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Diffuse Galactic hard X-ray and low-energy gamma-ray continuum

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Abstract.
We summarize some recent results related to observations and interpretation of hard X-ray and low-energy γ-ray diffuse Galactic continuum emission. Combined spectra based on data from OSSE, COMPTEL and EGRET are presented. In the energy range 1-30 MeV covered by COMPTEL the spectrum of the diffuse emission has been measured and is consistent with a combination of bremsstrahlung and inverse-Compton emission; spatial analysis shows strong evidence for a component with a wide latitude extent which is plausibly identified with inverse-Compton. Molecular hydrogen appears to be only a weak γ-ray emitter at low energies, which may indicate reduced MeV cosmic-ray electron density in molecular clouds. New data on the hard X-ray diffuse Galactic emission from OSSE indicates the need for a dramatic low-energy upturn in the electron spectrum, or for some other additional component of γ-ray emission.

The interstellar electron spectrum has been computed using a diffusive halo model and the resulting bremsstrahlung and inverse-Compton emission is compared with the observations.

Key words: gamma rays: general; cosmic rays; interstellar medium :clouds: general; interstellar medium :general

1. Introduction

This paper summarizes some recent results related to observations and interpretation of low-energy diffuse Galactic continuum γ-rays . One of the primary goals of the Compton Gamma Ray Observatory is to obtain information on the origin and propagation of cosmic rays in the Galaxy, supplementing the knowledge gained from direct measurements in the Solar vicinity. As valuable by-products we obtain also constraints on the gaseous interstellar medium, and construct models for the diffuse Galactic emission which provide a 'background' against which the search for discrete sources can be performed. Reviews of diffuse emission including some Compton Observatory results are in Bloemen (1993) and Strong (1994). One aim of this paper is to present spectra based on the combination of results from OSSE, COMPTEL and EGRET, analysing the data in a consistent way to ensure that they refer to the same region of sky or to the same diffuse emission model. This is a difficult task, and the results presented here are just a first step in this direction.

The modelling of the diffuse emission is essential to the interpretation of the results, and some recent model predictions are presented and compared with the observations.

2. Energy range 50 keV - 1 MeV

In the hard X-ray range pre-Compton Observatory measurements are available from HEAO-1 (Peterson et al. 1990) and GRIS (Gehrels and Tueller 1992); a study using the tertiary optics of the SIGMA coded mask telescope (Claret et al. 1995) has also provided useful information. Recently first results on diffuse continuum have been reported by the Compton/OSSE team (Purcell et al., this conference; Kurfess 1995, Purcell et al. 1995) for the Galactic centre region and l=20^o -30^o . They find a rather steep spectrum (photon index -2.3), a wide latitude extent (5.5^o full-width at half maximum), and quite similar continuum intensities for the two regions. Skibo et al. (1995) suggest that a sharp upturn in the electron spectrum below 1 MeV and the accompanying bremsstrahlung emission may be a plausible explanation (see also Section 6). However a population of unresolved γ-ray point sources is also a possibility. In any case it is hard to explain such a spectrum purely in terms of other diffuse processes such as inverse-Compton emission, although the latter will certainly make a significant contribution (see Sec. 5) and may help to give the observed wide latitude distribution.

The intensity spectrum for this energy range from these experiments is included in the wide-band spectra shown in Fig 4 and discussed in Sections 4 and 6.

3. Energy range 1-30 MeV: COMPTEL Analysis

The COMPTEL instrument on the Compton Observatory has sufficient imaging capability to allow a sensitive measurement of the diffuse radiation. Fig 1 shows full-sky images of the MeV gamma-ray sky from COMPTEL Phase 1+2+3 data, made with the maximum-entropy method (Strong 1995, Schönfelder et al. 1995). The Galactic plane stands out clearly in all energy ranges, indicating that we are detecting large-scale emission from the Galaxy. The bulk of the emission in these images is unresolved, presumably diffuse (see discussion below); point sources visible include the Crab, Cyg X-1, 3C273, 2GC135+1 and Cen A. Apart from the Crab these detected sources make only a small contribution to the total flux.

The diffuse continuum γ-ray emission from the Galactic plane at MeV energies is believed to originate in interactions of cosmic-ray electrons with interstellar gas via bremsstrahlung and with the interstellar radiation field via inverse-Compton scattering.

