Diffuse Galactic Continuum Gamma Rays

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Abstract. Galactic diffuse continuum γ-ray emission is intricately related to cosmic-ray physics and radio astronomy. We describe recent results from an approach which endeavours to take advantage of this. Information from cosmic-ray composition constrains the propagation of cosmic rays; this in turn can be used as input for γ-ray models. The GeV γ-ray excess cannot be explained as π^o-decay resulting from a hard nucleon spectrum without violating antiproton and positron data; the best explanation at present appears to be inverse-Compton emission from a hard interstellar electron spectrum. One consequence is an increased importance of Galactic inverse Compton for estimates of the extragalactic background. At low energies, an additional point-source component of γ-rays seems to be necessary.

I INTRODUCTION

This paper discusses recent studies of the diffuse continuum emission and their connection with cosmic-ray physics. The basic question concerns the origin of the intense continuum emission along the Galactic plane observed by EGRET, COMPTEL and OSSE. The answer is surprisingly uncertain. A comprehensive review can be found in [1]. The present work uses observational results given in [2–4]; new imaging and spectral results from COMPTEL are reported in [5]. Most of the analysis reported here is based on the modelling approach described in [6,7]. First we present some results from cosmic-ray isotopic composition which bear directly on the γ-ray models. We then discuss the problems which arise when trying to fit the γ-ray spectrum, and present possible solutions, both at high and low energies. The low energy (1–30 MeV) situation is addressed in more detail in [8], and additional references can be found at [9].

Our basic approach is to construct a unified model which is as far as possible realistic, using information on the gas and radiation fields in the Galaxy, and current ideas on cosmic-ray propagation, including possible reacceleration; we use these to predict many different types of observations: direct measurements in the heliosphere of cosmic ray nuclear isotopes, antiprotons, positrons, electrons; and astronomical measurements of γ-rays and synchrotron radiation. Any given model has to be tested against all of these data and it is a challenge to find even one which is consistent with all observations. In fact we will show that the full range of observations can only be accomodated by additional components such as γ-ray point sources and also differences between local direct measurements and large-scale Galactic properties of cosmic rays.

II COSMIC RAY NUCLEONS

First we show results from CR composition which are relevant to the propagation of cosmic rays. For a given halo size (defined here as the z value at which the cosmic-ray density goes essentially to zero) the parameters of the diffusion/reacceleration model can be adjusted to fit the important secondary/primary ratios, illustrated in Fig 1 for a halo size of 4 kpc. In addition we can use the constraints on the halo size given by the radioactive CR species ^{10}Be and ^{26}Al, Fig 2. For details of Ulysses results on radioactive nuclei see [10–13]. Based on Ulysses ^{10}Be data, a range for the halo height of 4–10 kpc was derived in [6,14]. This is consistent with other analyses [15,16]. New results from the Advanced Composition Explorer satellite (ACE) will constrain the halo size better, but the above range is consistent with ACE results as presented in [17]. Other radioactive nuclei (^{36}Cl and ^{54}Mn) will provide further independent information; at present one can only say that they are consistent with the other nuclei. Having obtained sets of propagation parameters based on isotopic composition, we can proceed to use the model to study diffuse γ-rays.

