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

Gamma-ray Astronomy studies cosmic accelerators through their electromagnetic radiation in the energy range between \(\sim 100\) MeV and \(\sim 100\) 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 or 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.

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. Accelerated electrons may produce gamma rays in the presence of magnetic fields by synchrotron emission, by bremsstrahlung in the presence of matter, or by (inverse) Compton scattering off ambient photons (sometimes those produced by synchrotron emission of the same electron population). On the other hand, gamma rays are also produced in the decay of the neutral pions resulting from the interaction of accelerated protons with the interstellar matter. Therefore, by studying gamma rays we learn about cosmic particle accelerators. Those include supernova remnants (SNRs), binary systems with a neutron star or a black hole, pulsars, pulsar wind nebulae, starburst galaxies and active galactic nuclei (AGNs). For a recent review see, e.g., [Aharonian 2011]. In addition, Gamma-ray Astronomy can shed light on fundamental questions of Physics:

i) By studying the gamma-ray emission produced by SNRs we can determine if that is produced by electrons or protons, and answer the question of whether or not SNRs are the main site of Galactic cosmic ray (CR) acceleration.

ii) Current gamma-ray observatories are the most sensitive instruments to measure the flux of cosmic electrons in the energy range between 20 GeV and 5 TeV, of special interest because it has been recently claimed to contain a component which cannot be accounted by conventional models of CR propagation and interaction in the Galaxy.

iii) By studying the gamma-ray emission from sources at cosmological distances we can indirectly measure the extragalactic background light (EBL). This is the light emitted by all extragalactic sources over the history of the universe, and measuring it provides constraints to models of star formation, galaxy evolution and Cosmology.

iv) Distant and variable gamma-ray sources offer the possibility to test Lorentz Invariance by looking for an energy dependence of the speed of light.

v) Finally, we can search for the gamma rays produced by dark matter (DM) annihilation or decay in over-density sites like the satellite galaxies, the Galactic center or galaxy clusters.

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 7. Finally, we summarize and conclude in Section 8.
2. GAMMA-RAY INSTRUMENTS

Gamma rays are currently most sensitively detected, from space, by the Fermi satellite and, from Earth, by the Imaging Air Cherenkov Telescopes (IACTs), MAGIC$^2$, H.E.S.S.$^3$ and VERITAS$^4$. On a time scale of five years, a new, more sensitive, IACT system, the Cherenkov Telescope Array (CTA)$^5$, could already be in partial operation.

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 more than 300 GeV. Fermi-LAT 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. It became operational in August 2008, and, after the first year of observations, data are publicly available in quasi real-time. The Fermi-LAT Collaboration has recently released the 2-year catalog (Abdo et al. [2011]), with almost 1900 detected sources (its predecessor, EGRET, detected a total of 270 sources in its 10-years lifetime, Hartman et al. [1999]), many of which still remain unidentified.

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. Using this technique, over a dozen sources were detected at energies of hundreds of GeV in the 1990s with the first generation of IACTs. These first exploratory instruments were then replaced in the 2000s by the current generation of facilities, which have revolutionized the field: gamma-ray source catalogues list now about a hundred of sources and several new populations have been established as gamma-ray emitters, including SNRs, pulsar wind nebulae, radio galaxies and gamma-ray binary systems (for a recent review see, e.g. Funk [2011]).

The next breakthrough in the field of gamma-ray astrophysics is bound to happen when CTA comes online a few years from now. This instrument will consist of two arrays of up to 100 telescopes of different reflector sizes in the southern and northern hemispheres. The CTA arrays will be ten times more sensitive than all the currently running experiments, and will extend further the lower and higher ends of the energy sensitive range.