An analysis of the diffuse continuum was performed on the COMPTEL Phase 1 Sky Survey (Strong et al. 1994). This original analysis used a model based on the gaseous interstellar medium only and made fits to a combination of HI and CO surveys. The new analysis (Strong et al. 1995) includes an inverse-Compton component in the model, uses data from Phases 1, 2 and 3, and covers the entire sky. A basic result is that the Galactic emission is detected with high significance; out of a total dataset containing about 20 million events about one million are attributed to the Galaxy, making it by far the strongest source of COMPTEL γ-rays . The majority of the remaining events are instrumental background.

It was found that the inclusion of a model for the inverse-Compton component (see Section 5) improves the fits very significantly in each energy range; this demonstrates at least the presence of a component with a broader latitude distribution than the gas; whether it is indeed inverse-Compton or some other broad emission (for example related to local Galactic structure) cannot yet be finally decided on the basis of the presently available evidence. The fitted inverse-Compton component is however quite close to the theoretical expectation.

The latitude profile of the 1-3 MeV intensity of the model components in the inner Galaxy is illustrated in Fig 2, showing the different latitude widths of the emission from gas and inverse-Compton; the latter dominates for $|b| > 5^o$.

Fig 3 shows the emissivity spectrum of the gas-related component from this work; the values are somewhat smaller than in Strong et al. (1994) owing to the inclusion of inverse-Compton which now accounts for some of the emission. Fig 4 shows the intensity spectrum for the inner Galaxy, $300^o < l < 60^o$,

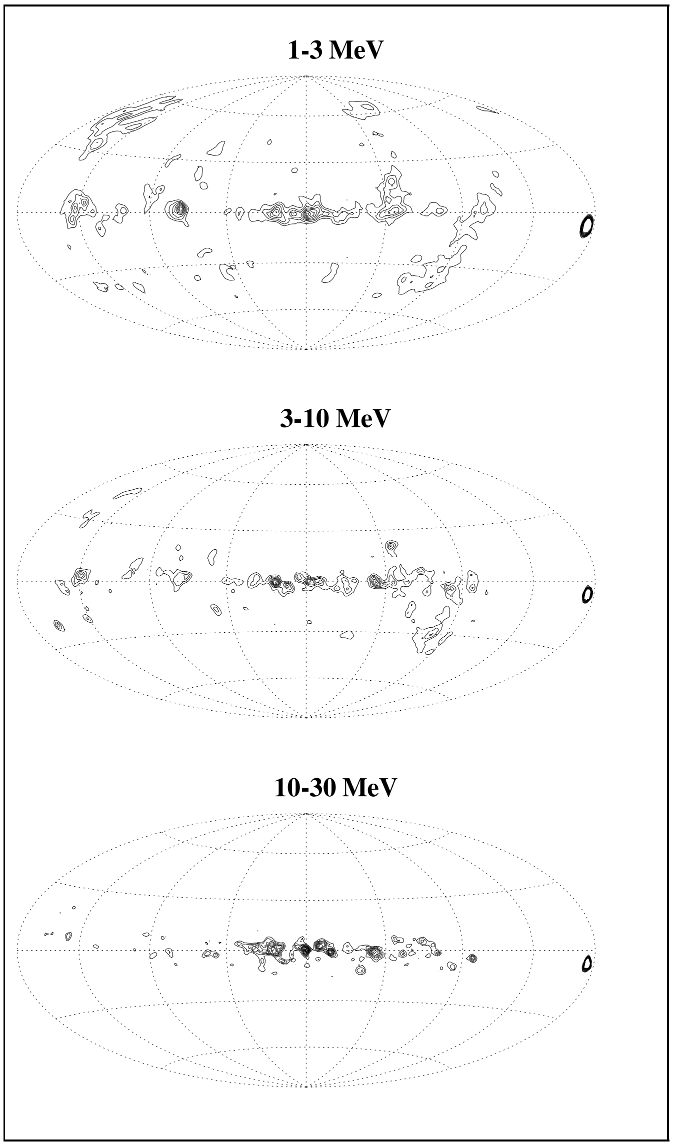

Fig. 1. Maximum-entropy images of the whole sky in the 1-3, 3-10 and 10-30 MeV ranges based on Phase 1+2+3 data (from Strong 1995, Schönfelder et al. 1995). Coordinates are Galactic centered on l=0, b=0.