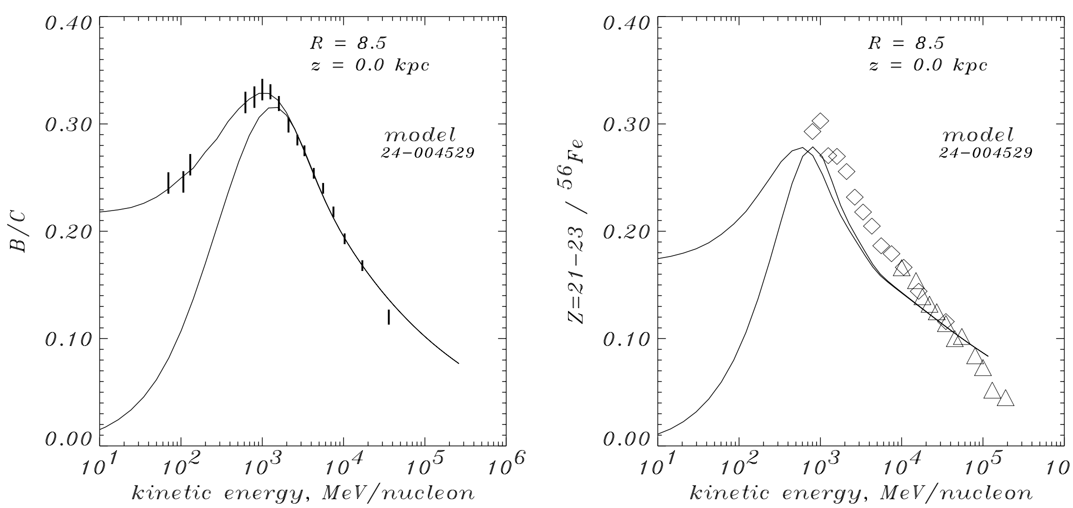

FIGURE 1. Cosmic-ray B/C and sub-Fe/Fe ratios for a diffusive halo model with reacceleration, halo height 4 kpc. For details of model and data see [14].

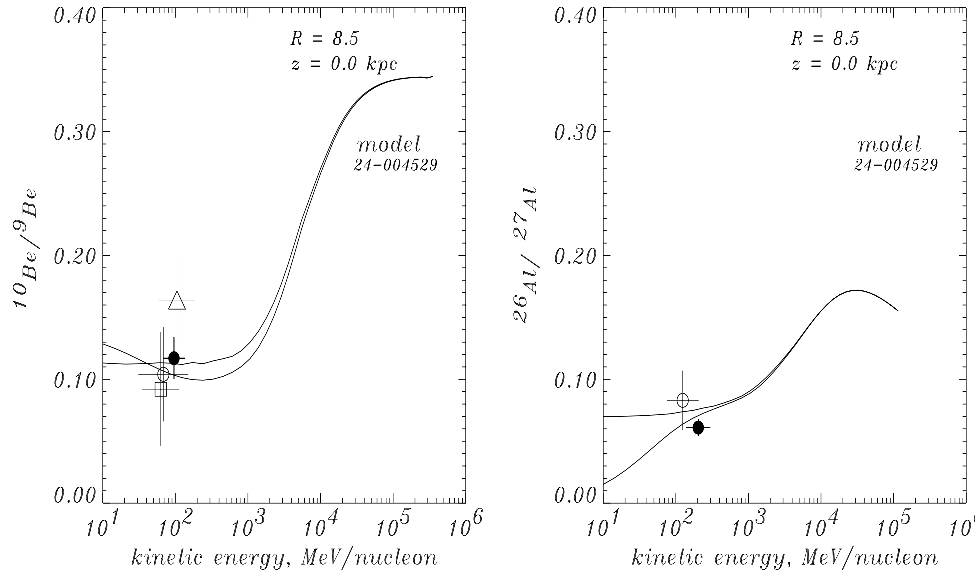

FIGURE 2. Cosmic-ray ^{10}Be/^{9}Be and ^{26}Al/ ^{27}Al ratio for the same model as used for Fig 1. For details of model and data see [14].

III GAMMA RAYS

Figure 3 shows the diffuse spectrum of the inner Galaxy for what we call a 'normal' or 'conventional' CR spectrum which is consistent with direct measurements of high energy electrons and synchrotron spectral indices (Figs 5, 6; see [7,8]). Clearly this model does not fit the γ-ray data at all well.

Consider first the well known problem of the high energy ($>$ 1 GeV) EGRET excess [18]. One obvious solution is to invoke π^o-decay from a harder nucleon spectrum than observed in the heliosphere, which might for example be the case if the local nucleon spectrum were dominated by a local source which is not typical of the large-scale average. Then the local measurements would give essentially no information on the Galactic-scale spectrum. One can indeed fit the EGRET excess if the Galactic proton (and Helium) spectrum is harder than measured by about 0.3 in the index (Fig 3).

But there are two critical tests of this hypothesis provided by secondary antiprotons and positrons. It was shown in [19] that such a hard nucleon spectrum produces too many antiprotons. The new MASS91 measurements [20], which give the absolute antiproton spectrum from 3.7 to 24 GeV, have clinched this test, as shown in Fig 4. Quite independently, secondary positrons give a similar test, which the hard nucleon hypothesis equally fails (Fig 4). Again new data, this time from the HEAT experiment [21], give a good basis for this test. We conclude that there are significant problems if one wants to explain the GeV excess with π^o-decay. This illustrates the importance of considering all the observable consequences of any model. Of course it is anyway difficult to imagine such spectral variations of nucleons given the large diffusion region and isotropy of CR nucleons.