3. ORIGIN OF GALACTIC COSMIC RAYS

CRs are energetic ($\sim 10^8$ to $\sim 10^{21}$ eV) particles which bombard the Earth almost isotropically, discovered 100 years ago by V. Hess [1912]. CR energy spectrum reveals a non-thermal origin: the flux is well described by a power law with index $-2.7$ up to $\sim 3 \times 10^{15}$ eV (a feature dubbed the “knee” and for which the absolute flux is $\sim 10^{-13}$ particles per m$^2$ sr GeV s), and index $-3.0$ up to $\sim 3 \times 10^{18}$ 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 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: the total energy released by a supernova is of the order of $10^{51}$ ergs and they happen with an approximate frequency of one every $\sim 50$ years. This should be enough to produce all observed Galactic CRs if about 10% of the total energy was used on their acceleration. Moreover, shock acceleration provides a mechanism by which charged particles may attain the observed energies: after the supernova explosion the ejected material sweeps the interstellar and circumstellar gas forming a shock, which is able to efficiently accelerate charged particles. Irrespectively of the nature of the accelerated particles, electrons or protons, this process produces gamma rays. Electrons lose energy through synchrotron producing X-rays and radio emission, and through bremsstrahlung and inverse Compton producing gamma rays. Protons lose energy through proton-proton interactions, producing gamma rays by the decay of the subsequent neutral pions. An important feature of the latter process is that protons and gamma rays both follow a power law spectrum with the same spectral shape, and the maximum energy attained by the gamma rays is $\sim 10\%$ of that of the protons.

Gamma-ray emission is observed in several young shell-type SNRs. A recent prototypical example is provided by the type Ia, shell-type SNR Tycho. This
source has an age of about 440 years, and lies at a distance of 2-5 kpc. It has been detected in gamma rays by VERITAS (Acciari et al. [2011]) and Fermi-LAT (Giordano et al. [2011]). The magnetic field is measured to be of 215 $\mu$G (Cassam-Chenaï et al. [2007]). This, together with the synchrotron spectrum measured by radio and X-ray observations constrains the electron population, whose spectrum can be well described by a power-law with index $\sim -2.2$ and a cutoff at 6-7 TeV. In such a situation, the inverse Compton process of electrons off photons of the Cosmic Microwave Background is not enough to reproduce the observed gamma-ray flux, which would require a lower magnetic field. Bremsstrahlung produces even lower fluxes at gamma-ray energies. On the other hand, accelerated protons interacting with the ambient medium are expected to produce gamma rays via pion decay, with a spectrum that can be fitted to the observations (see Figure 1). There are many examples of young shell-type SNRs detected in gamma rays, like Cassiopeia A (Albert et al. [2007a], Acciari et al. [2010a], Abdo et al. [2010a]), HESS J1731-347 (Abramowski et al. [2011a]), SN 1006 (Acero et al. [2010]), 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 increases dramatically and 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-ray sources compatible with this scenario, like IC443 (Albert et al. [2007b], Acciari et al. [2009a], Abdo et al. [2010b]), W51C (Fasson et al. [2010], Abdo et al. [2009a], Carmena et al. [2011]), W28 (Aharonian et al. [2008], Abdo et al. [2010c]) 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 2). M82 has been detected by VERITAS (Acciari et al. [2009b]), with an inferred CR density 500 times larger than in our Galaxy. NGC253 has been detected by H.E.S.S. (Acero et al. [2009]) 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 (Abdo et al. [2010d]).

In summary, there is a growing evidence that SNR might be (one of) the main accelerators of Galactic CRs, and some clear examples where such acceleration is happening have been observed. However, there are still some open questions. We still do not know if shocks are able to accelerated particles up to the highest Galactic CR energies. We observe gamma rays from SNRs of up to $10^{13}$ eV, meaning that they are produced by protons of up to $10^{14}$ eV, but we do not know if energies up to the “knee” and beyond are reached or not. We still do not know the ratio of protons and electrons accelerated in the shocks, and if SNRs are the only Galactic CR accelerators. To solve these questions, more observations allowing for a population study are needed.

4. COSMIC ELECTRON SPECTRUM

At the end of 2008, two independent measurements showing unexpected features in the electron-positron (Chang et al. [2008]) and positron fraction (Adriani et al. [2009]) spectra were reported. These discoveries immediately triggered a burst of possible theoretical explanations, ranging from a nearby pulsar...
Figure 3: Electron-positron spectrum in the energy range between 3 GeV and 5 TeV measured by different experiments. Figure taken from Borla Tridon et al. [2011].

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 (Abdo et al. [2009b]). 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 3. 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. The measurement deviates from the prediction of models of conventional CR diffusion and interaction (Strong et al. [2004]), but it can be reasonably well fitted by a $E^{-3.04}$ power law, when systematic errors are considered.