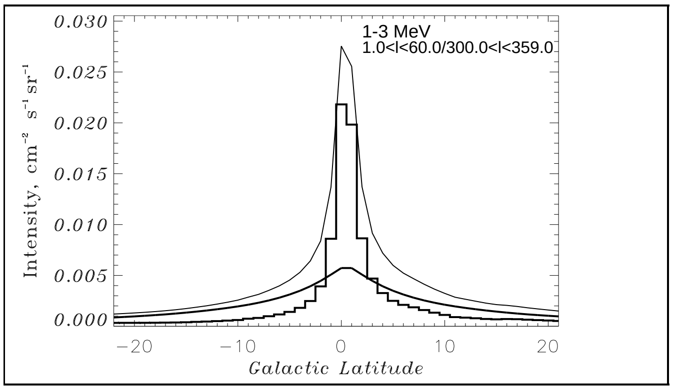

Fig. 2. Latitude profile of 1-3 MeV intensity in the inner Galaxy ($300^o < l < 60^o$) corresponding to the model fit to the COMPTEL data. The components are: bremsstrahlung (histogram), inverse-Compton (lower curve), total (upper curve). From Strong et al. (1995).

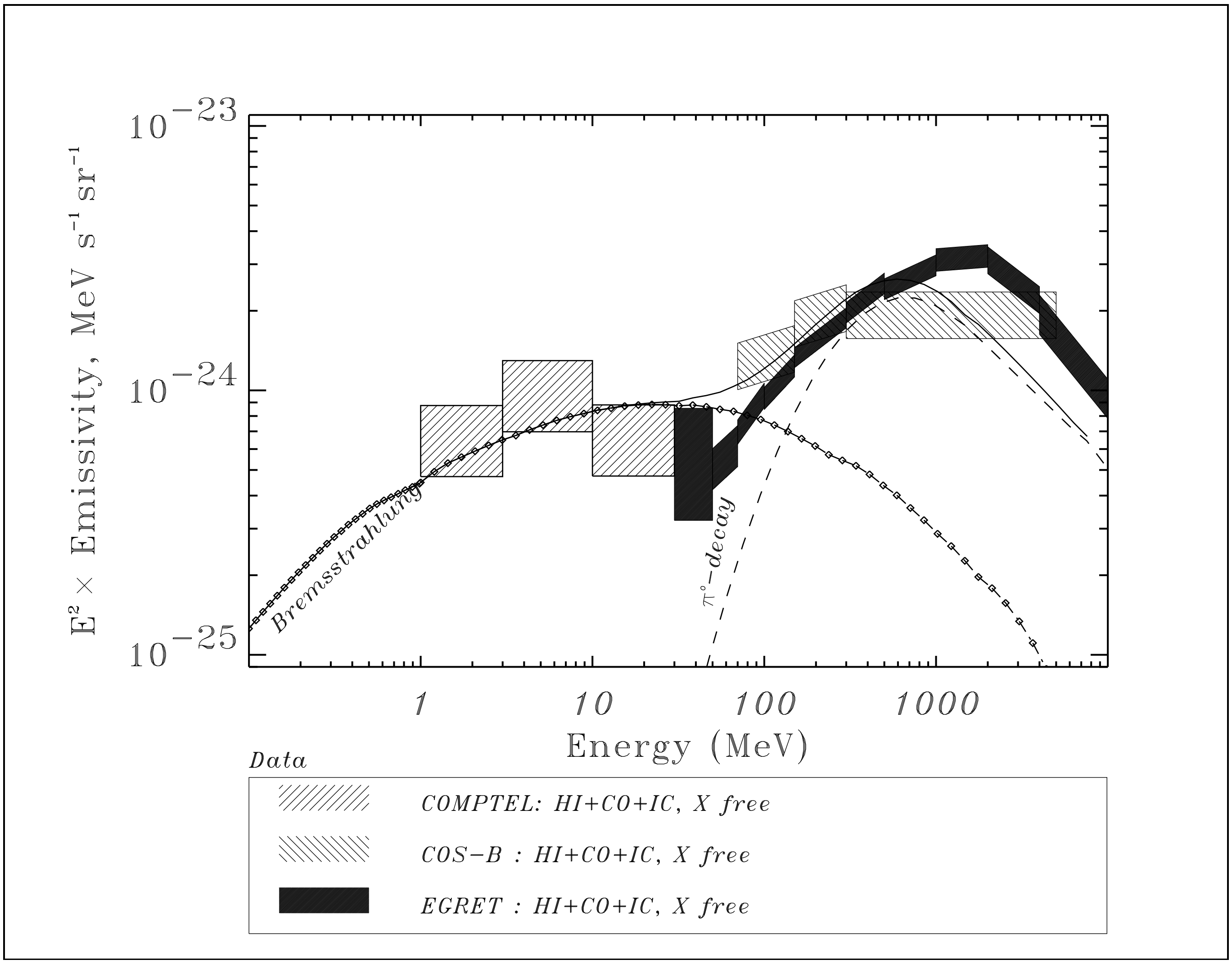

Fig. 3. Emissivity spectrum (per gas atom) of the diffuse Galactic continuum radiation, based on data from COMPTEL, EGRET and COS-B. The COMPTEL spectra are shown for fits to HI, CO and inverse Compton with X_γ free. The COS-B spectrum is based on fits to the same gas model. The EGRET spectrum is from a fit to Phase 1+2 data, again using the same gas model (Strong and Mattox 1996). The local emissivity for 8 kpc $<$R$<$12 kpc is plotted. A theoretical synthesis of the spectrum from bremsstrahlung and π^o-decay components is also shown. Note that this figure refers only to emission from the gas-related component, so that inverse Compton is not plotted.

$|b| < 20^o$, obtained by summing the components of the model fits to the COMPTEL data.

Another result for the 1-30 MeV range which comes from the COMPTEL analysis is a low value of the *apparent* CO-to-H_2 conversion factor X_γ ; the signal associated with CO appears to be very weak. The obvious implication is a reduction in the bremsstrahlung due to a lack of low energy cosmic electrons inside the molecular clouds. Possible physical processes for this have been proposed (Skilling and Strong 1976, Strong and Skilling 1977, Morfill 1982).

It must be emphasized that we have no *proof* that the emission is truly diffuse, and indeed a significant point-source contribution could be present, especially at low energies. In this sense the spectra should strictly be regarded as upper limits only; but note that this remark also applies to all diffuse radiation studies. An argument which could be made against the present interpretation is the apparent clumpiness of the images; this may be partly instrumental but it suggests a more patchy, perhaps local, origin for at least some of the emission (see Bloemen et al. 1994). Such clumpiness would not be expected on the basis of simple cosmic-ray/gas/interstellar radiation field interaction models, but could nevertheless be understood in the same context on the basis of the rapid energy losses of low-energy electrons which implies that they may not propagate far from their sources and thus tend to reflect the uneven distribution of cosmic-ray sources in the Galaxy.