An alternative idea, first investigated in detail in [22], is inverse Compton (IC) from a hard electron spectrum. The point is that the electron spectrum we measure locally may not be representative of the large-scale Galactic spectrum due to the large spatial fluctuations which arise because of the large energy losses at high energies. What is measured directly may therefore depend only on the chance locations of the nearest electron sources, and the average interstellar spectrum could

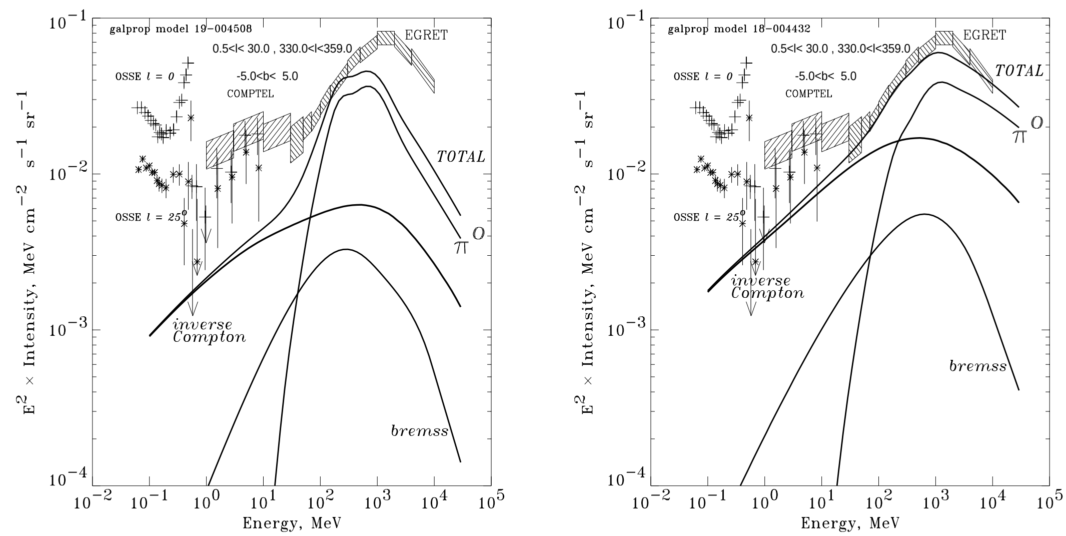

FIGURE 3. Gamma-ray spectrum of inner Galaxy for (left) 'conventional' CR spectra; (right) hard nucleon spectrum. Data: OSSE [4], COMPTEL [2], EGRET [3].

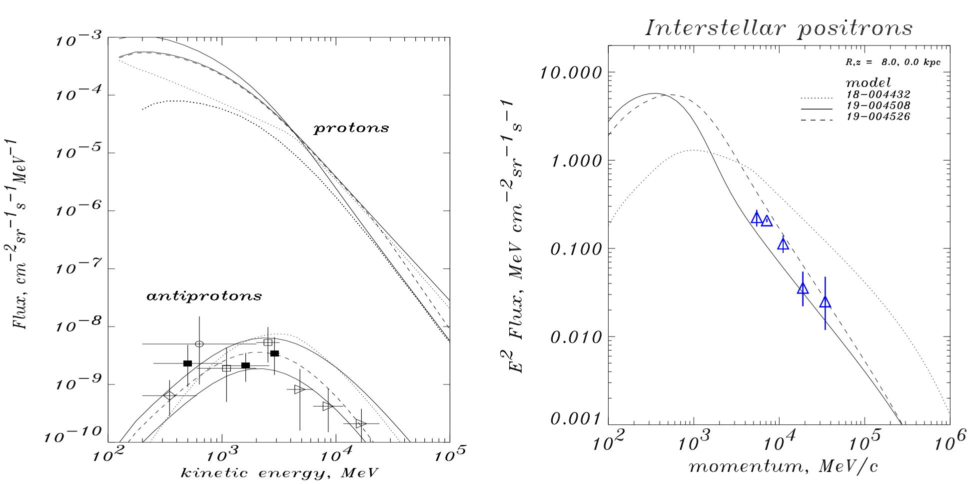

FIGURE 4. Secondary antiproton (left) and positron spectra (right) for a hard nucleon spectrum. Data: antiprotons [20], positrons [21].

