DIFFUSE GALACTIC GAMMA-RAY CONTINUUM EMISSION

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ABSTRACT

Some of the most important questions about the diffuse gamma-ray continuum emission from the Galaxy are reviewed, based on Compton Observatory (CGRO) results, especially COMPTEL and EGRET, and also earlier COS-B analyses. The key issues include the rôle of emission from cosmic-ray interactions with molecular hydrogen and its energy dependence, emissivity gradients and their interpretation, the cosmic-ray electron spectrum and the effect of discrete sources. The relative contribution of the various emission processes at low and high latitudes is estimated and a plausible synthesis of the observed spectrum over 5 decades of energy is presented. In the energy range above 30 MeV, models based either on explicit cosmic-ray gradients or cosmic-ray/gas coupling can give acceptable fits to the data, and a clear distinction has yet to be made. The quality of the EGRET data may make this possible in the future. The value of the CO-to-H_2 conversion factor from γ-rays is still uncertain and there is considerable evidence for cloud-to-cloud variations. The existence of a small emissivity gradient is well established, but is difficult to explain in a diffusive cosmic-ray propagation picture with sources distributed like SNR or pulsars unless there is a larger halo than suggested by cosmic-ray composition studies. 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 the inverse-Compton component. The molecular hydrogen appears to be only a weak γ-ray emitter at low energies, which can be interpreted in terms of reduced MeV cosmic-ray electron density in molecular clouds. New data on the hard X-ray diffuse Galactic emission is becoming available and indicates the need for a low-energy upturn in the electron spectrum or some other additional component. The contribution of unresolved sources to the 'diffuse' emission is unknown but probably lies in the range 10-20%. At high latitudes the Galactic emission is intense enough to significantly complicate the identification of the extragalactic component; in particular the inverse-Compton emission from a halo a few kpc in extent can account for much of the high-latitude Galactic emission. The detection of the Large Magellanic Cloud and the non-detection of the Small Magellanic Cloud provide constraints on extragalactic cosmic-rays, and provide an interesting comparison with the properties of the Galactic system. On account of the large amount of data from CGRO now available, this is a subject in rapid development, and this paper provides a snapshot of the situation around mid-1995.

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1. Introduction

This paper reviews some of the current issues related to observations and interpretation of diffuse Galactic continuum γ-rays . It should be remembered that the primary goal (and one of the stated objectives of the relevant satellite missions) 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, which is at the same time a 'foreground' which plays an essential part in the quest for the extragalactic diffuse emission.

Bloemen (1989) provided a very useful review of the situation at the end of the 'COS-B era' and to which the reader is referred for a full discussion up to that time. Results from the Compton Observatory (CGRO), launched in April 1991 and still operating well in 1995 are now available, and although the task of evaluating the enormous amount of data is by no means complete, they already provide us with important new information and a glimpse of what can be expected in the near future. Later reviews of diffuse emission including some CGRO results are in Bloemen (1993) and Strong (1994).

In this paper I cover first the 'classical' high energy range (> 30 MeV), discussing the spatial distribution and the question of molecular hydrogen based on COS-B and EGRET analyses. Moving to lower energies COMPTEL results in the for 1-30 MeV are then summarized. A broad-band γ-ray spectrum of the inner

Galaxy is then used as the basis for a discussion of the interpretation of the emission as the sum of contributions from the various processes. Attempts to provide a unified model for cosmic-rays and γ-rays in the Galaxy are then described. I give a brief discussion of the point-source contribution, and also address the important issue of the high-latitude intensity which bears on the determination of the extragalactic diffuse emission. Finally the interesting topic of the γ-ray emission from the Magellanic Clouds is reviewed.

The most important issues for which do not yet have fully satisfactory answers are: the rôle of molecular hydrogen, the cosmic-ray gradient, the spectrum and distribution of cosmic-ray electrons, and the point-source contribution. In this paper I try to summarize some of the current information on these topics.

2. Energy range >30 MeV

2.1 GENERAL

The pioneering work was based on the SAS-2 data (see e.g. Fichtel and Kniffen 1984 and references therein), which established the correlation of the diffuse emission with the gaseous interstellar medium including the molecular component. Useful summaries of this work can be found in Bertsch et al. (1994) and Bloemen (1989). Subsequently, COS-B provided the possibility to follow the correlation in more detail and address the important questions of gradients and molecular hydrogen. There have been two main approaches to the interpretation of the large-scale emission: models with an explicit emissivity gradient, and those which assume a correlation between cosmic-ray density and gas density on some scale. These approaches will be described in turn.

2.2 GRADIENT MODELS

2.2.1 METHODS

The method proposed originally by Lebrun et al. (1983) is to fit the γ-ray data to a linear combination of atomic hydrogen (21-cm) column density and molecular hydrogen column density as traced by the ^{12}CO (0-1 line) integrated temperature; later this method was extended to include a gradient in the emissivity by dividing the HI and CO data into Galactocentric rings on the basis of velocity information (Bloemen et al. 1984a, 1986, Strong et al. 1988). The basic assumption is that the emissivity (per gas atom) is a function of radius only, while the gas distribution is taken directly from the surveys. A characteristic of this method is the inclusion of both the gradient and X_γ as free parameters allowing a consistent treatment of the (correlated) statistical errors on these parameters; a resulting advantage of this analysis is that both the shape of q(R) and X_γ can either be energy dependent or constrained to be energy-independent. The main limitation is the assumption of cylindrical symmetry for the emissivity (but not for the gas itself). Using velocity information HI and CO maps were constructed for 6 galactocentric rings bounded by R = 0, 4, 8, 10, 12, 15 and 30 kpc. The method assumes the γ-ray intensity can be represented by the formula

$$I_\gamma(E) = \Sigma \frac{q_i(E)}{4\pi}(N_{HI,i} + 2X_\gamma(E)W_{co,i}) + f_{ics}(E)I_{ics} + I_B(E) \qquad (1)$$

where $I_\gamma(E)$ is the γ-ray intensity (cm^{-2} sr^{-1} s^{-1}), $q_i(E)$ is the γ-ray emissivity per H atom in the i'th ring, $N_{HI,i}(R)$ is the atomic hydrogen gas column density, $W_{co,i}$ is the integrated CO temperature in the i'th ring and $I_B(E)$ is a celestial background term. We assume that the molecular hydrogen column density is related to the integrated CO temperature by N_{H_2}/W_{co} =X_{CO} , molecules cm^{-2} (K km s^{-1})$^{-1}$, but since the relation of the 'γ-ray ' conversion factor to the true factor may be subject to other effects (e.g. cosmic-ray production or exclusion from molecular clouds) the symbol X_γ is used for this parameter. (Note that X_γ can be energy-dependent while X_{CO} by definition cannot.) I_{ics} is a model-based inverse-Compton intensity and f_{ics} is a scale factor. The free parameters of the model are $q_i(E)$, X_γ (E), $f_{ics}(E)$ and $I_B(E)$.

An important outcome of this type of approach is that it is possible to separate not only the HI and CO-related components, but also to distinguish the effect of changes in the gradient from those in the value of X_γ , despite the fact that both can have the same general effect on the γ-ray distribution; the separation is possible because of the difference in structural details between the atomic and molecular components. The fits to the COS-B data are rather good and encourage one to think that the source contribution is small unless sources are mimicking the CO distribution.