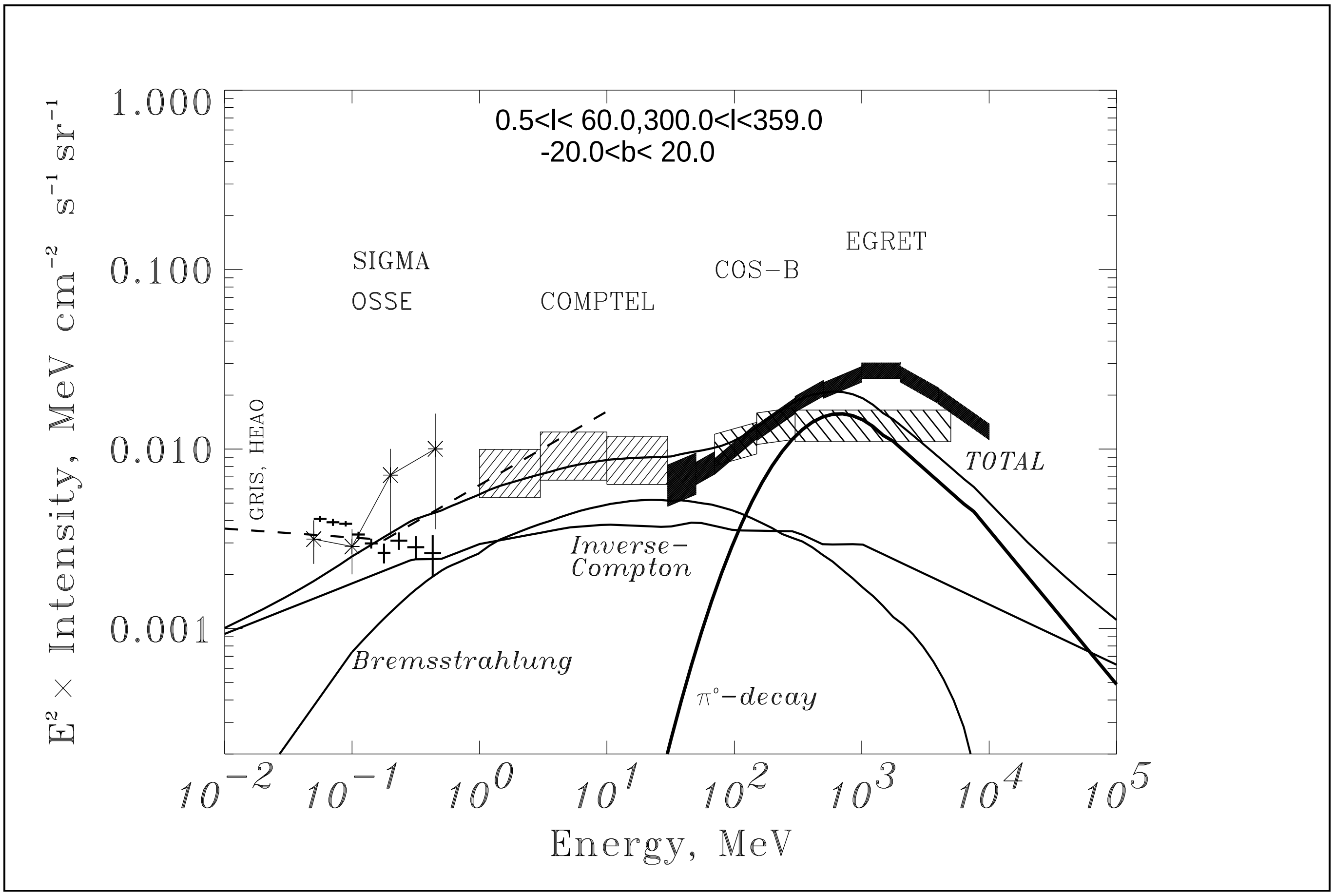

Fig. 4. Intensity spectrum of the inner Galaxy $300^o < l < 60^o$, integrated over $|b| < 20^o$. Narrow spaced shaded: COMPTEL; broad spaced shaded : COS-B (Strong et al. 1988); filled boxes: EGRET (Strong and Mattox 1996); + : OSSE. The OSSE spectrum was taken at $20^o < l < 30^o$ but the continuum spectrum is very similar to that for the Galactic centre (apart from the much reduced annihiliation emission) (Purcell et al. 1995). The dashed line is the summary spectrum based on HEAO-1 and GRIS data by Gehrels and Tueller (1992). SIGMA results for the region around l=315^o (Claret et al. 1995) are also indicated (stars). A theoretical synthesis of the spectrum from bremsstrahlung, inverse-Compton and π^o-decay components is shown.

4. Wide-band spectra of the diffuse emission

By combining the results of various experiments we can construct emissivity and intensity spectra covering a wide-band γ-ray range. In particular since the same fitting procedure was applied to COMPTEL and COS-B (Strong et al. 1988) and most recently, EGRET data, we can reliably combine the results from these instruments, and the resulting emissivity spectrum (Fig 3) should be dependable over the range 1 MeV to 10 GeV. The EGRET analysis (Strong and Mattox 1996) shown here is based on Phase 1+2 public data fitted to the same gradient model as used for COS-B.

The *emissivity* spectrum separates out that part of the emission attributable to cosmic-ray/gas interactions. In order to include also the inverse-Compton component an *intensity* spectrum is more appropriate (Fig 4). The intensities were computed by averaging the sum of the fitted components over $300^o < l < 60^o$ and integrating over $|b| < 20^o$. The OSSE points are based on fitting the *same* diffuse model to OSSE data using the instrumental response; hence these data are treated in a way consistent with the others. The OSSE data used here refer to $20^o < l < 30^o$ but the continuum spectrum is very similar to that for the Galactic centre and the longitude variation of intensity is small (Purcell et al. 1995) so that combination of the spectra is justified.

The extension to lower energies using the OSSE data is satisfactory although there is an indication for a possible normalization problem around 1 MeV (about a factor 2) between the OSSE and COMPTEL spectra, perhaps due to the fact that OSSE makes on/off measurements which may not be sensitive to broader components of the emission.

For other hard X-ray results the combination of the spectra is more problematic since the analyses do not refer to such well-defined sky regions and so there is some normalization uncertainty in such a combined spectrum; with this caveat the

SIGMA results and the Gehrels and Tueller (1992) summary of HEAO-1 and GRIS results are also shown on the same plot.

5. Cosmic-ray electrons in the Galaxy

Strong and Youssefi (1995) developed a numerical code for diffusive cosmic-ray propagation of nucleons and electrons with full spatial and energy dependence. This enables us to compute the spectrum over the Galaxy for quite general models based on realistic distributions of cosmic-ray sources, matter and radiation fields. The model is first tuned to give consistency with secondary/primary nucleon data; it is then used to compute the electron spectrum and finally γ-ray intensities from bremsstrahlung and inverse-Compton emission.