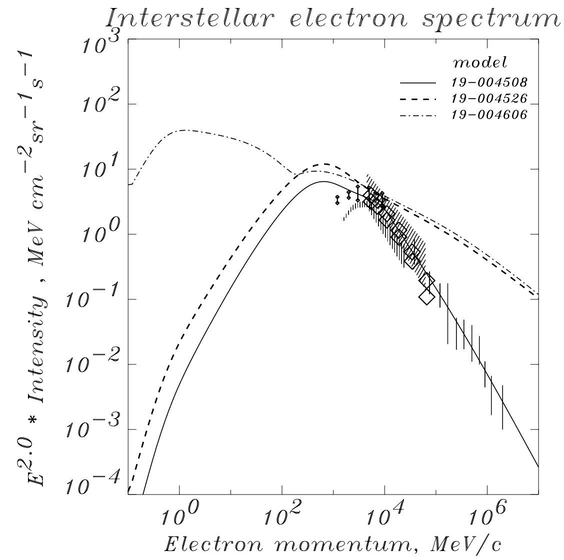

FIGURE 5. Electron spectra observed locally and for various models. Solid line: 'conventional' model, dashed line: injection spectrum 1.8, dash-dot line: spectrum reproducing low-energy γ-rays. For data see [7].

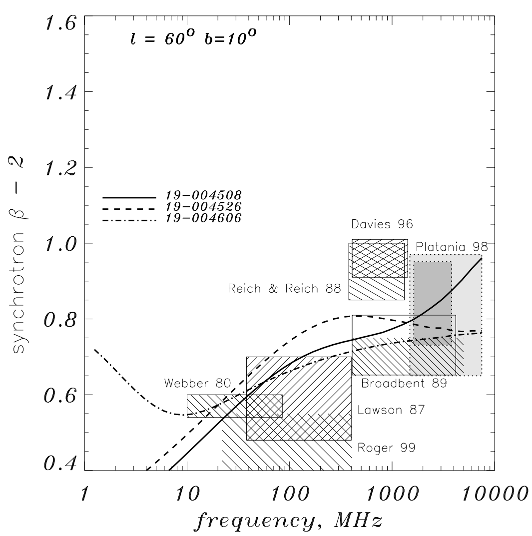

FIGURE 6. Synchrotron index for various electron spectra as in Fig 5. For data see [7,8].

be very different, in particular it could be much harder. An injection spectral index around 1.8 is required (Fig 5) and the corresponding γ-ray spectrum is shown in Fig 7. Note that modern theories of SNR shock acceleration can give hard electron injection spectra [23] so such a behaviour is not entirely unexpected.

To predict reliably the IC emission, we also need an updated model for the interstellar radiation field; we have recomputed it [7] using new information from IRAS, COBE, and stellar population models. There is still much scope for further improvement in the ISRF calculations however.

Note that for these hard electron spectra IC dominates above 1 GeV, and is everywhere a very significant contributor, while bremsstrahlung is relegated to third position in contrast to the more conventional picture (presented e.g. in [24]). Even if we can fit the inner Galaxy spectrum, the critical test is the spatial distribution: from Fig 8 one can see that it can indeed reproduce the longitude and latitude profiles. In fact it can reproduce latitude profile up to the Galactic pole (Fig 9) which is not the case for models with less IC. This can be seen as one proof of the importance of IC. But there is at least one problem associated with the hard electron spectrum hypothesis. A recent reanalysis of the full EGRET data for the Orion molecular clouds [25] determined the γ-ray emissivity of the gas, and this also shows the GeV excess, which would not expected since it should not involve IC. This could be a critical test. Perhaps the increased radiation field in the Orion star-forming region could boost the IC, and this ought to be investigated in detail.

An earlier analysis correlating EGRET high-latitude γ-rays with 408 MHz survey data [26] found evidence for IC with an $E^{-1.88}$ spectrum. This is very much in accord with the present models. More recently a study [27] which used a wavelet analysis to look for deviations from the Hunter et al. [18] model provided evidence for a γ-ray halo with a form similar to that expected from IC.

An effect which may be important at high latitudes is the enhancement due to the anisotropy of the ISRF and the fact that an observer in the plane sees preferentially downward-travelling electrons due to the kinematics of IC [28]. This can enhance the flux by as much as 40% for a large halo. Even in the plane it can have a significant effect. Note that the halo sizes considered here imply an increased contribution from Galactic emission at high latitudes, which will affect determinations of the isotropic extragalactic emission. More precise evaluation of these implications is in progress.

