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ORIGIN AND PROPAGATION OF COSMIC RAYS (SOME HIGHLIGHTS)

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Abstract

The detection of high-energy particles, cosmic rays (CRs), deep inside the heliosphere implies that there are, at least, three distinctly different stages in the lifetime of a CR particle: acceleration, propagation in the interstellar medium (ISM), and propagation in the heliosphere. Gamma rays produced by interactions of CRs with gas, radiation, and magnetic fields can be used to study their spectra in different locations. Still, accurate direct measurements of CR species inside the heliosphere (such as their spectra and abundances) are extremely important for the understanding of their origin and propagation. In this paper, an emphasis is made on very recent advances and especially on those where GLAST and PAMELA observations can lead to further progress in our understanding of CRs.

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1 Introduction

Cosmic rays and γ-rays are intrinsically connected: γ-ray emission is a direct probe of proton and lepton spectra and intensities in distant locations of the Galaxy. Diffuse emission accounts for $\sim$80% of the total γ-ray luminosity of the Milky Way and is a tracer of interactions of CR particles in the ISM [1]. On the other hand, direct measurements of CR species can be used to probe CR propagation, to derive propagation parameters, and to test various hypotheses [2]. Luckily, two missions of the present and near future are targeting these issues and present unique opportunities for breakthroughs. The Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics (PAMELA) [3] has been launched in June 2006 and is currently in orbit. During its projected 3 yr lifetime it will measure light CR nuclei, antiprotons, and positrons in the energy range 50 MeV/n – 300 GeV/n with high precision. The Gamma-ray Large Area Space Telescope (GLAST) [4] is scheduled for launch in early 2008. It has significantly improved sensitivity, angular resolution, and much larger field of view than its predecessor EGRET and will provide excellent quality data in the energy range 20 MeV – 300 GeV.

2 Cosmic-ray accelerators

A supernova (SN) – CR connection has been discussed since the mid-1930s when Baade and Zwicky proposed that SNe are responsible for the observed CR flux. The first direct evidence of particle acceleration up to very high energies (VHE) came from observations of synchrotron X-rays from the supernova remnant (SNR) SN1006 [5]. More recently, observations of TeV γ-rays [6] confirm the existence of VHE particles. Still, definitive proof that SNRs are accelerating protons is absent. Recent observations of the SNR RX J1713 by HESS suggest that its spectrum is consistent with the decay of pions produced in *pp*-interactions [6], while the spectrum from inverse Compton scattering (ICS) does not seem to fit the observations. However, a calculation of ICS and synchrotron emission using a one-zone model [7] and a new calculation of the interstellar radiation field (ISRF) shows that a leptonic origin is also consistent with the data [8]. Another interesting case study is the composite SNR G0.9+0.1 near the Galactic center [9] which can also be fitted using the leptonic model [8]. In this instance, the major contribution comes from ICS off optical photons while the γ-ray spectrum exhibits a "universal" cutoff in the VHE regime due to the Klein-Nishina effect. If this modelling is correct, GLAST observations can be used to probe the ISRF in the Galactic center. Observations of SNRs by GLAST will be vital in distinguishing between leptonic or hadronic scenarios as their predictions for the spectral shape in the GeV energy range are distinctly different.

A new calculation of the ISRF shows that it is more intense than previously thought, especially in the inner Galaxy where the optical and infrared photon density exceeds that of the cosmic microwave background (CMB) by a factor of 100 [8]. For a source in the inner Galaxy, properly accounting for inverse Compton energy losses flattens the electron spectrum in the source compared to the case of pure synchrotron energy losses [10]. This effect leads to a flatter intrinsic γ-ray spectrum at the source. On the other hand, the intense ISRF also leads to $\gamma\gamma$-attenuation which starts at much lower energies than for the CMB alone [11]. For VHE γ-ray sources located in the inner Galaxy, the attenuation effects should be seen for energies $\sim$30 TeV [12].

A new class of VHE γ-ray sources and thus CR accelerators, close binaries, has been recently found by HESS [13]. The observed orbital modulation due to the $\gamma\gamma$-attenuation on optical photons of a companion star testifies that the VHE γ-ray emission is produced near the compact object. Such an effect has been predicted long ago in a series of papers [14], where the light curves were calculated for binaries which were suspected to be VHE emitters at that time, like Cyg X-3. The phase of the maximum of the emission depends on the eccentricity of the orbit and its orientation; for orbital parameters of LS 5039 it is about 0.7 [14], in agreement with observations. For a recent discussion of the orbital modulation in LS 5039, see [15]. GLAST observations in the GeV–TeV range will be the key to understanding the emission mechanism(s).