Several different processes are involved including diffusion and spatially varying energy losses; our Galaxy model has properties derived from observational data on gas and radiation distributions and uses plausible cosmic-ray source distributions. An important feature of our approach is the inclusion of cosmic-ray nucleons and electrons in the same model, which ensures consistent treatment of the two components. The energy loss term includes the (spatially dependent) effects of ionization, bremsstrahlung, synchrotron and inverse-Compton losses. We impose the boundary condition $\psi(-z_h) = \psi(z_h) = 0$ for 'halo' height z_h. The electron injection spectrum is assumed to be a power-law with index -2.4, based on radio data (Webber 1983).

The distribution of cosmic-ray *sources* is assumed to follow one particular estimate of the SNR distribution (Kodaira 1974); the uncertainty in this distribution is one of the main problems for such predictions. For inverse-Compton losses the radiation field is based on our calculation (Youssefi and Strong 1991), including optical, far-infrared and 2.7K components; for synchrotron losses the magnetic field is taken as 6 $e^{-z/5kpc}\mu$G. A halo scale height of 3 kpc (Webber et al. 1992; Bloemen et al. 1993; Lukasiak et al. 1994) and a diffusion coefficient D= 2.5 10^{28} cm^2 s^{-1} for rigidities $\varrho < 3$GV and increasing as $\varrho^{0.6}$ above 3GV, were used, chosen to be consistent with the cosmic-ray B/C ratio and ^{10}Be data.

Fig 5 shows sample electron distributions in Galactic (R,z) for energies 1 MeV, 1 GeV and 100 GeV. At low energies the effect of energy losses forces the distribution in R to follow closely the sources; at higher energies the distribution is broader, and eventually the inverse-Compton and synchrotron losses curtail the distribution at large distances.

Fig 6 compares the modelled electron spectrum (R=8.5 kpc, z=0) with direct measurements and estimates based on radio and COS-B gamma-rays. The agreement is satisfactory up to 100 GeV, although at high energies the observations indicate a slightly steeper spectrum which could imply that a larger halo or a different rigidity-dependence of the diffusion coefficient is required. The constraints on electrons with E< 100 MeV from γ-rays are also reasonably well satisfied (Fig 3,4).

We use the model to compute the γ-ray intensity distribution from bremsstrahlung and inverse-Compton interactions. The interstellar radiation field calculation for inverse-Compton is the same as used for the energy loss calculation. Fig 7 shows a sample set of inverse-Compton longitude profiles for various latitudes for the energy interval 1-3 MeV. It should be emphasized that the interstellar radiation field is uncertain, particularly in the optical where the input luminosity is uncertain by a factor 2, and the absorption calculation very approximate (see Youssefi and Strong 1991, Chi and Wolfendale 1991). The FIR is less uncertain since we have the IRAS data which can be unfolded to give the spatial distribution of the FIR emissivity (Bloemen et al. 1990). The electron z-distribution is of course also unknown due to the uncertain size of the halo. So the inverse-Compton emission is *a priori* uncertain by at least a factor 2 and it is a challenge to determine better its properties on the basis of γ-ray data.

6. Comparison of theoretical γ-ray emission with observations

We consider first the emissivity spectrum (Fig 3). The π^o-decay spectrum is fairly well known; our π^o emissivity uses the analytical representation of the Stecker (1988) computation given in Bertsch et al. (1994). The main remaining uncertainty is the electron spectrum. Direct measurements of electrons are reliable only above a few GeV due to solar modulation; using radio (synchrotron) data an extrapolation back to about 300 MeV is possible. Below this energy the γ-rays themselves are our main source of information.

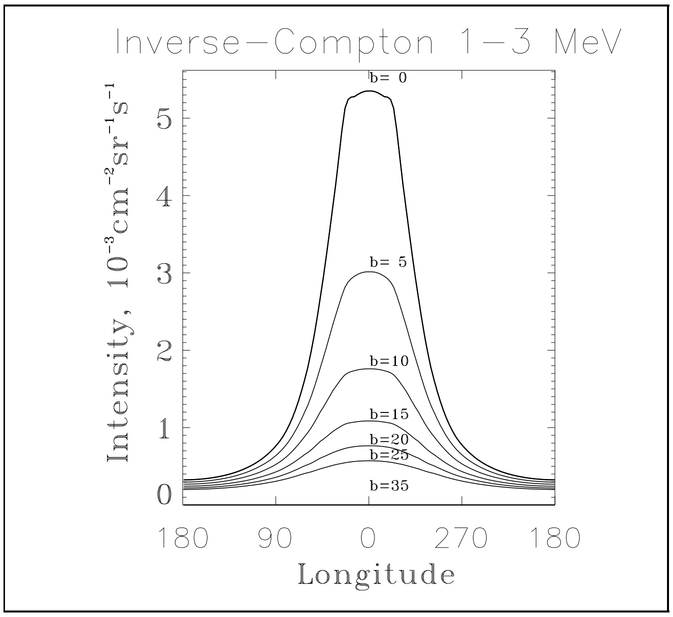

Fig. 7. Longitude distribution of predicted inverse-Compton gamma-ray intensity in the 1-3 MeV range, for various latitudes.

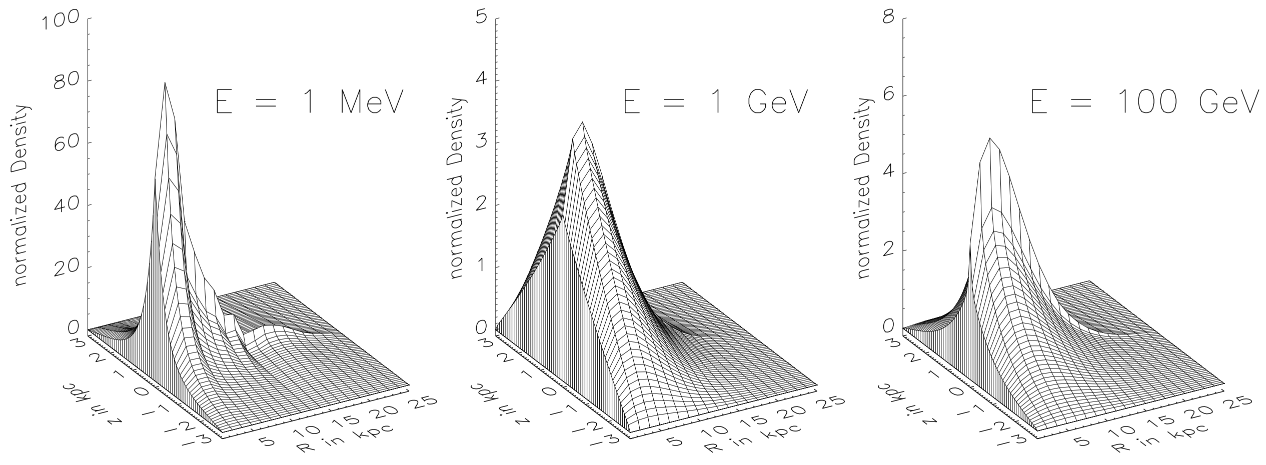

Fig. 5. Illustrative electron distribution as function of radius R and height z from the Galactic plane, for 1 MeV, 1 GeV and 100 GeV, based on the model of Strong and Youssefi (1995).

The bremsstrahlung prediction from our standard model is somewhat higher than the fits to the data indicate, so a factor 0.7 has been applied to this component in Fig 3. The overall agreement for 1 MeV - 1 GeV is then satisfactory; the excess above 1 GeV has been noted by Hunter et al. (1995), and the excess below 1 MeV is discussed below.

The intensity spectrum for $300^o < l < 60^o$, $|b| < 20^o$ (Fig 4) is used to illustrate a plausible synthesis in terms of the various processes at work. As described in Section 2 the COMPTEL data strongly suggest the presence of an inverse-Compton component, and the importance of this can be seen from this figure; at 1 MeV the contributions from inverse Compton and bremsstrahlung are about equal for the wide latitude range shown here; at low latitudes the bremsstrahlung contribution dominates as shown by the profile in Fig 2. In the $>$100 MeV range the prediction is also in accord with the estimate of $\approx$10% inverse-Compton contribution based on COS-B data (Strong et al. 1988).

At very high energies inverse-Compton again becomes dominant since it is then harder than the other components; however it cannot explain the excess derived in the EGRET analysis above 1 GeV.

The sharp decrease in the bremsstrahlung due to ionization losses at low energies and the rather flat inverse-Compton spectrum causes the latter to dominate below 1 MeV in this model. However the new OSSE results at low energies suggest the model is in fact quite inadequate below 1 MeV (Skibo et al. 1995), as already mentioned in Section 3.

Apart from the deviations at low and high energies, the general agreement indicates that the model is good within a factor 2 over 5 decades of energy.

Extensive calculations of the electron spectrum in the framework of a 'leaky box' model have been made by Skibo and Ramaty (1993 a,b,c) and most recently by Skibo et al. (1995); the latter work includes the case of a low-energy upturn in the injection spectrum which may be required to explain the OSSE results as mentioned in Section 3. They point out that the low energy electrons ($<$ 1 MeV) can make an important contribution to heating the warm ionized medium; also that the *injection* spectrum of cosmic-ray electrons contains comparable power to that of (relativistic) nuclei although the *ambient* electron spectrum has much less energy content due to the large energy losses. The spectral turn up below 1 MeV (Purcell et al. 1995; Skibo et al. 1995), if due to electrons and not a γ-ray point-source population, would imply that the power required exceeds that of the nuclear component!

7. Conclusions

This is a subject in rapid development on account of the large amount of new data coming from the Compton Observatory. It is important to combine the data from the different instruments in a consistent way, and a start on this has been attempted here. The importance of inverse-Compton is becoming clear, and the separation of this component will be much easier with such combined data. Although the spectrum agrees well with the expectations in the 1 MeV - 1 GeV range, very significant deviations both at the low and high end are apparent; although

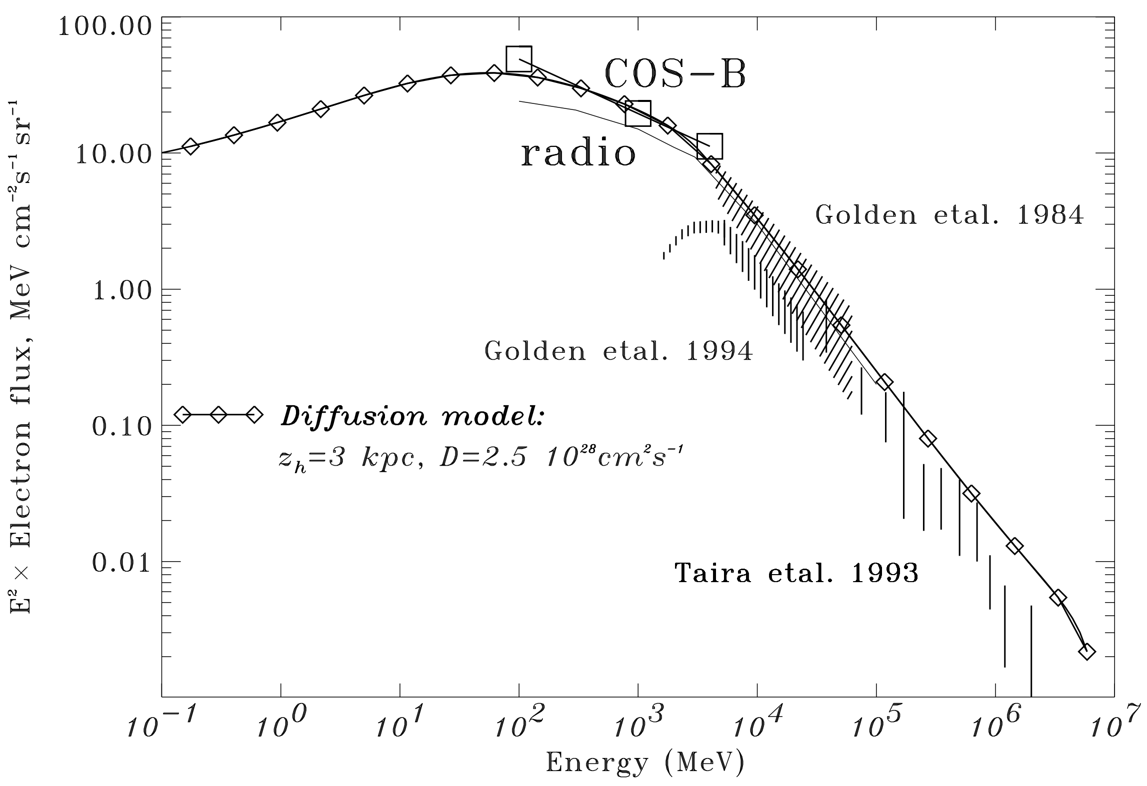

Fig. 6. Local electron spectrum based on the model (diamonds) compared to direct measurements (Golden et al. 1984, 1994, Taira et al. 1993) and estimates based on COS-B gamma rays (Strong et al. 1985) and radio data (Webber 1983).

instrumental effects cannot be excluded at this stage, these results point to interesting new astrophysics.

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