We mention finally low energies, for which a detailed account is given in [7,8]. Conventionally one invoked a soft electron injection, $E^{-2.1}$ or steeper, and this could then explain the 1–30 MeV emission as the sum of bremsstrahlung and IC. However it seems impossible to find an electron spectrum which reproduces the γ-rays without violating the synchrotron constraints, unless there is a very sharp upturn below 200 MeV; but even there it fails at to give the intensities measured by OSSE below 1 MeV. Therefore a source contribution appears to be the most likely explanation.

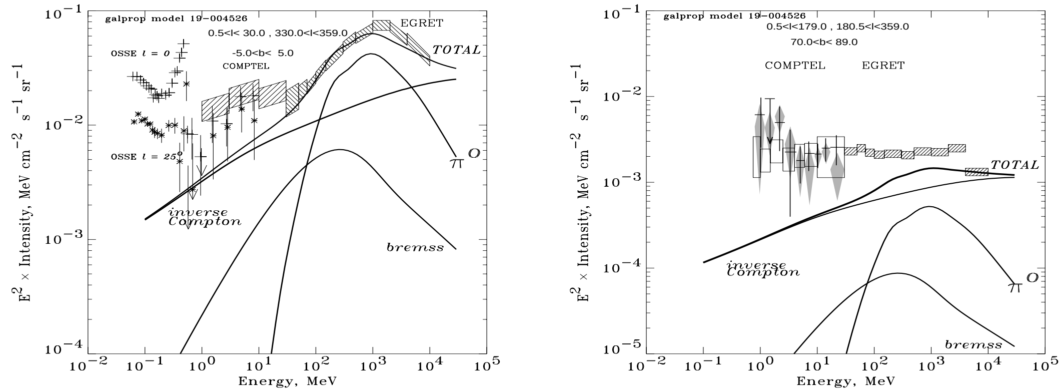

FIGURE 7. Gamma-ray spectrum for a hard electron injection spectrum. Left: inner Galaxy ; Right: high latitudes. Data as Fig 3.

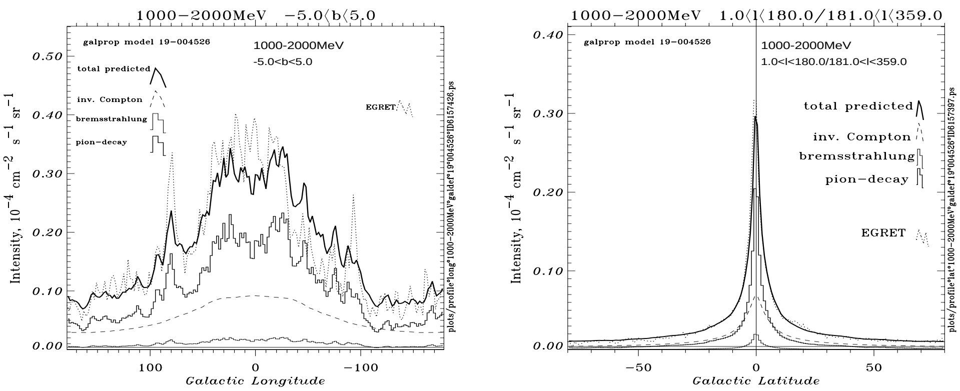

FIGURE 8. Gamma-ray profiles in the energy range 1–2 GeV for a model with a hard electron spectrum [7]. Dotted line: EGRET data, dashed line: inverse Compton, upper histogram: π^o-decay, lower histogram: bremsstrahlung, upper solid line: sum of components. Left: longitude profile, right: latitude profile.

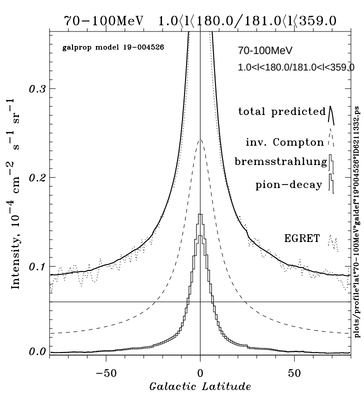

FIGURE 9. Gamma-ray profile at high latitudes, for the energy range 70–100 MeV [7]. Components as Fig 8; horizontal line: isotropic background.

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