3 Propagation of cosmic rays and diffuse gamma-ray emission

3.1 Particle propagation near the sources

Diffuse γ-ray emission in the TeV energy range has been recently observed by HESS [16] from the Galactic center. The emission clearly correlates with the gas column density as traced by CS. If this emission is associated with a relatively young SNR, say Sgr A East, observation of the individual clouds will tell us about CR propagation there. A simple back-of-the-envelope calculation shows that if the SNR age is $<$10 kyr and the shock speed is $<10^4$ km/s, the shell size should be $<$100 pc, while the emission is observed from distant clouds up to 200 pc from the Galactic center. The emission outside the shock, therefore, has to be produced by protons which were accelerated by the shock and left it some time ago. The spectrum of such particles can be approximated by a δ-function in energy which depends on the SNR age; the resulting γ-ray spectrum is essentially flatter than expected from a power-law proton spectrum in the shell (Figure 1) [17, 18]. Observations of individual clouds in the GLAST energy range will be a direct probe of this model and thus of proton acceleration in SNRs.

Milagro has recently observed the diffuse emission at 12 TeV from the Cygnus region [19]. The observed emission, after subtraction of point sources

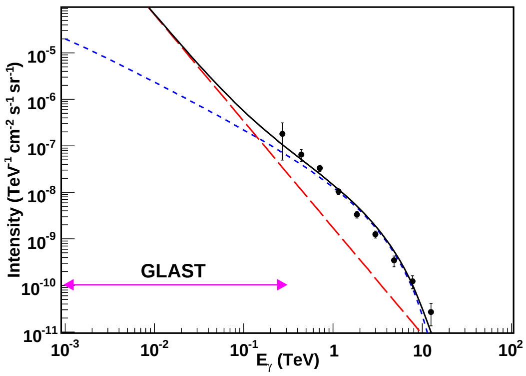

Figure 1: The spectrum of γ-rays [18] from the gas clouds outside of the SNR shell (monoenergetic protons of 25 TeV, dots) and from the shell (power-law with index -2.29, dashes); normalisations are arbitrary. The solid line is the total spectrum. Data: HESS observations of the Galactic center ridge [6].

correlates with gas column density. The VHE γ-ray flux is found to be larger than predicted by the conventional and even optimized model tuned to fit the GeV excess [25]. This may imply that freshly accelerated particles interact with the local gas, but other possibilities such as ICS or unresolved point sources can not be excluded on the base of Milagro observations alone.

These observations show that the diffuse emission exists even at VHE energies and variations in brightness are large. A contribution of Galactic CRs to the diffuse emission in this energy range is still significant. Observations of the diffuse emission may be used to study CR propagation and their penetration into molecular clouds. GLAST is ideally suited to address these issues.

3.2 Galactic cosmic rays

Propagation in the ISM changes the initial spectra and composition of CR species due to spallation, energy losses, energy gain (e.g., diffusive reacceleration), and other processes (e.g., diffusion, convection). The destruction of primary nuclei via spallation gives rise to secondary nuclei and isotopes which are rare in nature (i.e., Li, Be, B), antiprotons, pions and kaons that decay producing secondary leptons and γ-rays. Studies of stable secondary nuclei (Li, Be, B, Sc, Ti, V) allow the ratio (halo size)/(diffusion coefficient) to be determined and the incorporation of radioactive secondaries (^{10}Be, ^{26}Al, ^{36}Cl, ^{54}Mn) is used to find the diffusion coefficient and the halo size separately. For a recent review on CR propagation see [2].

Measurement of the B/C ratio with a single instrument and in a wide energy range is long overdue. The best data >0.8 GeV/n to-date are those taken by the HEAO-3 experiment more than 25 years ago, while modern spacecraft, e.g., ACE, provide high quality data at low energies 150–450 MeV/n [20]. The sharp maximum in the B/C ratio observed at ∼1 GeV/n is difficult to explain in a physical model and has been long debated; it may well be an instrumental artefact. On the other hand, the high energy tail of the B/C ratio is sensitive to the rigidity dependence of the diffusion coefficient and thus its accurate measurement can be used to distinguish between models of CR propagation in the ISM. The PAMELA has the capability of measuring the B/C ratio in the energy range 100 MeV/n – 250 GeV/n and will address both issues.

