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Understanding limitations in the determination of the diffuse Galactic γ-ray emission

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We discuss uncertainties and possible sources of errors associated with the determination of the diffuse Galactic γ-ray emission using the EGRET data. Most of the issues will be relevant also in the GLAST era. The focus here is on issues that impact evaluation of dark matter annihilation signals against the diffuse γ-ray emission of the Milky Way.

1. INTRODUCTION

Diffuse emission (DE) from the Milky Way dominates the γ-ray sky. About 80% of the high-energy luminosity of the Milky Way comes from processes in the interstellar medium (ISM). The DE traces interactions of energetic particles, primarily protons and electrons, in the ISM, thus delivering information about cosmic-ray (CR) spectra in distant locations [1]. The DE may contain signatures of exotic physics, e.g., interactions of dark matter (see [1] for references). Calculation of the DE requires first calculating the CR spectra throughout the entire Galaxy [2]. The components of the DE model (π^0-decay, inverse Compton – IC, bremsstrahlung) are not independent and can not be arbitrarily re-scaled (e.g., as in [3]). The DE is the celestial foreground for the study of γ-ray point sources and the extragalactic DE which may contain information about the early universe.

A comparison between the EGRET data and the Galactic DE model used by the EGRET team reveals an "excess" above 1 GeV of approximately a factor of 2 in all sky directions [2,4,5]. Therefore, we need to look at the uncertainties associated with both the data and the model to understand the origin of this excess. In this paper, we consider the sources of systematic uncertainties in the EGRET calibration, data handling, and in models of the DE.

2. SOURCES OF UNCERTAINTIES

2.1. EGRET data analysis

EGRET was in orbit between April 1991 and June 2000, and operated for much longer than its 2-year design lifetime. Owing to ageing of the spark chamber gas and the limited number of gas changes possible during the mission, the best data taking occurred during the early years of operation. Details of pre- and in-flight calibrations are given in [6,7].

The data that we discuss here were taken during Cycles 1–4, the "prime" years of EGRET operation. These are the data that were used to produce the 3rd EGRET catalog of γ-ray point sources [8], and so for these data subtracting the (generally variable) point source contribution to the DE can be done accurately and correctly using the catalog fluxes. The overall exposure, accumulated during the individually pointed observations, is rather uneven [7].

The DE model used for the source detections was derived on the assumption that the CR proton and electron spectra do not change shape across the Galaxy, and that the CR density is proportional to the

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surface density of gas [4]. This leads to incorrect predictions at intermediate and high latitudes.

The calibration of an instrument in orbit is a complicated matter. Issues that cannot be controlled may affect the instrument performance, for example the launch vibrations and accelerations, while radiation exposure and unknown factors occur during the whole mission lifetime. Several failures occurred during EGRET's operational years: the spark chamber readout (switched to the redundant side), the gas circulation pumps, and some PMTs of the trigger telescopes. This complicates the analysis since the symmetry of the instrumental response was lost, and thus the direct comparison to the pre-flight calibration.

The efficiency of EGRET for registering reconstructable events from γ-ray detections decreased with time as the spark chamber gas aged. Several times during the mission the gas in the spark chamber was replenished to improve the degraded efficiency. Efficiencies were determined based on normalization to "standard candles" (pulsars) where possible, or by comparing to the DE predictions [7]. The individual EGRET viewing periods were corrected for the varying spark chamber performance under the assumption that the energy dependence of the correction did not vary with time [7]. This results in time-dependent systematic uncertainties.

Several other uncertainties also must be considered [7]: contribution of unresolved point sources; fisheye effect corrections for events under large viewing angles; contamination by Earth albedo events [9]; a direction-dependent PSF which results in residuals in source-subtracted DE maps; several orbital reboosts which changed the particle background of the detectors; plus, late in the mission, operation in different modes (narrow, strip) for which the instrument performance is less well understood.