H.E.S.S. and MAGIC have also measured the cosmic electron-positron spectrum between 100 GeV and 5 TeV (Aharonian et al. [2009], Borla Tridon et al. [2011]). 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 (Albert et al. [2008a]), which requires extensive MC simulations of shower development in the atmosphere. The results (see Figure 3) are in agreement, within systematic uncertainties, with what was observed by Fermi-LAT: the spectral feature claimed by Chang et al. [2008] is not confirmed, and the spectrum is well fitted by a power law with index -3, and a steepening starting at $\sim 1$ TeV.

Fermi-LAT has also measured separate CR positron and electron spectra (Ackermann et al. [2011]). 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 4). The results are in agreement with Adriani et al. [2009] and shows, for the first time, that the unexpected increase in the positron fraction continues at least up to 200 GeV.

MAGIC is currently developing a conceptually similar measurement that exploits the Moon shadow and the dependence of its position on the particle’s charge (Colin et al. [2011]). With this strategy, the measurement of the positron fraction is expected to be extended up to $\sim 700$ GeV. This is a very challenging measurement due to the high level of noise induced by the scattered moonlight during the observations. Although the major technical drawbacks of the technique have now been overcome, the detection of the electron Moon shadow with MAGIC will still require several years because of the short observation window available every year.

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 outshines the EBL over the whole spectral range.

Gamma-ray instruments provide indirect constraints to the EBL at the \( \mu \)m range. That is possible because gamma rays traveling cosmological distances have a non-negligible probability of interaction with EBL photons through \( e^+ e^- \) pair creation. That probability depends on the gamma-ray energy, the traveled 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. (Aharonian et al. [2006]) and MAGIC (Albert et al. [2008b] and Figure 5) have set upper limits to the EBL using observations of distant AGNs. In this case, two different assumptions on the intrinsic spectrum are normally used, namely: that a fit using a power-law yields a photon index larger than 1.5; and that there is no spectral pile-up, i.e. no presence of an extra high-energy component. Fermi-LAT (Abdo et al. [2010e]), 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 (see Figure 6 and Domínguez et al. [2011]).

In addition, if the EBL and the intrinsic spectrum of an observed distant source are perfectly known, the measured spectrum depends only on the distance to the source. Based on this idea, Blanch and Martinez [2005] have proposed to use the measured energy spectrum of distant sources to fit cosmological parameters.

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 \( (M_P = 1.2 \times 10^{19} \text{ GeV}) \). In such a case, there should be an energy dependence of the speed of light, whose expression can be expanded as

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

where \( \xi \) and \( \zeta \) parameterize the strength of the linear and quadratic dependences of the speed of light with the energy, respectively.

The effect 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 time delay per unit energy for gamma rays
traveling a distance $z$ can be written as

$$\frac{\Delta t}{\Delta E} \simeq \frac{\xi}{M_P H_0} \int_0^z \frac{(1 + z')dz'}{\sqrt{\Omega_m(1 + z')^3 + \Omega_\Lambda}}$$  \hspace{1cm} (2)

Or, if $\xi = 0$, the time delay per unit of energy square can be written as:

$$\frac{\Delta t}{\Delta E^2} \simeq \frac{3z^2}{2M_P^2 H_0} \int_0^z \frac{(1 + z')^2dz'}{\sqrt{\Omega_m(1 + z')^3 + \Omega_\Lambda}}$$  \hspace{1cm} (3)

The first limits were obtained using MAGIC observations \cite{Albert et al. 2008c} of an intense flare in Markarian 501 \cite{Albert et al. 2007c}, 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 (see Figure 7). Several innovative analysis methods were specially developed for this study, and the measured time delays per unit energy and energy square were, respectively: $\tau_l = (30 \pm 12)$ s/TeV and $\tau_q = (3.7 \pm 2.6)$ s/TeV$^2$. Although these results could be interpreted as significant detection of an energy-dependence of the speed of gamma rays, delays produced at the source cannot be excluded by a single observation. 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 measured time delays were $\tau_l = (-6 \pm 11)$ s/TeV and $\tau_q = (1.7 \pm 6.3)$ s/TeV$^2$, corresponding to limits to the mass scale of Lorentz Invariance violation: $M_P/\xi > 2.1 \times 10^{18}$ GeV and $M_P/\zeta > 6.4 \times 10^{10}$ GeV \cite{Abramowski et al. 2011b}.

