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Diffuse γ-ray emission: lessons and perspectives

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Abstract. The Galactic diffuse emission is potentially able to reveal much about the sources and propagation of cosmic rays (CR), their spectra and intensities in distant locations. It can possibly unveil WIMP dark matter (DM) through its annihilation signatures. The extragalactic background may provide vital information about the early stages of the universe, neutralino annihilation, and unresolved sources (blazars?) and their cosmological evolution. The γ-ray instrument EGRET on the CGRO contributed much to the exploration of the Galactic diffuse emission. The new NASA Gamma-ray Large Area Space Telescope (GLAST) is scheduled for launch in 2007; study of the diffuse γ-ray emission is one of the priority goals. We describe current understanding of the diffuse emission and its potential for future discoveries.

INTRODUCTION

Diffuse galactic emission dominates the γ-ray sky. About 90% of the total luminosity of the Milky Way galaxy at high energies comes from the processes in the interstellar medium (ISM). What can we learn from studies of the diffuse emission? First of all, the diffuse emission is a tracer of energetic interactions of particles in the ISM and is produced via inverse Compton (IC) scattering, bremsstrahlung, and π^0-decay. It thus delivers information about spectra and intensities of CR species, primarily protons, He, electrons, and positrons, at distant locations and allows one to study CR acceleration in supernova remnants (SNRs) and other sources as well as propagation in the ISM. Emission from the local ISM can be used to study the local CR spectrum and thus provides a valuable input for studies of solar modulation and CR variations in the Galaxy. γ-rays can be used to trace interstellar gas independently of other astronomical methods, e.g. the relation of molecular H_2 gas to the CO molecule [1] and hydrogen overlooked by other methods [2]. The diffuse emission may contain signatures of new physics (e.g., DM) or may be used to put restrictions on cosmological models and the parameter space of supersymmetric particle models, and/or provide some hints for accelerator experiments. On the other hand, the diffuse emission is a background for point sources and its accurate determination is important for accurate localization of such sources and their spectra especially at low latitudes. It is also a foreground in studies of extragalactic diffuse emission, which is in itself is a complicated subject and may contain information about early stages of the universe and new physics (DM, black hole evaporation etc.). Besides, GLAST may be able to detect and spatially resolve the *diffuse* γ-rays from normal galaxies and thus will enable us to study CR in other galaxies [3]. This will give us an external view of a sister spiral galaxy Andromeda (M31) much like the Milky Way, and the dwarf irregular galaxies LMC and SMC.

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DIFFUSE GAMMA RAYS AND COSMIC RAYS

To understand the diffuse emission one needs to know particle spectra in the entire Galaxy. The conventional sources of CR are believed to be supernovae (SNe) and SNRs, pulsars, compact objects in close binary systems, and stellar winds. Observations of synchrotron emission (e.g., [4]), γ-rays [5], and even TeV γ-rays [6] reveal the presence of energetic particles in these objects thus testifying to efficient acceleration processes. Propagation in the ISM changes the initial composition and spectra of CR species due to the energy losses (ionization, Coulomb scattering, bremsstrahlung, IC scattering, and synchrotron emission), energy gain (diffusive reacceleration), and other processes (i.e., diffusion and convection by the Galactic wind). 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, and pions ($\pi^{\pm}$, π^0) that decay producing secondary $e^{\pm}$'s and γ-rays. γ-rays are also produced by electrons (and positrons) via IC and bremsstrahlung. The observation of diffuse γ-rays gives us the intensity integrated over the line of sight and provides the most direct probe of the proton and electron spectra in distant locations.

The propagation parameters are determined from studies of the nuclear component in CR using the transport equation [7], which may also include convection by a Galactic wind (e.g., [8]), distributed acceleration in the ISM due to the Fermi 2nd-order mechanism [9] (so-called "reacceleration"), and non-linear wave-particle interactions [10]. The abundances of stable (Li, Be, B, Sc, Ti, V) and radioactive (^{10}Be, ^{26}Al, ^{36}Cl, ^{54}Mn) secondaries in CR are used to derive the diffusion coefficient and the halo size [11, 12].

K-capture isotopes in CR (e.g., ^{49}V, ^{51}Cr) can serve as important energy markers and can be used to study the energy-dependent effects such as diffusive reacceleration in the ISM and heliospheric modulation [13]. Such nuclei usually decay via electron-capture and have a short lifetime in the medium; in CR they are stable or live longer as they are created bare by fragmentation of heavier nuclei. At low energies, their lifetime depends on the balance between the energy-dependent probabilities of the electron attachment from the ISM and stripping.