After these considerations, any model of DE must be convolved with the instrumental PSF before comparison with the data. The effect is large below 1 GeV affecting the overall spectral shape. This is especially important for small areas on the sky. For comparisons with data obtained by a different instrument, a deconvolution of the data is preferred [2]: in this case the procedure is model-dependent since the predicted spectrum is convolved with the PSF first, and subsequently the appropriate factors are applied to the data.

The EGRET team made corrections for the described effects taking into account the limited statistics. The quoted error bars [7] are not separable into statistical and systematic parts (e.g., as in [3]) because of the implicit time dependence and interplay of the applied corrections.

2.2. CR propagation

The Galactic diffuse γ-ray emission is the product of particle interactions with gas in the ISM and the interstellar radiation field (ISRF). Therefore, its spectrum depends on the particle spectra throughout the entire Galaxy [1]. Diffusion, energy losses, and other processes change the particle spectra during propagation in the Galaxy over long time periods. Additionally, the CR isotopic composition changes. During propagation within the heliosphere, solar modulation further alters the particle spectra. These spectra are what can be measured directly using satellite- and balloon-borne instruments. To calculate the γ-ray emission we thus need to "reconstruct" the particle spectra in the ISM.

Gamma rays from π^0-decay are produced in the same processes as other secondaries such as antiprotons and positrons, which can also be used to test the models of the DE [2,10]. A realistic model of CR propagation has to include the gas and source distributions, ISRF, nuclear and particle cross sections and nuclear reaction network, γ-ray production processes, energy losses, and solve the transport equations for the individual CR species. The propagation parameters, the diffusion coefficient, halo size, Alfvén speed, convection velocity, and so on, which depend on the assumed propagation model, are derived by comparing model predictions with CR data, such as secondary/primary nuclei ratios, e.g. B/C, and radioactive isotope ratios like ^{10}Be/^{9}Be. Therefore, the accuracy of the nuclear cross sections is one of the major concerns for uncertainties in all subsequent analysis tasks.

Semi-empirical estimates of the nuclear cross sections [11,12] have been tuned to match the isotopic production cross sections between $\sim$400 and 700 MeV/n. They can not provide the same accuracy over the whole energy range which is required for CR propagation calculations. Furthermore, the cross sections often have resonances at energies below $\sim$200 MeV/n. These are particularly important for propagation models including diffusive reacceleration. This adds to the overall uncertainty in determination of the propagation parameters (e.g., see [13]).

The interpretation of the peak in the B/C ratio depends on the assumed propagation model. Different models predict different rigidity dependencies for the diffusion coefficient. Therefore, determination of the diffusion parameters is model-dependent. Two examples are the reacceleration [14] and convection [15] models. Reacceleration is a Fermi 2nd order acceleration in the ISM; it predicts a diffusion coefficient rigidity power-law index of 1/3. Convection is essentially a Galactic wind moving away from the Galactic plane which affects mostly particles below a few GeV; consistency with high-energy data requires a diffusion coefficient rigidity index of 0.6. A recently developed "damping" model includes CR particle – MHD wave interactions which lead to a concave shape in the diffusion coefficient, where the true rigidity dependence is derived via self-consistent modeling [16].

Above 1 GeV, π^0-decay and IC scattering are the dominant γ-ray production processes. The π^0-production cross section is based on data from the 1960s that themselves have large error bars. The proposed parameterizations ([17] and references therein) fit these data well, but they do not provide the required accuracy. New details are still being added, e.g. the diffraction dissociation and violation of the Feynman scaling [18], while various Monte Carlo event generators produce results which differ by $\sim$20–30% [19]. The IC scattering contribution is dependent on the underlying model of the ISRF, and the treatment of the scattering process using the proper ISRF angular distribution [20]. Conventionally, the ISRF is assumed to be isotropic, which is only true for the cosmic microwave background. Using the full angular distribution for the ISRF will alter the model predictions [20].

The random nature of CR sources leads to fluctuations of CR intensity in space and time. Very high energy (VHE) electrons cannot propagate far from their sources due to rapid energy losses. Their interstellar spectrum is expected to exhibit imprints from their nearby sources [21].

Finally, "solar modulation" changes the interstellar spectra of CR particles below $\sim$20 GeV/n during their propagation within the heliosphere. It is a combination of the effects of convection by the solar wind, diffusion, adiabatic cooling, drifts, and diffusive acceleration. The theory of solar modulation is far from complete [22]; current models are based on the solution of Parker's transport equation. The unknown is the interplay of the different terms and the CR spectrum in the ISM. Spherically symmetric solutions, the force-field [23], and Fisk [24] approximations are most often used. However, they include only the effect of adiabatic losses. The Pioneer, Voyager[3], and Ulysses missions contributed to understanding the global aspects of modulation.

2.3. Astrophysical input

Most of the interstellar gas is in the form of neutral hydrogen H I and H_2. The H_2 gas is not observed directly but via the mm-wave spectral line of a rotational transition of CO. A proportionality is assumed between CO surface brightness and H_2 column density. H I gas is detected by its 21 cm line. Determinations of H I column densities rely on difficult-to-verify assumptions about the spin temperature of the gas, and in many directions colder H I gas is seen in absorption against warmer background gas, making overall distributions of H I difficult to disentangle. The spatial distribution of the gas is derived using velocity measurements and assuming a rotation curve for the Milky Way. However, streaming motions and velocity dispersions between individual gas clouds introduce systematic uncertainties. In the outer Galaxy the gradient of velocity approaches zero at large distances. In the inner Galaxy the "kinematic distance" is double valued except toward the Galactic center and anticenter, where the line-of-sight velocities provide no useful kinematic information. Therefore, no unique solution exists for the 3D distribution of gas. Studies starting with the same data produced gas distributions which are different in many details [4,26].

The CR source distribution is also not very well known. The pulsar distribution [27] is too peaked to reproduce the CR gradient in the Galaxy. Consistency with the latter requires the X-factors (essentially H_2/CO ratio) to increase with the distance from the Galactic center [28]. Such behavior indeed is observed in other galaxies [29].

The ISRF modeling incorporates a stellar distribution model, a model for the dust distribution and properties, and a treatment of scattering, absorption, and subsequent re-emission of the stellar light by the dust

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[3] The Voyager 1 spacecraft is currently approaching the outer boundary of the solar system [25].

[30]. The stellar emission model incorporates details for the distribution of stellar types in discrete geometrical components (bulge, disc, spiral arms, etc.), adjusted to agree with results from experiments such as 2MASS, SDSS, and others. Dust is modeled with a mixture of PAH, graphite, and silicate. Details of the dust absorption and scattering efficiencies, abundances, and size distribution are included in the scattering and heating calculations. The dust is assumed to follow the Galactic gas distribution and metallicity gradient. Uncertainties in each of these inputs contribute to the overall uncertainty in the ISRF modeling. The model can be compared with the ISRF only at the solar system position. The deviations from an earlier model [5,31] give an idea of possible systematic errors.

3. DISCUSSION AND CONCLUSION

We discussed only the most obvious sources of uncertainties; the systematic effects are numerous, but not all of them are equally important. Considering the many sources of uncertainties, the agreement between the predictions of conventional DE models with the EGRET data is remarkable: the discrepancy is only a factor of two at worst; this is the famous "GeV excess." With some reasonable assumptions, such as CR intensity fluctuations, agreement with the data can be obtained in the framework of conventional astrophysics [2].

The Gamma Ray Large Area Space Telescope (GLAST), to be launched in 2007, will have improved sensitivity, angular resolution, a wider field of view, and uses a different technology [32] than EGRET. Therefore, many of the instrumental uncertainties associated with EGRET will become irrelevant. However, issues associated with CR propagation, gas distribution, and other astrophysical input will remain waiting for the next generation of instruments.

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