The main result of the final analysis (Strong et al. 1988) was to establish the presence of a small but significant emissivity gradient and a to obtain an estimate of X_γ consistent with this gradient (see Sec 2.5.1). The energy dependence was also investigated; in the most probable solution the gradient had no significant energy-dependence provided X_γ was allowed to vary with energy, and in fact an increase in X_γ in the 70-150 MeV range was suggested (and indeed required if the gradient is in fact energy-independent).

2.2.2 EMISSIVITY GRADIENTS AND COSMIC-RAY SOURCES

Fig 1a shows the gradient from COS-B based on a fit to all energies and assuming that the gradient is energy-independent. It is compared with the distribution of various possible CR sources - pulsars (Lyne et al. 1985) and a recent reappraisal of SNR by Li et al. (1991) who showed that there is considerable uncertainty in the distribution. Also shown is the total gas surface density distribution. It is striking how much flatter the COS-B distribution is compared to SNR or pulsars.

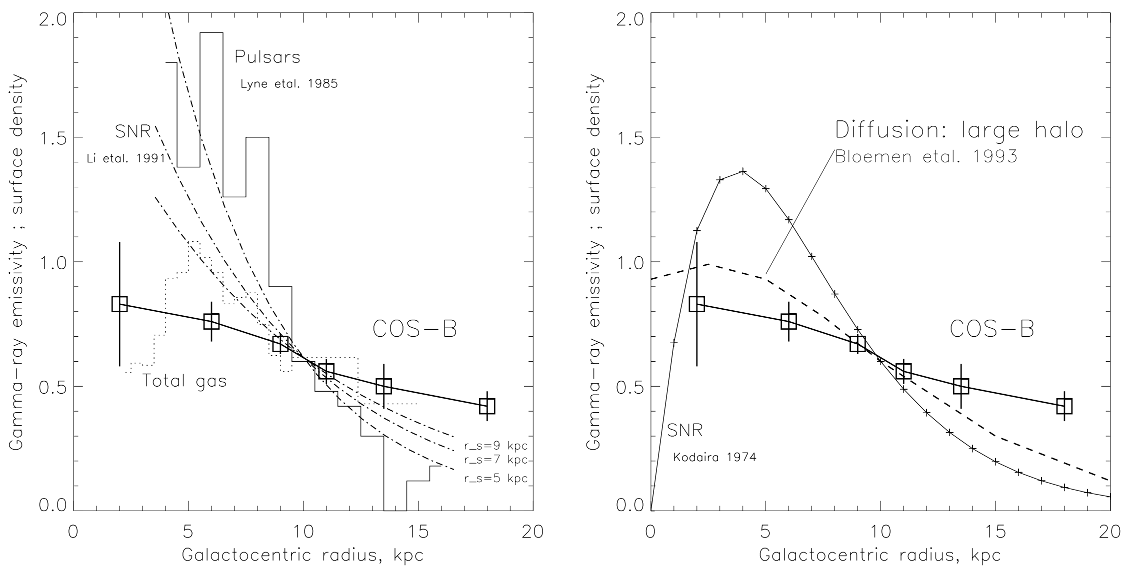


Fig 1 (a) Emissivity gradient from COS-B (squares: Strong et al. 1988) compared with various potential cosmic-ray sources. Upper histogram: pulsars, Lyne et al.

(1985); dash-dot line: SNR, Li et al. (1991), various possible scale lengths; dotted histogram: surface density of total gas (HI & H_2) based on Dickey and Lockmann (1990) and Bronfman et al. (1988).

(b) Diffusive halo model of cosmic-ray gradient from Bloemen et al. (1993) compared with COS-B gradient. Solid line is the assumed distribution of CR sources based on SNR from Kodaira (1974), dashed line is the cosmic-ray distribution *after* diffusive propagation in a large halo.

If we adopt the conventional diffusive propagation model, with SNR as cosmic-ray sources, then it is hard to obtain the small gradient. Webber et al. (1992), Bloemen et al. (1993) and Strong and Youssefi (1995) have investigated this and found that for a source distribution based on SNR a very large halo (>10 kpc) is required to smooth out the source distribution so that it agrees with the observed gradient (Fig 1b). Bloemen et al. (1993) point out that this is a real problem since CR composition studies seem to limit the size of the halo to 3 kpc; this is confirmed in a recent analysis by Lukasiak et al. (1994). Webber et al. (1992) proposed a flatter source distribution. This is a possible solution because of the uncertainty in the SNR distribution - a scale length of 10 kpc is possible (Li et al. 1991) and this would ease the situation. In this case gamma-rays have told us something about the distribution of SNR.

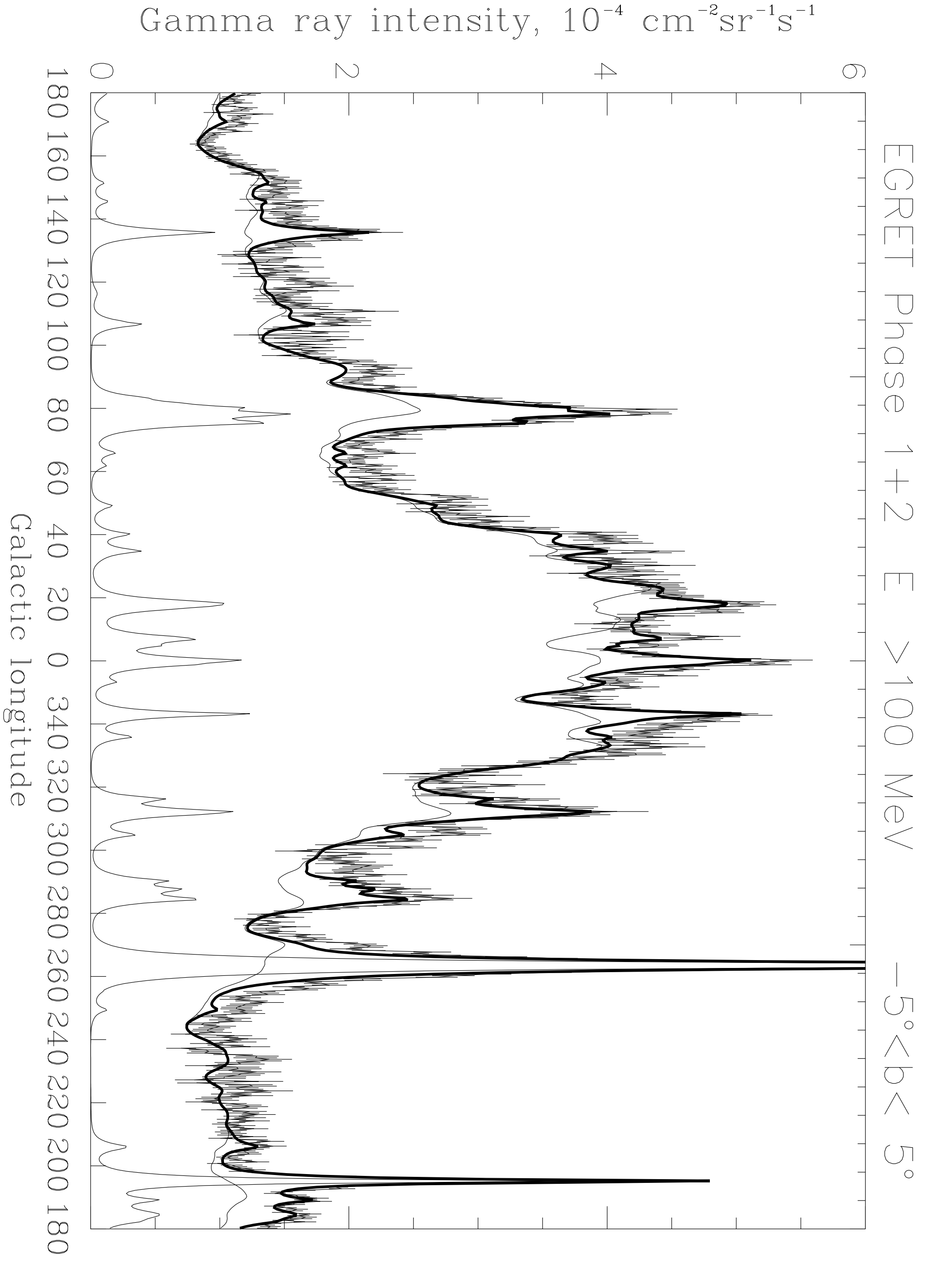
Wolfendale and co-workers (see Issa et al. 1990 and references therein) have consistently argued for a low X_{CO} (see Table 2) and a correspondingly larger cosmic-ray gradient which would in fact be more in accord with putative source distributions; it is to be hoped that the excellent EGRET data will soon allow this controversial issue finally to be settled.