Study of the light nuclei in CR (Li–O) allows us to determine propagation parameters averaged over a larger Galactic region, but the local ISM is *not* necessarily the same and the *local* propagation parameters may significantly differ. To probe the local ISM one should look at isotopes with shorter lifetimes (e.g., ^{14}C) [14] and heavy nuclei since larger fragmentation cross sections lead to a smaller "collection area." The CR source composition is derived from direct CR data by correcting for the effects of propagation, spallation, and solar modulation. The derived source abundances may provide some clues to mechanisms and sites of CR acceleration. Obviously, such information is also valuable for a number of astrophysical/astroparticle applications far beyond the scope of the diffuse emission. For a more comprehensive review see [15, 16].

The GeV excess

The puzzling excess in the EGRET diffuse emission data above 1 GeV relative to that expected [17, 18] has shown up in all models that are tuned to be consistent with directly measured CR nucleon and electron spectra [15, 19]. The excess has shown up in all directions, not only in the Galactic plane; it is possible but unlikely to be an instrumental artefact due to the uncertainty in calibration.

The CR spectrum in the local ISM should be similar to the one directly measured corrected for the effects of solar modulation; thus future observations of γ-ray emission from local ISM could provide some clues to its origin. If the GeV excess appears in the emission from the local ISM, it may be either the result of the poor knowledge of pion production cross section (e.g., [20]) or the DM signal. If the local ISM does not exhibit the GeV excess seen on the large Galactic scale, it probably has something to do with CR spatial fluctuations. In the latter case, the normalization of the global calculated CR spectrum to the local CR measurements is wrong since the local spectrum is not representative of the *local* Galactic average and we should look for another way of fixing the global normalization. Currently available EGRET data on the local clouds have large error bars (see [21] for a summary plot and references) and therefore are not conclusive.

Secondary $\bar{p}$'s are produced in the same interactions of CR particles with interstellar gas as diffuse γ-rays and e^+'s and provide another probe of the interstellar CR proton spectrum. Recent $\bar{p}$ data with larger statistics [22] triggered a series of calculations of the secondary $\bar{p}$ flux in CR. The observed flux has been shown to be consistent with their secondary origin in calculations using plain diffusion (or the leaky-box model) and a Galactic wind model [23, 24]. The diffusive reacceleration models have certain advantages compared to other propagation models: they naturally reproduce secondary/primary nuclei ratios in CR and have only three free parameters. Detailed analysis shows, however, that the reacceleration models *underproduce* $\bar{p}$'s by a factor of $\sim$2 at 2 GeV [24] where the statistics are largest; this is because matching the B/C ratio at all energies requires the diffusion coefficient to be too large. Note that this is an essential feature of reacceleration models.

HYPOTHESES

There are quite a few hypotheses trying to explain the γ-ray and $\bar{p}$ excesses. Among these are: harder CR proton [25] and/or electron spectra [18, 26] in distant Galactic regions, a local CR component at low energies perhaps associated with the Local Bubble [27], contribution of unresolved point sources [28] or SNRs with freshly accelerated particles [29], CR spatial intensity variations [19], and DM signals (e.g., recent discussions [30, 31]).

The harder CR proton spectrum hypothesis has been shown to be problematic in the past [32] because the harder proton spectrum needed to explain diffuse γ-rays would produce too many $\bar{p}$'s. The harder electron spectrum model is more feasible, but does not resolve the $\bar{p}$ excess. The contribution of unresolved point sources and SNRs may explain some part of the γ-ray GeV excess in the Galactic plane, but not at high Galactic latitudes. A low energy local component in CR, while improving agreement with $\bar{p}$'s does not explain the excess in γ-rays.

As will be explained in the following sections, we are, in fact, left with at least two possibilities to explain the excesses in γ-rays, and $\bar{p}$'s, simultaneously: to invoke CR intensity variations or DM signals.

CR intensity variations

There are a number of reasons why CR intensity may fluctuate in space and time. First is the stochastic nature of SN events. Dramatic increases in CR intensity perhaps connected with SN explosions nearby are recorded in terrestrial concentrations of cosmogenic isotopes. Concentrations of ^{10}Be in Antarctic and Greenland ice core samples [34] and ^{60}Fe in a deep-sea ferromanganese crust [35] indicate highly significant increases of CR intensity $\sim$40 kyr and 2.8 Myr ago, correspondingly. The SN rate is larger in the spiral arms [33]; this may lead to lower CR intensity in the interarm region where the solar system is located. In case of anisotropic diffusion or convection by the Galactic wind such fluctuations may be even stronger. The intensity variations and spectra of CR protons and heavier CR nuclei may be uncorrelated. The total inelastic cross section for protons is $\sim$30 mb vs. $\sim$300 mb for Carbon, so that their Galactic "collecting areas" differ by a factor of 10 or more for heavier nuclei; this possibly implies that the directly measured CR protons and CR nuclei come from different sources. Besides, CR electrons and positrons suffer large energy losses [11] and thus their spectral and intensity fluctuations can be considerable.

Antiprotons in CR are presumably secondary and produced by mostly CR protons in interactions with the interstellar gas. Because of their secondary origin, their intensity fluctuates less than that of protons. The total cross section of $\bar{p}$'s is about the same as protons, except at low energies due to the annihilation, and thus they trace the *average* proton spectrum in the Galaxy. If the directly measured local CR spectrum is not representative of the *local* Galactic average, the *antiproton measurements* can still be used instead to derive the intensity of CR *protons*.

When normalized to the local CR proton spectrum, the reacceleration model underproduces $\bar{p}$'s and diffuse γ-rays above 1 GeV by the *same* factor of $\sim$2 [18, 24] while it works well for other CR nuclei. It is thus enough to renormalize the CR proton spectrum up by a factor of 1.8 to remove the excesses; the model then predicts a factor of 2 too many photons at $\sim$100 MeV. The 100 MeV photons are produced mostly by $\sim$1 GeV protons where many uncertainties simultaneously come into play: poor knowledge of the π^0-production cross section at *low* energies and/or low-energy interstellar proton spectrum and/or solar modulation (see [27] for more discussion). To get agreement with the EGRET data effectively requires a corresponding adjustment of the spectrum of CR protons at low energies. Since the IC and π^0-decay photons have different distributions, the electron spectrum also needs to be renormalized up by a factor of 4 using the diffuse γ-ray flux itself. Thus, our "optimized" model is able to reproduce the spectrum of the diffuse γ-rays in *all directions* as well as the latitude and longitude profiles for the whole EGRET energy range 30 MeV – 50 GeV, and is consistent with our current understanding of CR variations in the Galaxy [19].

A logical extension of this analysis is a new determination of the extragalactic background [36], which is lower than previously thought due to the increased Galactic component, mostly IC. It has also a positive curvature as expected in blazar population studies and various scenarios of cosmological neutralino annihilation [37].

Dark Matter

The existence of non-luminous DM is now generally accepted by most of the astrophysical community though its nature is uncertain. The major division is between baryonic and non-baryonic DM with the preference given to the non-baryonic option over the last years. A number of particle DM candidates is discussed in the literature [38], where the most popular are the lightest supersymmetric neutralino χ^0 and a Kaluza-Klein hypercharge B^1 gauge boson. Annihilation of DM particles creates a soup of standard and supersymmetric constituents, which eventually decays to ordinary mesons, baryons, and leptons. The DM particles in the halo or at the Galactic center may thus be detectable via their annihilation products (e^+, $\bar{p}$, $\bar{d}$, γ-rays) in CR. The standard approach is to scan the SUSY parameter space [39] to find a candidate able to fill the excesses in diffuse γ-rays, and/or $\bar{p}$'s, and/or e^+'s over the predictions of a conventional model (as discussed in the previous sections). The diffuse γ-ray data are far richer than the CR particle data because γ-rays are coming from distant locations and different directions on the sky. The EGRET data used in a recent analysis [31] reveal a "perturbed" DM halo profile of the Milky Way possibly indicating galactic mergers in the past. Though very interesting, these results may only be taken as a hint which will require a lot of work to confirm. The DM search is one of the primary goals of the near-future space missions and the new CERN collider LHC.

CONCLUSION

There are essential lessons which we have learned from EGRET. The diffuse γ-ray flux is consistent with being produced mostly in energetic CR particle (p, He, $e^{\pm}$) interactions with interstellar gas and radiation fields. However, there is an excess above $\sim$1 GeV observed in all directions in the sky. Understanding the excess is important because it contains possibly new astrophysical information. The γ-ray data must be evaluated in conjunction with CR particle data because this may lead to better understanding of both CR and diffuse γ-rays.

The near future prospects are encouraging: several missions complementing each other are planned. The first one will be PAMELA to be launched in December of 2005 and designed to measure $\bar{p}$'s, $e^{\pm}$'s, and isotopes H–C over 0.1–300 GeV. Though its detector is small, it will provide enough exposure during its three-year mission. BESS-Polar instrument has had a successful test flight in Antarctica in winter 2004–05, and is planned to launch again in 2006 during the next solar minimum. It will provide accurate data on $\bar{p}$'s and light elements. The new γ-ray telescope, the GLAST mission, is scheduled for launch in the fall of 2007. It will be capable of measuring γ-rays in the range 20 MeV – 300 GeV with much better sensitivity and resolution than EGRET; studies of the diffuse emission is one of its primary goals. The AMS mission should make its flight to the International Space Station in 2008 and will measure CR particles and nuclei $Z \lesssim 26$ from GeV to TeV energies.

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