The majority of CR antiprotons observed near the Earth are secondaries produced in collisions of CRs with interstellar gas. Because of the kinematics of this process, the spectrum of antiprotons has a unique shape distinguishing it from other CR species. It peaks at ∼2 GeV decreasing sharply toward lower energies. Because of their high production threshold and the unique spectral shape antiprotons can be used to probe CR propagation in the ISM and the heliosphere, and to test the local Galactic average proton spectrum (for a discussion and references see [21]). Because the pp (and $\bar{p}p$) total inelastic cross section is ten times smaller than that of carbon, the ratio $\bar{p}/p$ can be used to derive the diffusion coefficient in a much larger Galactic volume than the B/C ratio. The CR $\bar{p}$ spectrum may also contain signatures of exotic processes, such as, e.g., WIMP annihilation. However, currently available data (mostly from BESS flights [22]) are not accurate enough, while published estimates of the expected flux differ significantly; in particular, the reacceleration model underproduces antiprotons by a factor of ∼2 at 2 GeV [21]. Secondary CR positrons are produced in the same interactions as antiprotons and are potentially able to contribute to the same topics. Accurate measurements of the CR e^+ spectrum may also reveal features associated with the sources of primary positrons, such as pulsars. During its lifetime, PAMELA will measure CR antiprotons and positrons in the energy range 50 MeV – 250 GeV with high precision [23]. Independent CR $\bar{p}$ measurements below ∼3 GeV will be provided by the new BESS-Polar instrument scheduled to fly in December of 2007 [22].

The diffuse emission is a tracer of interactions of CR particles in the ISM and is produced via ICS, bremsstrahlung, and π^0-decay. The puzzling excess in the EGRET data above 1 GeV [24] relative to that expected has shown up in all models that are tuned to be consistent with local nucleon and electron spectra [25]. The excess has shown up in all directions, not only in the Galactic plane. If this excess is not an instrumental artefact, it may be telling us that the CR intensity fluctuates in space which could be the result of the stochastic nature of supernova events. If this is true, the local CR spectra are not representative of the local Galactic average. Because of the secondary origin of CR antiprotons, their intensity fluctuates less than that of protons and $\bar{p}$ measurements can be used instead to derive the *average* local intensity of CR protons. Interestingly, a model based on a renormalized CR proton flux (to fit antiprotons) and a CR electron flux (using the diffuse emission itself), the so-called optimized model, fits the all-sky EGRET data well [25] providing a feasible explanation of the GeV excess. The GLAST observations of the diffuse emission will be able to resolve this puzzle. On the other hand, accurate measurements of CR antiprotons by PAMELA can be used to test the CR fluctuation hypothesis.

4 Cosmic rays in the heliosphere

Interestingly, GLAST will be able to trace the CRs in the heliosphere as well. The ICS of CR electrons off solar photons produces γ-rays with a broad distribution on the sky contributing to a foreground that would otherwise be ascribed to the Galactic and extragalactic diffuse emission [26]. Observations by GLAST can be used to monitor the heliosphere and determine the electron spectrum as a function of position from distances as large as Saturn's orbit to close proximity of the Sun, thus enabling unique studies of solar modulation. A related process is the production of pion-decay γ-rays in interactions of CR nuclei with gas in the solar atmosphere [27]. The albedo γ-rays will be observable by GLAST providing a possibility to study CR cascade development in the solar atmosphere, deep atmospheric layers, and magnetic field(s). The original analysis of the EGRET data assumed that the Sun is a point source and yielded only an upper limit [28]. However, a recent re-analysis of the EGRET data [29] has found evidence of the albedo (pion-decay) and the extended ICS emission. The maximum likelihood values appear to be consistent with the predictions.

GLAST will also be able to measure CR electrons directly. It is a very efficient electron detector able to operate in the range between $\sim$20 GeV and 2 TeV [30]. The total number of detected electrons will be $\sim 10^7$ per year. Accurate measurements of the CR electron spectrum are very important for studies of CR propagation and diffuse γ-ray emission. There is also the possibility to see the features associated with the local sources of CR electrons.

The Moon emits γ-rays [28, 31] due to CR interactions in its rocky surface. Monte Carlo simulations of the albedo spectrum using the GEANT4 framework show that it is very steep with an effective cutoff around 3 GeV and exhibits a narrow pion-decay line at 67.5 MeV [32]. The albedo flux below $\sim$1 GeV significantly depends on the incident CR proton and helium spectra which change over the solar cycle. Therefore, it is possible to monitor the CR spectrum at 1 AU using the albedo γ-ray flux. Simultaneous measurements of CR proton and helium spectra by PAMELA, and observations of the albedo γ-rays by GLAST, can be used to test the model predictions. Since the Moon albedo spectrum is well understood, it can be used as a standard candle for GLAST. Besides, the predicted pion-decay line at 67.5 MeV and the steep spectrum at higher energies present opportunities for in orbit energy calibration of GLAST.

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