A component not included in most of these models is the warm ionized gas. It is now known that the distribution of this gas dominates at high z (scale height 1 kpc) and contributes about 1/3 of the column density at the pole (Reynolds 1990, 1991a,b, 1993; Cordes et al. 1991). The HII may explain the disagreement between observed and predicted diffuse emission at intermediate latitudes (Bloemen 1989).

2.3 COSMIC RAY/GAS COUPLING MODELS

An alternative model which in which the emissivity variation is computed explicitly is described by Bertsch et al. (1994); this assumes coupling of the cosmic-ray density to the gas on a scale of 2-3 kpc and is the basis of the EGRET team's diffuse emission model, of particular utility for point-source searches in the plane. Bertsch et al. (1994) applied the model first to the COS-B data, and obtained acceptable fits. From Fig 1a it is clear that the gas surface density distribution is quite similar to the emissivity gradient, thus explaining why both 'gradient' and 'coupling' models can give good fits. More recently Hunter et al. (1995) have refined this model for the EGRET sky-survey data; they account explicitly for the point sources in the EGRET catalog and obtain rather good agreement with the observed diffuse emission except for E_γ>1 GeV. Fig 2 compares the longitude profile from EGRET Phase 1+2 archival data for E>100 MeV and $|b|<5^o$; the agreement with the sources included is indeed impressive. This figure also serves to illustrate the high quality of the EGRET data and its potential for future studies in this area. Above 1 GeV the model predicts too little emission; the origin of this discrepancy in this energy range where π^o-decay presumably dominates is a tantalizing puzzle, possibly reflecting variations in the cosmic-ray nucleon spectrum in the Galaxy. The results on X_γ from this work are discussed in Sec. 2.5.1.

Fig 2: Longitude profile of γ-ray intensity > 100 MeV from EGRET Phase 1+2 data, compared to the Hunter et al. (1995) model. Latitude range is $|b| < 5^o$. Vertical bars: data. Lower curve: point sources from 2nd EGRET catalog (Thompson et al. 1995); middle curve: model ; upper curve: model + sources.



The only explicit comparison up to now between 'gradient' and 'coupling' approaches was made by Melisse and Bloemen (1990); they considered coupling of the form $n_{CR} \propto n_{gas}^{\alpha}$ on short scales (100 pc) and concluded from COS-B data that in this case the value of the exponent has to be near zero, mainly due to the small cosmic-ray scale height in such a model. They also concluded that the gradient model was definitely superior to such a coupling model. It is important to note that the Bertsch et al. model is quite different from that of Melisse and Bloemen in that it uses gas surface density rather than volume density as the cosmic-ray estimator, and has a much longer coupling scale-length. For this reason it is much more successful in reproducing the observations. The possibility of distinguishing gradient and coupling models with the EGRET data poses a real challenge for the future. It may be that more indirect considerations will be important: in particular it does seem hard to reconcile coupling models with the picture of cosmic-ray diffusion which is currently favoured in the cosmic-ray literature.

2.4 FURTHER CGRO/EGRET RESULTS

A recent analysis of the EGRET data in the outer Galaxy (Digel et al. 1995b) finds a significant and energy-dependent gradient from the local region to the Perseus arm. Above 100 MeV the emissivity decreases by a factor 1.7±0.2; however below 70 MeV the gradient appears in the opposite sense; it is not clear how this should be interpreted. The excess above the expected π^o-decay emission for E_γ>1 GeV noted in for the whole Galaxy (see above) also appears here.

Analyses of EGRET data for Orion (Digel et al. 1995a) and the ρ Oph region (Hunter et al. 1994) indicate emissivities very similar to the large-scale Galaxy. The Ophiuchus emissivity (2.4±0.2 10^{-26}sr^{-1}s^{-1}) appears in fact to be about 30% larger than the Orion (1.68±0.13 10^{-26}sr^{-1}s^{-1}) and the 'local' value (1.84±0.1 10^{-26}sr^{-1}s^{-1} : Digel et al. 1995b). However the uncertainty in X_γ must play a part here and one should be cautious in drawing conclusions on possible cosmic-ray enhancements in clouds. Orion and ρ Oph are found to have X_γ lower than the large-scale Galaxy (see Section 2.5.1).

Giller et al. (1995) have presented evidence based on the EGRET Phase 1 data for a large inverse-Compton contribution at intermediate and high Galactic latitudes. They find that the ratio of inverse-Compton to total diffuse is 32±10% for 10^o <b<20^o and 44±17% at the NGP. On this basis they estimate the scale height of the halo as 2.5±1 kpc. Further discussion of the inverse-Compton component is given in Sections 6 and 8.

Chen et al. (1995) find a large region away from the Galactic plane with unusually high γ-ray emissivity. It extends from about (l,b)=(90^o , 52^o) to (45^o , 77^o). It could be interpreted either as enhanced cosmic-ray density, or unseen matter; if the latter is the case, additional column densities of order 2 10^{20} cm^{-2}are required, comparable to the HI.

2.5 THE ROLE OF MOLECULAR HYDROGEN

2.5.1 GAMMA-RAY DETERMINATIONS OF H_2/CO

Table 1 summarizes some determinations of X_γ including recent EGRET results. All these values are on the revised CO scale (Bronfmann et al. 1988) which reduces X_γ by a factor 1.22 relative to values based on the Dame et al. (1987) CO survey. On the large scale, the EGRET analysis (Hunter et al. 1995) seems to substantiate the COS-B value, the 20% lower figure is within the error quoted by Strong et al. (1988) and probably reflects more the different assumptions in the models than differences in the γ-ray data; the larger gradient in the Hunter et al. (1995) model seems to be compensated by a lower X_γ relative to the Strong et al. value. For local clouds (Orion, ρ Oph) X_γ appears to be consistently lower (see Table 1); perhaps this is due to a difference in X_{CO} between the low-mass nearby clouds which can be detected individually in γ-rays and the Galactic population of massive giant molecular clouds, although the effect is in the opposite direction from the theoretically expected mass-dependence of X_{CO} (see 2.5.2). It may equally reflect just cloud-to-cloud variations (see 2.5.2), individual clouds differing by a factors at least 2 from the global mass-weighted average (see also discussion in Digel et al. 1995a). Yet another possibility is that emissivity is correlated with cloud mass, for example if cosmic-rays are enhanced in massive clouds, or perhaps we are just seeing cloud-to-cloud variations in cosmic-ray intensity.

The Galactic centre appears to be a special case; the lack of a large γ-ray peak in the COS-B data was interpreted by Blitz et al. (1985) to indicate a low X_{CO} rather than reduced cosmic-ray density, and this appears substantiated by analysis of far-infrared COBE data (Sodrowski et al. 1995), who find a value 3-10 less than the local X_{CO} . EGRET does detect a point-like source within 0.2^o of the Galactic centre (Mayer-Hasselwander et al. 1995), but this is clearly distinct from the CO maximum at $l=2^o$, so that the conclusions based on COS-B are not affected.

Reference	Region	Energy range (MeV)	X_γ	Comments
Strong et al. 1988	Galaxy	150-5000	1.9 $\pm$0.3	COS-B; gradient model
Bertsch et al. 1994	Galaxy	100-10000	1.6	COS-B; coupling model
Hunter et al. 1995	Galaxy	100-10000	1.5 $\pm$0.2	EGRET; coupling model
Hunter et al. 1994	Ophiuchus	100-10000	1.1$\pm$0.2	EGRET
Bloemen et al. 1984b	Orion	100-5000	2.2$\pm$0.6	COS-B
Digel et al. 1995a	Orion	100-10000	1.06$\pm$0.14	EGRET
Digel et al. 1995b	Perseus arm	100-10000	2.5$\pm$0.9	EGRET; outer galaxy
Digel et al. 1995b	Cepheus, Polaris	100-10000	0.92$\pm$0.14	EGRET ;local

Table 1. Some published estimates of X_γ . All values on the revised CO scale as described in Digel et al. 1995a

2.5.2 NON-GAMMA DETERMINATIONS OF H_2/CO

Table 2 gives a compilation some recent independent estimates of X_{CO} , mainly based on the assumption of virial equilibrium. For a recent discussion of methods see Solomon and Barrett (1991). Another method is that based on soft-X-ray absorption in ρ Oph from ROSAT (Snowden 1993), which gives a value consistent with the other methods. Infrared survey data also supports an average inner Galaxy value of 2 10^{20} mols. cm^{-2}/(K km s^{-1}) (Kent et al. 1991). Note that very low values based on IRAS observations of cirrus (Heithausen and Mebold 1989) suggest that the situation here is quite different from giant molecular clouds which contribute the bulk of the mass. At least for the *inner* galaxy X_{CO} is consistent with X_γ ; but note first that there is evidence that X_{CO} is dependent on the cloud mass (decreasing with mass) so one should really fold in the cloud mass distribution for a valid comparison; second that there is still a scatter of a factor 2 in the inner Galaxy values: the radio astronomers are not in a position to tell us what the 'correct' value is and it is still important to fit X in gamma-ray analyses. There is in any case evidence for large cloud-to-cloud variations (Magnani and Onello 1995). An interesting result is the possibility of higher X_{CO} in the *outer* Galaxy which would indicate that anticentre clouds could be brighter in γ-rays than the standard X_{CO} would predict. The difference between inner and outer Galaxy is an effect which should be easily detectable by EGRET and a search for this should be given high priority. It is interesting to note that the larger outer Galaxy value may be related to reduced cloud heating which might itself be influenced in part by cosmic-rays (Suchkov et al. 1993).

Reference	Method	X_{CO}/ 10^{20} mols. cm^{-2}/(K km s^{-1})
Solomon et al. 1987	virial	2.2 $(M/3\ 10^5)^{-.23}$
Lee, Snell, Dickman 1990	virial, LTE	1.6-2.8 (inner Galaxy)
Issa et al. 1990	various	1.0-1.5
Sodroski 1991	virial	1.8-2.6 (inner Galaxy)
Sodroski 1991	virial	4.7-6.7 (outer Galaxy: R$\approx$ 11 kpc)
Digel, Bally, Thaddeus 1990	virial	4-14 (outer Galaxy: R$\approx$ 13 kpc)
Carpenter,Snell,Schloerb 1990	virial, LTE	3.6** (outer Galaxy: R$\approx$ 11 kpc)
Wolfire et al. 1993	cloud models	2.0 $(M/3\ 10^5)^{-.25}$
Snowden 1993	X-ray abs. ρ *Oph*	2.5-3.5
Magnani, Onello 1995	CH	2.0 (average for 12 translucent clouds)
Magnani, Onello 1995	CH	3.5 (average for 13 dark clouds)
Sodroski et al 1995	FIR COBE	0.2-0.7 Galactic centre R$<$ 400 pc

** Carpenter et al. value (1.7) corrected to standard cloud radius and profile. (S. Digel, private communication).

Table 2. Recent published estimates of X_{CO}

3. Energy range 1-30 MeV

3.1 COMPTEL ALL-SKY MAPS

The COMPTEL instrument on the Compton Observatory has sufficient imaging capability to allow a sensitive measurement of the diffuse radiation. Fig 3 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; 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 bremsstrahlung interactions of cosmic-ray electrons with interstellar gas and inverse-Compton interactions with the interstellar radiation field. Measurement of the γ-ray spectrum at low energies therefore provides important constraints on the spectrum and propagation of cosmic-ray electrons. This information is complementary to results from radio synchrotron and direct measurements of electrons.

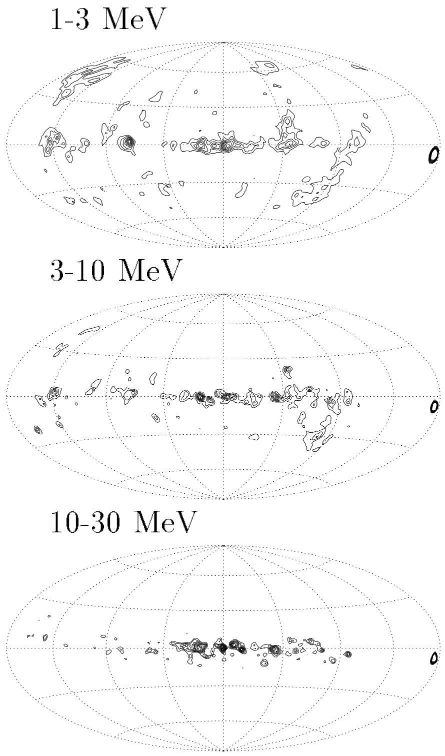


Fig 3: Maximum-entropy images of the whole sky in the 1-3, 3-10 and 10-30 MeV ranges based on Phase 1+2+3 data (from Strong 1995, Schoñfelder et al. 1995).
Coordinates are Galactic centered on l=0 .

3.2 ANALYSIS OF DIFFUSE EMISSION IN COMPTEL RANGE

An analysis similar to that described above for COS-B has been performed on the COMPTEL Phase 1 Sky Survey (15 months) (Strong et al. 1994) and subsequently on Phases 1, 2, and 3 (30 months) (Strong et al. 1995). The method is the same as for COS-B described in (2.2), except that no gradient is included (it can and should be included but has little influence on the results reported here). 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, since COMPTEL is background dominated which makes the analysis much more complicated than for e.g. EGRET.

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 (see section 7 on the point source contribution).

It was found that the inclusion of the inverse-Compton component 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 quite close to the theoretical expectation ($f_{ics} \approx 1 - 2$). In view of the considerable uncertainties in this prediction (the distribution of electrons, the ISRF) , this is quite satisfactory.

Fig 5 shows the emissivity spectrum of the gas 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 6 shows the intensity spectrum for the inner Galaxy, $300^o < l < 60^o$, $|b| < 20^o$, obtained by summing the components of the model fits to the COMPTEL data.

The latitude profile of the 1-3 MeV intensity of the model components in the inner Galaxy is illustrated in Fig 4. Since the fits indicate that the inverse-Compton component is quite close to the theoretical expectation there is an independent plausibility argument for the spectral decomposition illustrated in Fig 6.

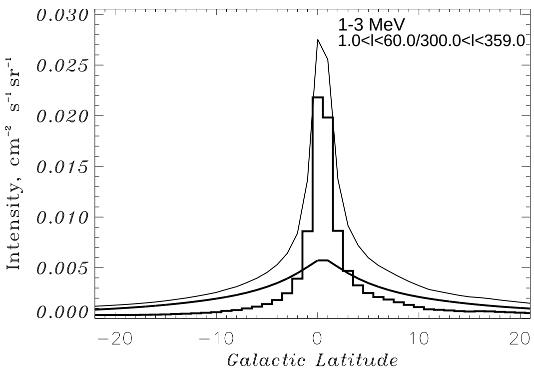


Fig 4: Latitude profile of 1-3 MeV intensity in the inner Galaxy $300^o < l < 60^o$ corresponding to the model fit to the COMPTEL data. The components are: bremsstrahlung (histogram), inverse-Compton (lower curve), total (upper curve), From Strong et al. (1995).

An argument *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/ISRF 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.

3.3 COSMIC-RAY ELECTRONS IN MOLECULAR CLOUDS

Another result for the 1-30 MeV range which comes from the COMPTEL analysis is an apparently low value of X_γ ; in other words 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. There is interesting physics connected with the possibility that the electron spectrum in molecular clouds is different from that of the intercloud medium. There is a mechanism to exclude low-energy electrons which could explain a low value of X_γ at low energies: primary MeV protons entering clouds set up a local cosmic-ray gradient due to ionization losses, which leads to the generation of waves which scatter low-energy electrons, inhibiting free entrance (Skilling and Strong 1976, Strong and Skilling 1977). Similar mechanisms (including possible acceleration) have been studied by Morfill (1982) and Dogiel and Sharov (1990). There is clearly much scope for interesting theoretical work here.

4. Energy range 50 keV - 1 MeV

Although the hard X-ray range is not the subject of this review, it must be mentioned in view of its great relevance to the higher energy results. In the hard X-ray range pre-CGRO measurements are available from HEAO-1 (Peterson etal al 1990), 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 CGRO/OSSE team (Kurfess et al. 1995, Purcell 1995, Skibo 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 (5.5^o) full-width at half maximum, and quite similar continuum intensities for the two regions. The interpretation of this is beyond the scope of this article, but 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. In any case it is hard to explain such a spectrum purely in terms of other 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.

5. Wide-band spectra of the diffuse emission

By combining the results of various experiments we can construct emissivity and intensity spectra covering the full γ-ray range. In particular since same fitting procedure was applied to COMPTEL and COS-B data we can reliably combine the results from the two instruments, and the resulting emissivity spectrum (Fig 5) should be dependable over the range 1 MeV to 1 GeV. The emissivity spectrum q(E) separates out that part of the emission attributable to cosmic-ray/gas interactions.

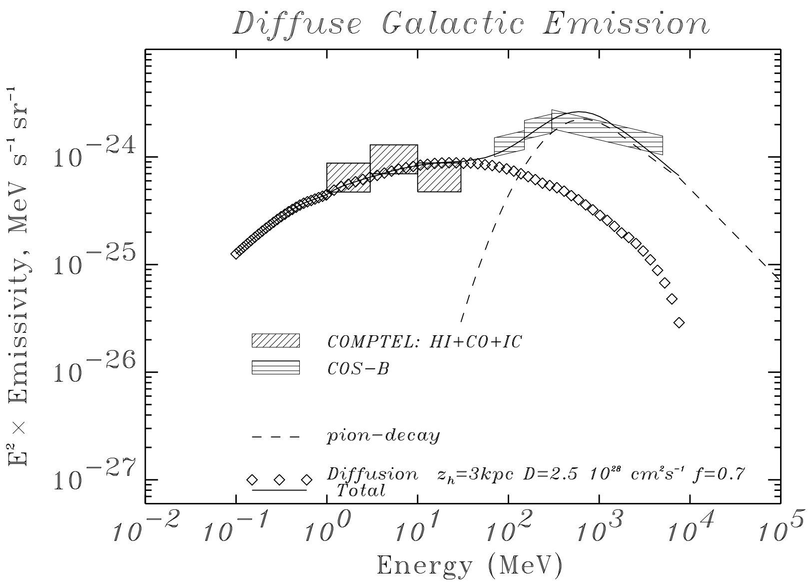


Fig 5: Emissivity spectrum of the diffuse Galactic continuum radiation, based on data from COMPTEL and COS-B. The COMPTEL spectra are shown for fits to HI, CO and inverse Compton with X_γ free. A theoretical synthesis of the spectrum from bremsstrahlung and π^o-decay components is shown.

In order to include the part of the emission not associated with gas (e.g. inverse-Compton) an intensity spectrum is more appropriate (Fig 6). 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 COMPTEL MeV intensities are consistent with a smooth connection to the COS-B spectrum. The extension to lower energies 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 I use the SIGMA, HEAO-1 and GRIS results (see Section 4) to extend the spectrum down to 50 keV. These spectra are compared to the theoretical predictions in Section 6.

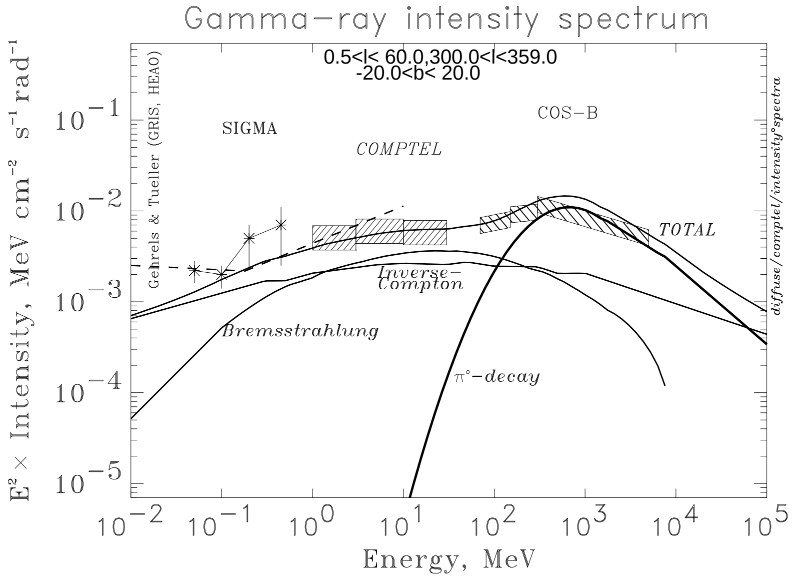


Fig 6: Intensity spectrum of the inner Galaxy $300^o < l < 60^o$, integrated over |b| <20^o derived from COMPTEL data together with values from COS-B (Strong et al. 1988). The dashed line is the summary spectrum based on HEAO-1 and GRIS data by Gehrels and Tueller (1992). SIGMA results for the region around l=315^o (Claret et al. 1995) are also indicated (crosses). A theoretical synthesis of the spectrum from bremsstrahlung, inverse-Compton and π^o-decay components is shown.

6. Cosmic-ray electrons and their contribution to diffuse γ-rays

6.1 THE EMISSIVITY SPECTRUM

The observed emissivity spectrum shown in Fig 5 has been deduced without any assumptions about the physical processes involved; the interpretation in terms of cosmic-ray/gas interactions can proceed independently. Since the π^o-decay spectrum is rather well known (the most recent calculations are due to Dermer 1986 and Stecker 1988), the main uncertainty is the electron spectrum, which contributes via bremsstrahlung radiation. Direct measurements 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. One approach is to compute theoretical spectra based on propagation models and compare the computed bremsstrahlung emissivities with the observations.

Electron spectra for diffusive halo models of cosmic-ray propagation have been calculated (see below). The bremsstrahlung prediction from this model is somewhat higher than the fits to the data indicate, so a factor 0.7 has been applied to this component in Fig 5. The π^o emissivity uses the analytical representation of the Stecker (1988) computation given in Bertsch et al. (1994). The overall agreement is satisfactory; the use of the more accurate EGRET data above 30 MeV will soon allow a more precise evaluation.

6.2 THE INTENSITY SPECTRUM

The intensity spectrum for 300^o <l<60^o , |b| <20^o (Fig 6) is used to illustrate a plausible synthesis in terms of the various processes at work. The intensity spectrum has the advantage of showing the gas and inverse Compton components and allowing combination with data from other experiments. The bremsstrahlung and inverse Compton predictions are based on the model for the electron spectrum and ISRF described in (6.3)

As described in (3.2) 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 lower latitude ranges the contribution decreases as shown by the profile in Fig 4. In the >100 MeV range the prediction is also in accord with the estimate of ≈10% inverse-Compton contribution based on COS-B data (Strong et al. 1988). The computed inverse-Compton contribution extends with approximately an E^{-2} spectrum at least down to 100 keV so that it may be dominant there; it appears to be consistent with the SIGMA detection of the plane around $l=315^o$ in the 50-500 keV range (Claret et al. 1995).

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; at high energies inverse-Compton again becomes important since it is harder than the other components. The general agreement indicates that the model is already good within a factor 2 over 5 decades of energy. However the new OSSE results at low energies (not shown) suggest the model is in fact quite inadequate below 1 MeV (Skibo et al. 1995), as already mentioned in Section 4.

6.3 MODELLING COSMIC-RAY PROPAGATION 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 CR 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. The rationale is that a great variety of observational data - composition and spectrum, gamma-rays, radio, etc. all give constraints of different kinds on Galactic cosmic-ray origin and propagation. The aim is to find at least one model which is consistent with all types of available data, and then to see what variations on this model are allowed; the present results are still just a first step in that direction. For example we might hope to be able to shed some light on the question of the extent of the propagation region, for which current estimates vary widely. 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 CR nucleons and electrons in the same model, which ensures consistent treatment of the two components.

The standard cosmic-ray transport equation for nucleons and electrons is written in the form: $\partial\psi(\vec{r},E,t)/\partial t = q(\vec{r},E)+\vec{\nabla}.[D\vec{\nabla}\psi]+\frac{\partial}{\partial E}[\psi\frac{dE}{dt}]-\sigma_i\rho v\psi-\frac{\psi}{\tau_r}$ where ψ is the cosmic-ray density, q is the source function, D is the diffusion coefficient, σ_i the total spallation cross section for destruction (for nucleons), ρ the gas density, v is velocity and τ_r the decay time (for radioactive nuclei). We solve numerically the cylindrically symmetric 3-D case with $\psi = \psi(R,z,E,t)$. 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 a 'halo' full thickness of $2z_h$. The electron injection spectrum $q(E)$ is assumed to be a power-law with index -2.4 (Webber 1983). As normalization for the local electron spectrum we use the interstellar value at 1 GeV ($2\ 10^{-5}$cm^{-2}sr^{-1}s^{-1}MeV^{-1}) derived from an analysis of COS-B γ-ray data (Strong 1985). The distribution of CR *sources* is assumed to follow that of SNR. 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 (Bloemen et al. 1993; Lukasiak et al. 1994) and a diffusion coefficient D= 2.5 10^{28} cm^2 s^{-1} were used, chosen to be consistent with the cosmic-ray B/C ratio and ^{10}Be data.

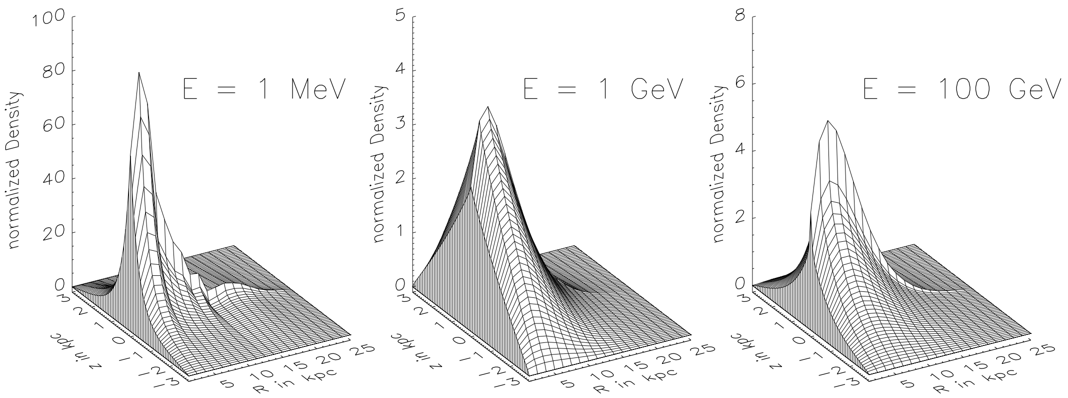


Fig 7: Illustrative electron distribution as function of radius R and height z from the Galactic plane, for 1 MeV, 1 GeV and 100 GeV, based on the model of Strong and Youssefi (1995).

Fig 7 shows sample electron distributions in (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.

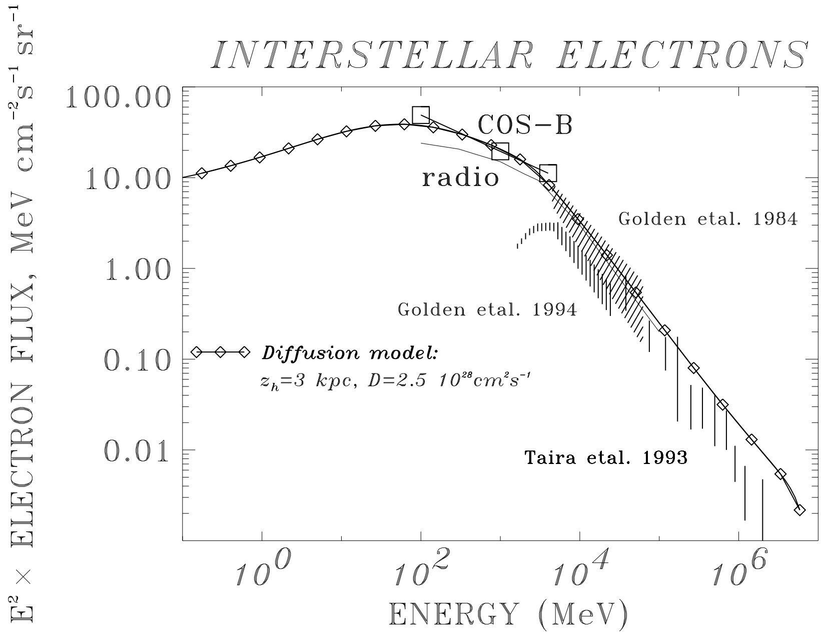


Fig 8: Local electron spectrum based on the model (diamonds) compared to direct measurements (Golden et al. 1984, 1994, Taira et al. 1993) and estimates based on gamma rays (Strong et al. 1985) and radio data (Webber 1983).

Fig 8 compares the local 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 would imply a larger halo as also suggested by the γ-ray results in (2.2.2). The constraints on electrons with E$<$ 100 MeV from γ-rays are also reasonably well satisfied (Fig 5, 6).

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 (6.2). 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. If the spectrum turns up below 1 MeV (Skibo et al. 1995) then the power required exceeds that of the nuclear component!

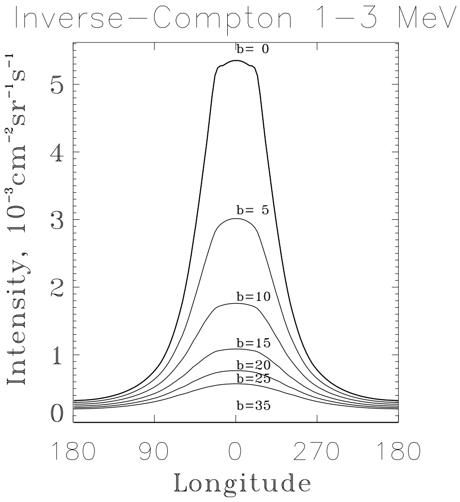


Fig 9: Longitude distribution of predicted inverse-Compton gamma-ray intensity in the 1-3 MeV range, for various latitudes.

Strong and Youssefi (1995) used their model to compute the γ-ray intensity distribution from bremsstrahlung (using hydrogen column densities based on HI and CO surveys) and inverse Compton interactions. The interstellar radiation field calculation for inverse-Compton is the same as used for the energy loss calculation. It should be emphasized that the ISRF 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 uncertain by at least a factor 2 and it will be a challenge to separate it observationally based on its wide latitude distribution; this should certainly be possible with the EGRET data (see Giller et al. 1995).

Fig 9 shows a sample set of inverse-Compton longitude profiles for various latitudes for the energy interval 1-3 MeV.

7. Source contribution

The contribution to the 'diffuse' emission from unresolved sources is unknown, and has generally been presumed rather small; quantitative estimates are very difficult. It is worth noting that the Galactic plane ($|b| < 10^o$) resolved sources in the 2nd EGRET Catalog (Thompson et al. 1995) contribute a total flux about 10% of the diffuse emission (cf. Fig 2), so that the entire population is unlikely to contribute more than twice this. In view of the model uncertainties the best test will be the extent to which the CR/gas models provide a detailed fit to the observed distribution. The fits to COS-B data did not indicate the need for any non-gas component beyond the 10% level. The results of Hunter et al. (1995) show that the EGRET data can be fitted rather precisely with a combination of gas and the catalogued sources. The detected sources can of course be explicitly included in analyses so as not to contaminate the diffuse signal.

Turning to the specific case of pulsars as contributors to the unresolved emission, Bailes and Kniffen (1992) showed (on the basis of the two γ-ray pulsars known up to COS-B) that anything between a few and 100% of the emission could come from pulsars depending on the pulsar evolution model adopted. Schnepf et al. (1993) extended this analysis to place limits on the pulsar birth function. Hartmann and Brown (1994) have pursued this issue using EGRET data. Since γ-ray efficiency appears to increase with pulsar age, the wide z-distribution of old pulsars may be a problem for models with a large pulsar contribution. A good way to distinguish may be on the basis of the spectrum, since this is certainly very different from that of the diffuse emission (e.g. they exhibit no π^o-decay bump).

The next step is clearly to include unresolved sources in the analysis, via model populations of γ-ray sources such as pulsars, taking care to satisfy the constraints imposed by the number and flux distribution of the catalog sources.

8. High Latitudes

Estimates of the components of the diffuse spectrum at a typical high Galactic latituded, based on the model described in (6.3), are shown in Fig 10. They are compared to the SAS *total* high-latitude intensity from Thompson and Fichtel (1982).

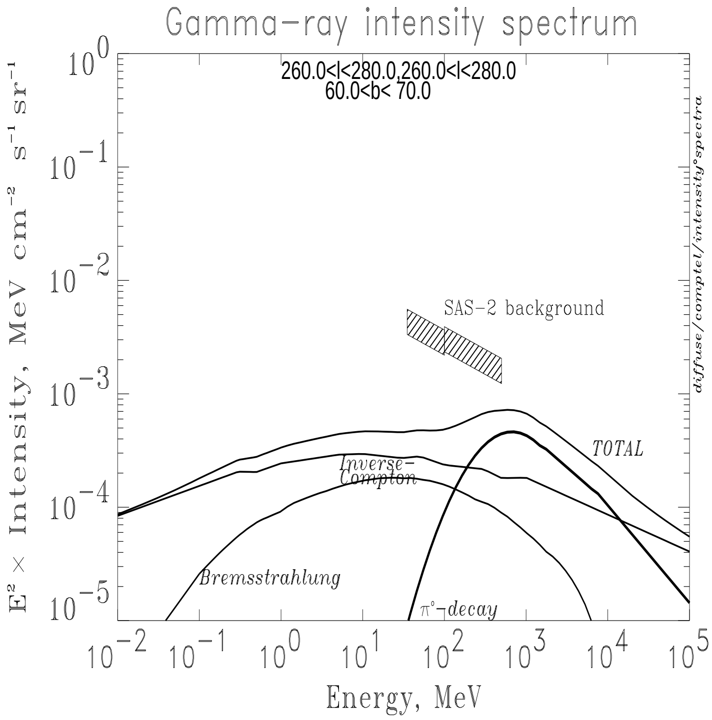


Fig 10 The components of γ-ray emission in a typical high latitude region (60^o $<b<70^o$, 260^o $<l<280^o$), based on the model of Strong and Youssefi (1995). SAS-2 high-latitude intensities are total values based on Thompson and Fichtel (1982).

The interstellar radiation field is much broader in z than the gas component and so the inverse-Compton component is especially important at high latitudes.

The calculations shown here are consistent with Giller et al. (1995) who find that about half the high-latitude Galactic emission is probably inverse Compton. Note that the sum of the bremsstrahlung, pion-decay and inverse-Compton components is not far from the SAS-2 polar intensity (Thompson and Fichtel 1982), becoming more dominant with increasing energy. One thing seems certain: the inverse-Compton will eventually dominate at high latitudes above 10 GeV because of its very flat spectrum; it also dominates at low energies (below 100 MeV). The high-latitude γ-ray intensity will eventually put the most stringent limits on the z-extent of the electron distribution and hence the size of the 'halo'.

9. The Magellanic Clouds

The Large and Small Magellanic Clouds (LMC, SMC) are the only 'normal' galaxies apart from our own for which the sensitivity of current γ-ray instruments gives some hope of detection. The detection of the LMC (Sreekumar et al. 1992) and the upper-limit on the SMC (Sreekumar et al. 1993) based on EGRET data are therefore of great importance and relevant to the interpretation of the Galactic diffuse emission. Sreekumar et al. (1992) find that the flux from the LMC appears quite consistent with a cosmic-ray intensity similar to that in our Galaxy. The non-detection of the SMC provides the long-awaited 'proof' that cosmic rays cannot be of universal origin; the upper limit (>100 MeV) is only 20% of the expected flux based on the Galactic emissivity. The meaning of these results has been discussed in the context of a possible energy equipartition between cosmic rays and magnetic field. Sreekumar et al. (1992, 1993) concluded that equipartition is possible in the LMC but not in the SMC. Chi and Wolfendale (1993) claimed that the cosmic-ray density in the LMC is much lower that in the Galaxy and hence that very large magnetic fields are required to give the observed synchrotron emission; in this case the situation is far from equipartition in the LMC. These conclusions have been contested by Pohl (1993) who concludes that, when the energy density of cosmic-ray electrons is taken into account, equipartition cannot be excluded in either system as long as the average e/p ratio is higher than in the Solar neighbourhood. However there seems to be no evidence either *in favour* of the equipartition idea, so these arguments appear somewhat academic.

The prospects for observing other spiral galaxies appear poor; Pohl (1994) estimates the flux (>100 MeV) from M31 and M82 as less than 2 10^{-8} cm^{-2} s^{-1} , well below the EGRET sensitivity.

10. Conclusions

This is a subject in rapid development on account of the large amount of new data coming from CGRO; this report only provides a snapshot of some aspects of the field as of mid-1995. Among the most important questions for the near future are are: the properties of the emission from molecular clouds (the spatial and energy dependence of X_γ), the relation of X_γ to X_{CO} , the size and energy-dependence of the CR gradient, the observational distinction between various ideas on the cosmic-ray distribution, the magnitude of the point-source contribution and the determination of the electron spectrum over the whole 100 keV - 10 GeV range. Another important goal is to identify the inverse-Compton component and measure its intensity. Given the current high level of activity, we can expect that improved answers to at least some of these questions will come quite soon.

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REFERENCES

Bailes, M., Kniffen D. A. 1992, ApJ **391**, 659
Bertsch D. et al., 1994 Ap. J. 416, 587
Blitz L., Bloemen H., Hermsen W, Bania T.M., 1985, A&A, **143**, 267
Bloemen, H. 1989, Ann. Rev. Astron. Astrophys. **27**, 469
Bloemen, H. 1993, in 'Back to the Galaxy', Holt, S.S., Verter, F. (eds), AIP Conf. Proc. **278**, 409
Bloemen, H. et al. 1984a, A&A **135**, 12
Bloemen, H. et al. 1984b, A&A **139**, 37
Bloemen, H. et al. 1986, A&A, **154**, 25
Bloemen, H. et al. 1994, Ap.J.Supp. **92**, 419
Bloemen, H., Deul, E.R., Thaddeus, P. 1990, A&A, **233**, 437
Bloemen, H., Dogiel, V.A., Dorman, V.L., Ptuskin, V.S. 1993, A&A, **267**, 372
Bronfman, L. et al. 1988, ApJ, **324**, 248
Carpenter, J.M., Snell, R.L., Schloerb, F.P. 1990, ApJ, 1990, **362**, 147
Chen, A., Dwyer, J., Kaaret, P. 1995, ApJ Lett, **445**, L109
Chi, X., Wolfendale, A. W. 1993, Nature **362**, 610
Chi, X., Wolfendale, A. W. 1991, J. Phys. G. **17**, 987
Claret, A. et al. 1995 Adv. Sp. Res. **15**, 557
Cordes J M et al. 1991 Nature **354**, 121
Dame T. M. et al. 1987, ApJ **322**, 706
Dermer, C.D. 1986, A&A, **157**, 223
Dickey, J.M., Lockman, F.J., 1990, Ann. Rev, Astron. Astrophys. **28**, 215
Digel, S., Bally, J., Thaddeus, P. 1990, ApJ, **357**, L29
Digel, S.W., Hunter, S.D., Mukherjee, R. 1995a, ApJ **441**, 270
Digel, S.W., Grenier I.A., Heithausen A., Hunter S.D., Thaddeus P., 1995b, ApJ (submitted)
Dogiel, V. A., Sharov G. S. 1990, A&A, **229**, 259
Fichtel C.E., Kniffen D.A. 1984, A&A **134**, 13
Gehrels N., Tueller J., 1992, ApJ **407**, 597
Giller, M., Wdowczyk, J., Wolfendale, A.W., Zhang, L. 1995, J. Phys. G. *in press*
Golden, R.L. et al. 1984, ApJ, **287**, 622
Golden, R.L. et al. 1994 ApJ **436**, 769
Hartman D., Brown L.E.. 1994 in 'The Second Compton Symposium', College Park MD 1993, AIP Conf. Proc. **304**, 101
Heithausen, A., Mebold, U. 1989, A&A, **214**, 347
Hunter, S.D., Digel, S.W., de Geus, E.J., Kanbach, G. 1994 ApJ **436**, 216
Hunter, S.D. et al. 1995, Proc. 24th ICRC, Rome, **2**, 182
Issa, M., Maclaren, I., Wolfendale A.W. 1990, ApJ, **352**, 132
Kent, S.M., Dame, T.M., Fazio, G. 1991, ApJ **378**, 131

Kodaira, K. 1974, PASJ, **26**, 255
Kurfess J.D. 1995, Proc. Texas Symp. on Relativistic Astrophysics, Munich *in press*
Lebrun, F. et al. 1983, ApJ, **274**, 231
Lee, Y., Snell, R.L., Dickman, R.L. 1990, ApJ, **355**, 536
Li, Z., Wheeler, J.C., Bash, F.N., Jefferys, W.H. 1991, ApJ, **378**, 93
Lukaskiak A et al. 1994 ApJ **423**, 426
Lyne, A.G., Manchester, R.N., Taylor J.H. 1985, MNRAS, **213**, 613
Magnani, L., Onello J.S., 1995, ApJ, **443**, 169
Mayer-Hasselwander H et al. 1995 Poster at 3rd Compton symposium, Munich 1995
Melisse J, Bloemen H., 1990, Proc. 21st ICRC, Adelaide, **1**, 137
Morfill, G.E. 1982, ApJ, **262**, 749
Pohl, M., 1993, A&A **279**, L17
Pohl, M., 1994, A&A **287**, 453
Peterson L.E. et al., 1990 Proc 21st ICRC, **1**, 44
Purcell W., Talk at 3rd Compton symposium, Munich 1995
Reynolds R J 1990 ApJ Lett **349**, L17
Reynolds R J 1991a ApJ Lett **372**, L17
Reynolds, R.J. 1991b, IAU Symposium 144, H. Bloemen (ed.), 67
Reynolds, R.J. 1993, in 'Back to the Galaxy', Holt, S.S., Verter, F. (eds), AIP Conf. Proc **278**, 156
Schnepf, N.G. et al., 1993, in 'Compton Gamma-Ray Observatory', St. Louis, AIP Conf. Proc. **280**, 85
Schönfelder,V. et al., 1995, Proc. Texas Symp. on Relativistic Astrophysics, Munich *in press*
Skibo, J.G., Ramaty. R. 1993a, A&A Suppl., **97,145**
Skibo, J.G., Ramaty. R. 1993b, in 'Compton Gamma Ray Observatory', St. Louis, AIP Conf. Proceedings **280**, 70
Skibo, J.G., Ramaty. R. 1993c, