceedings [2, 3]). Finally, we summarize and conclude in Section 7.

2. GAMMA RAY INSTRUMENTS

Gamma rays are currently most sensitively detected, from space, by the Large Area Telescope (LAT) onboard the Fermi satellite and, from Earth, by the Imaging Air Cherenkov Telescopes (IACTs) MAGIC, H.E.S.S. and VERITAS.

Fermi-LAT is composed of an anti-coincidence shield plus a tracker and a calorimeter, which allow almost background-free, highly efficient detection of gamma rays in the energy range between 30 MeV and 300 GeV. It has a wide field of view (FoV) of about $4\pi/5$ steradian and a duty cycle close to 100%. It normally works in survey mode, covering the full sky every three hours.

On the other hand, IACTs are sensitive to the energy range from $\sim$100 GeV to $\sim$100 TeV. The typical FoV of IACTs is of few (3-5) degrees in diameter, and they usually operate in pointing mode, with a duty cycle of $\sim$10%. They image the Cherenkov light produced in the electromagnetic showers initiated by cosmic radiation in our atmosphere. The main background affecting the observations of gamma rays using this technique is the overwhelming flux of charged CRs –about 100 times more abundant than gamma rays for intense sources–, which is reduced through the analysis of image properties.

3. ORIGIN OF GALACTIC COSMIC RAYS

CRs are energetic ($\sim 10^8$ to $\sim 10^{21}$ eV) particles which bombard the Earth almost isotropically. CR energy spectrum reveals a non-thermal origin: the flux is well described by a power law with index -2.7 up to $\sim 3\times10^{15}$ eV (a feature dubbed the "knee"), and index -3.0 up to $\sim 3\times10^{18}$ eV. They are composed mainly by protons and heavier nuclei, but also contain a non-negligible fraction of electrons, gamma rays, neutrinos and anti-particles. Galactic magnetic fields are intense enough so that CRs up to, at least, 10^{16} GeV are confined within the Galaxy, and therefore it is usually assumed that CRs up to the "knee" have a Galactic origin. The assumption is supported by the fact that several Galactic CR accelerator candidates are known, including supernova remnants (SNRs), pulsar wind nebulae, binary systems, star forming regions or super-bubbles. Among them, and based on energy budget and abundance arguments, the main contributors are thought to be SNRs,

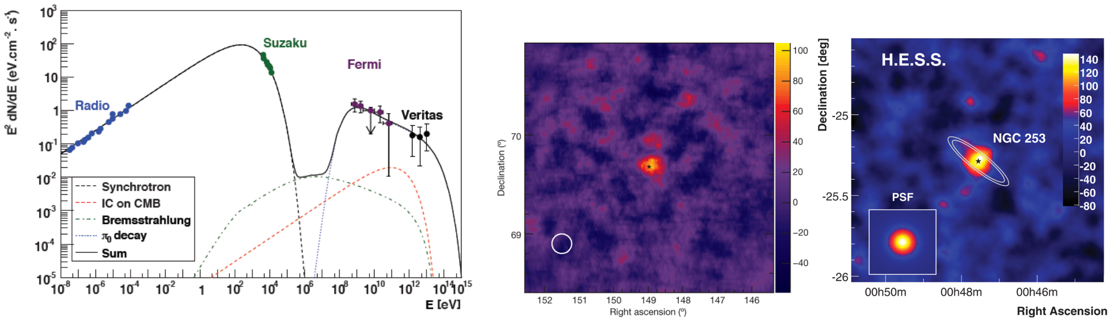

Figure 1: Left: Broadband SED model for Tycho SNR compared to experimental data. Figure taken from Ref. [4]. Right: Starburst galaxies detected in gamma rays. M82 as detected by VERITAS after 137 hours of observation with a flux of 0.9% of the Crab Nebula above 700 GeV [18] (center). NGC253 as detected by H.E.S.S. after 119 hours of observation with a flux of 0.3% of the Crab Nebula above 220 GeV [19] (right).

through the acceleration in the shocks formed by the ejected material and the interstellar medium. The accelerated protons lose energy through proton-proton interactions, producing gamma rays by the decay of the subsequent neutral pions, with a maximum energy $\sim 10\%$ that of the protons.

Gamma ray emission is observed in several young shell-type SNRs. Measuring the synchrotron spectrum and magnetic field provides a constraint on the accelerated electron population, and may point to interacting protons as the origin of the observed gamma rays. A recent prototypical example is provided by the type Ia, shell-type SNR Tycho, detected by Fermi-LAT [4] and VERITAS [5]. Accelerated protons interacting with the ambient medium provides the best fit to the observations (see Figure 1). There are many examples of young shell-type SNRs detected in gamma rays, like Cassiopeia A [6, 7, 8], HESS J1731-347 [9], SN 1006 [10], and others.

Another possible way to look for evidence of proton acceleration is to search older SNRs close to dense molecular clouds. In this case the number of targets for proton-proton collisions may increase dramatically and the gamma ray emission is expected to be produced in the interaction region between the remnant and the molecular cloud, or by the "illumination" of farther clouds by the high energy protons escaping the SNR shock. There are several examples of gamma rays sources compatible with this scenario, like IC443 [11, 12, 13], W51[14, 15], W28 [16, 17] and others.

Further evidence for the Galactic origin of CRs up to the "knee" is provided by the observations of starburst galaxies. This kind of galaxies have large abundances of SNRs and massive star winds. If CRs are accelerated by this kind of objects, starburst galaxies should contain larger CR densities than our Galaxy, and we should detect the gamma rays produced by their interaction with the interstellar gas and radiation. The two most favorable cases have been recently observed (see Figure 1). M82 has been detected by VERITAS [18], with an inferred CR density 500 times larger than in our Galaxy. NGC253 has been detected by H.E.S.S. [19] with an estimated CR density up to 2000 times that of our Galaxy. Fermi-LAT has also reported the detection of gamma rays from these two starburst galaxies[20].

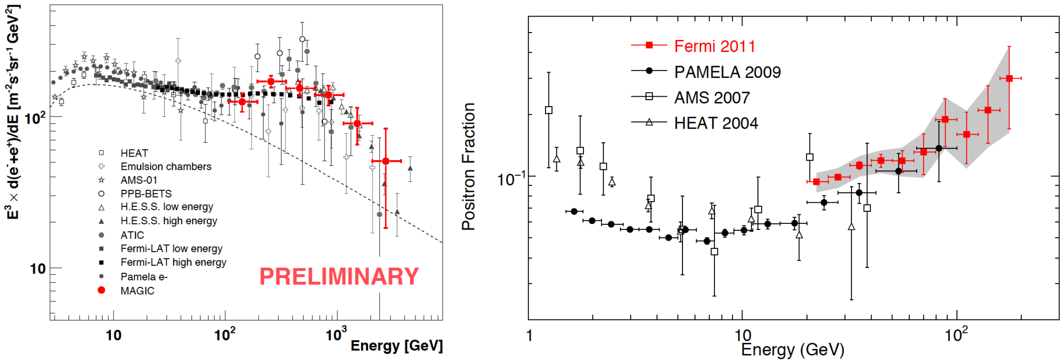

Figure 2: Left: Electron-positron spectrum in the energy range between 3 GeV and 5 TeV measured by different experiments. Figure taken from Ref. [25]. Right: Positron fraction measured by Fermi-LAT and other experiments in the energy range between 1 GeV and 200 GeV. Figure taken from Ref. [26].

4. COSMIC ELECTRON SPECTRUM

At the end of 2008, two independent measurements showing unexpected features in the electron-positron [21] and positron fraction [22] spectra were reported. These discoveries immediately triggered a burst of possible theoretical explanations, ranging from a nearby pulsar to dark matter annihilation. Gamma ray instruments are contributing to shed light into this issue by providing the most precise measurement of the electron-positron spectrum between 20 GeV and 5 TeV, and of the excess in the positron fraction between 20 and 200 GeV.

Fermi-LAT is actually a fine electron spectrometer, and it records $\sim 10^7$ electron-positrons per year above 20 GeV [23] . For this kind of measurement, however, it has to deal with a non-negligible fraction of hadron contamination. Separation of signal and background relies on extensive Monte Carlo (MC) simulations validated with beam-test and flight data. The measured spectrum is shown in Figure 2. Fermi-LAT results are the most precise between 20 GeV and 1 TeV. They show a smooth spectrum, and the spectral feature claimed by previous experiments is not found.

H.E.S.S. and MAGIC have also measured the cosmic electron-positron spectrum between 100 GeV and 5 TeV [24, 25]. Electron and gamma ray signals are in first approximation indistinguishable for IACTs. The measurement is based on the fact that the former are the dominant electromagnetic component of the diffuse CR flux. The main background comes from hadronic CRs, and can be reduced using multi-variate statistical analyses that exploit the differences in the Cherenkov shower images between electrons and hadrons. The results (see Figure 2) are in agreement, within systematic uncertainties, with what was observed by Fermi-LAT: the spectral feature claimed at Ref. [21] is not confirmed, and the spectrum is well fitted by a power law with index -3, and a steepening starting at ~1 TeV.

Fermi-LAT has also measured separate CR positron and electron spectra [26]. Since the detector has no magnet, both populations are separated by exploiting the Earth's shadow on the CR flux, whose position depends on the particle's charge. This allows Fermi-LAT to produce a measurement of both components separately, and of the positron fraction between 20 GeV and 200 GeV (see Figure 2). The results are in agreement with Ref. [22] and shows, for the first time, that the

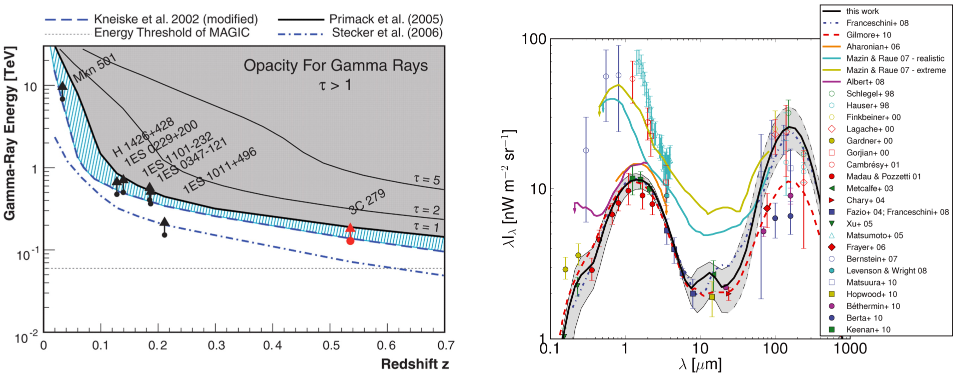

Figure 3: Left: For a given distance (z), the lines show, for different EBL models, the gamma ray energy for which a reduction of the flux of $\sim$63% is expected. Observation of AGNs at different distance and energies are used to constrain EBL models. Figure taken from Ref. [28]. Right: Recent EBL limits, measurements and theoretical models. Figure taken from Ref. [30].

unexpected increase in the positron fraction continues at least up to 200 GeV.

5. EXTRAGALACTIC BACKGROUND LIGHT

The EBL is composed of low-energy ($\lambda \sim 10^{-1} - 10^{3}\,\mu$m) photons radiated by stars and galaxies in the course of cosmic history. The EBL spectrum contains information about the history of the Universe, star formation, galaxy evolution and cosmology. It consists of two main components: the redshifted light from stars and the redshifted light reprocessed by dust. Although solid lower limits to EBL can be obtained by galaxy count experiments, direct measurements are extremely challenging, due to the intense foreground light, dominated by terrestrial, zodiacal and Galactic sources, and which is about 100 times more intense than the EBL over the whole spectral range.

Gamma ray instruments provide indirect constraints to the intensity of EBL at the μm range. That is possible because gamma rays traveling cosmological distances have a non-negligible probability of interaction with EBL photons, creating e^+e^- pairs. That probability depends on the gamma ray energy, the travelled distance, and the details of EBL (intensity, spectrum, time evolution, etc). Therefore, the spectrum of cosmological gamma ray sources measured at Earth is the convolution of the *intrinsic* spectrum and the energy-dependent modification produced by the interaction with the EBL. Thus, by measuring the gamma ray spectrum of distant sources and making some assumptions on the properties of the intrinsic one, we can constrain the EBL.

H.E.S.S. [27] and MAGIC [28] (see Figure 3) have set upper limits to the EBL using observations of distant active galactic nuclei (AGNs), and the assumption that a fit to the intrinsic spectrum using a power-law yields a photon index larger than 1.5. Fermi-LAT [29], on the other hand, excludes EBL models by imposing lower limits to the probability of detection of the highest-energy photon recorded in observations of distant AGNs and gamma ray bursts (GRBs). These measurements have resulted in the exclusion of all those models predicting high EBL levels, and present limits and theoretical understanding suggest an EBL close to the lower limits inferred from galaxy counts [30] (see Figure 3).

6. TESTS OF LORENTZ INVARIANCE

Gamma ray instruments have also been used to test Lorentz Invariance. Several Quantum Gravity theories predict that Lorentz Invariance is not preserved at energy scales close to the Planck Mass ($M_P = 1.2 \times 10^{19}$ GeV). In such a case, there should be an energy dependence of the speed of light, whose expression can be expanded as

$$v = c\left(1 \pm \xi \frac{E}{M_P} \pm \zeta^2 \left(\frac{E}{M_P}\right)^2 + ...\right) \tag{6.1}$$

where ξ and ζ parameterize the strength of the dependence of the speed of light linearly and quadratically with the energy, respectively. The effect on v is expected to be tiny for energies below M_P, but nevertheless measurable in the time delay of photons traveling cosmological distances (from far AGNs or GRBs), observed over a wide enough energy range.

The first limits to these effects were obtained using MAGIC observations [31] of an intense flare in Markarian 501, a relatively close AGN ($z = 0.034$). Variations in the flux of factors close to 10 were observed, with doubling times of the order of 1-2 minutes, in the energy range between 150 GeV and 10 TeV. Several innovative analysis methods were specially developed for this study. The corresponding 95% confidence level (CL) lower limits to the mass scale of Lorentz Invariance violation are $M_P/\xi > 0.3 \times 10^{18}$ GeV and $M_P/\zeta > 5.7 \times 10^{10}$ GeV.

Shortly after, H.E.S.S. observed an exceptionally intense flare in PKS 2155-304 ($z = 0.116$) happened in July 28, 2006, with flux peaks up to 15 times the Crab flux and doubling times of 1-3 minutes. The energy range of the observations covered from 200 GeV to 4 TeV. The inferred limits to the mass scale of Lorentz Invariance violation are: $M_P/\xi > 2.1 \times 10^{18}$ GeV and $M_P/\zeta > 6.4 \times 10^{10}$ GeV [32].

Fermi-LAT can observe sources from the farthest distances in a comparatively narrower energy range, of the order of tens of GeV. The observation of the GRB on May 10th 2009 ($z = 0.903$) in the energy range between 10 MeV and 30 GeV [33], whose duration was shorter than 1 s, allowed to set the lower limits: $M_P/\xi > 1.5 \times 10^{19}$ GeV and $M_P/\zeta > 3.0 \times 10^{10}$ GeV.

Fermi-LAT constrains better the linear term due to the larger distances travelled by the observed gamma rays and the limit exceeds, for the first time in this kind of tests, the Planck Mass. The quadratic term is better constrained by observations with IACTs, due to the wider accessible energy interval.

7. SUMMARY AND CONCLUSIONS

In this paper we have shown how gamma ray instruments have been used to probe several topics of fundamental physics. We have summarized the most relevant results in several fronts: the role of SNRs as the primordial sites of CR acceleration, the electron-positron spectrum, EBL constraints and tests of Quantum Gravity.

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