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 \cite{Abdo et al. 2009c}, whose duration was shorter than 1 s, allowed to set an upper limit to the gamma-ray time delay (considering the linear term in Equation 2) of $\tau_l < 30$ s/TeV. The corresponding lower limits to the mass scale of Lorentz Invariance violation are $M_P/\xi > 1.5 \times 10^{19}$ GeV and $M_P/\zeta > 3.0 \times 10^{10}$ GeV.

Fermi-LAT constrains better the linear term (see Equation 2), due to the larger distances traveled 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. For a summary of the limits obtained with the different observatories, see Table I.

### 7. DARK MATTER SEARCHES

In indirect DM searches with gamma rays we look for either primary or secondary gamma rays produced in annihilation and/or decay of DM particles. In first approximation, we can consider that these gamma rays do not interact on their way to Earth, since all relevant known source candidates are at relatively short

| Telescope | $M_P/\xi$ [GeV] | $M_P/\zeta$ [GeV] |
|-----------|----------------|------------------|
| MAGIC     | $0.03 \times 10^{19}$ | $5.7 \times 10^{10}$ |
| H.E.S.S.  | $0.21 \times 10^{19}$ | $6.4 \times 10^{10}$ |
| Fermi-LAT | $1.50 \times 10^{19}$ | $3.0 \times 10^{10}$ |

Figure 7: Gamma-ray light curve during the night of July 9 2005, with time binning of 4 minutes and in different energy bands. The dotted line represents the flux from the Crab Nebula. Figure taken from \cite{Albert et al. 2007c}.
Figure 8: Upper limits to $\langle \sigma v \rangle$ (in the mSUGRA scenario) obtained by observations of H.E.S.S. on the Galactic halo. Figure taken from Abramowski et al. [2011c].

from 30 hours of observations of the satellite galaxy Segue 1 (Aleksić et al. [2011]), reaching limits of the order of $\langle \sigma v \rangle \sim 10^{-23}$ cm$^3$ s$^{-1}$ for DM masses $\sim$few×100 GeV (considering mSUGRA models). Similar limits are also obtained using observations of satellite galaxies with VERITAS (Acciari et al. [2010a]).

The most stringent limits obtained with IACTs are provided by H.E.S.S., using observations of the Galactic halo (Abramowski et al. [2011c]), which yield limits at the level of $\langle \sigma v \rangle \sim$few×$10^{-25}$ cm$^3$ s$^{-1}$ for a similar DM range (see Figure 8).

For DM mass below a few×100 GeV, the best limits are provided by the observations of Fermi-LAT. Thanks to its large FoV and duty cycle, Fermi observes all possible candidates almost simultaneously. Observations of dwarf satellite galaxies (Abdo et al. [2010a], Lena Garde et al. [2011]) provide limits maybe reaching $\langle \sigma v \rangle \sim 10^{-25}$ cm$^3$ s$^{-1}$ for a DM mass $\sim$ 100 GeV (see Figure 9).

The ultimate sensitivity in DM searches using the present generation of gamma-ray instruments has not been still reached. Deeper observations, together with improvements in the analysis techniques will produce in the next few years a more sensitive search, reaching predictions of mSUGRA, and will be continued in the future by CTA.

8. SUMMARY AND CONCLUSIONS

In this paper we have shown how gamma-ray instruments have been (and still are) used to probe several
topics of fundamental physics. We have summarized the most relevant results in several fronts: i) Gamma-ray instruments are gathering evidence on the role of SNRs as the primordial sites of CR acceleration. ii) CR electrons-positrons have been measured between 30 GeV and 5 TeV, confirming a harder spectrum than previously thought but discarding sharp spectral features. iii) Models of EBL have been constrained down to almost the lower limits allowed by galaxy counts. iv) The Quantum Gravity scale has been probed up to Planck Mass in Lorentz Invariance tests v) Ongoing DM searches have not yielded yet any positive result, but are expected to constrain mSUGRA models in the coming years.

Acknowledgments

I thank the MAGIC, H.E.S.S., VERITAS and Fermi-LAT Collaborations for their help in reviewing and improving this document.

References

F. Aharonian, in 32nd International Cosmic Ray Conference, Beijing, China (2011).
A. A. Abdo et al., ArXiv e-prints (2011), 1108.1435.
R. C. Hartman et al., Astrophys. J. Supp. 123, 79 (1999).
S. Funk, in 32nd International Cosmic Ray Conference, Beijing, China (2011).
V. F. Hess, Physikalische Zeitschrift 13, 1084 (1912).
F. Giordano et al., ArXiv e-prints (2011), 1108.0265.
V. A. Acciari et al., Astrophys. J. Lett. 730, L20+ (2011), 1102.3871.
G. Cassam-Chenaï et al., Astrophys. J. 665, 315 (2007), arXiv:astro-ph/0703239.
J. Albert et al., Astron. and Astrophys. 474, 937 (2007a), 0706.4065.
V. A. Acciari et al., Astrophys. J. 714, 163 (2010a), 1002.2974.
A. A. Abdo et al., Astrophys. J. Lett. 710, L92 (2010a), 1001.1419.
A. Abramowski et al., Astron. and Astrophys. 531, A81+ (2011a), 1105.3206.
F. Acero et al., Astron. and Astrophys. 516, A62+ (2010), 1004.2124.
J. Albert et al., Astrophys. J. Lett. 664, L87 (2007b), 0705.3119.
V. A. Acciari et al., Astrophys. J. Lett. 698, L133 (2009a), 0905.3291.
A. A. Abdo et al., Astrophys. J. 712, 459 (2010b), 1002.2198.
A. Fiasson et al., in 31st International Cosmic Ray Conference, Lodz, Poland (2010).
A. A. Abdo et al., Astrophys. J. Lett. 706, L1 (2009a), 0910.0908.
E. Carmona, J. Krause, I. Reichardt, and for the Magic Collaboration, ArXiv e-prints (2011), 1110.0950.
F. Aharonian et al., Astron. and Astrophys. 481, 401 (2008), 0801.3555.
A. A. Abdo et al., Astrophys. J. 718, 348 (2010c).
F. Acero et al., Science 326, 1080 (2009), 0909.4651.
V. A. Acciari et al., Nature 462, 770 (2009b), 0911.0873.
A. A. Abdo et al., Astrophys. J. Lett. 709, L152 (2010d), 0911.5327.
J. Chang et al., Nature 456, 362 (2008).
O. Adriani et al., Nature 458, 607 (2009), 0810.4995.
A. A. Abdo et al., Physical Review Letters 102, 181101 (2009b), 0905.0025.
A. W. Strong, I. V. Moskalenko, and O. Reimer, Astrophys. J. 613, 962 (2004), arXiv:astro-ph/0406254.
D. Borla Tridon et al., ArXiv e-prints (2011), 1110.4008.
F. Aharonian et al., Astron. and Astrophys. 508, 561 (2009), 0905.0105.
J. Albert et al., Nuclear Instruments and Methods in Physics Research A 588, 424 (2008a), 0709.3719.
M. Ackermann et al., ArXiv e-prints (2011), 1109.0521.
P. Colin et al., ArXiv e-prints (2011), 1110.0183.
J. Albert et al., Science 320, 1752 (2008b), 0807.2822.
A. Domínguez et al., MNRAS 410, 2556 (2011), 1007.1459.
F. Aharonian et al., Nature 440, 1018 (2006), arXiv:astro-ph/0508073.
A. A. Abdo et al., Astrophys. J. 723, 1082 (2010c).
O. Blanch and M. Martinez, Astroparticle Physics 23, 588 (2005), arXiv:astro-ph/0107582.
J. Albert et al., Astrophys. J. 669, 862 (2007c), arXiv:astro-ph/0702008.
J. Albert et al., Phys. Lett. B 668, 253 (2008c), 0708.2889.
A. Abramowski et al., Astroparticle Physics 34, 738 (2011b), 1101.3650.
A. A. Abdo et al., Nature 462, 331 (2009c), 0908.1832.
A. Abramowski et al., Physical Review Letters 106, 161301 (2011c), 1103.3266.
A. A. Abdo et al., Astrophys. J 712, 147 (2010f), 1001.4531.
J. Aleksić et al., JCAP 6, 35 (2011), 1103.0477.
V. A. Acciari et al., Astrophys. J. 720, 1174 (2010b), 1006.5955.
M. Llena Garde et al., ArXiv e-prints (2011), 1111.0320.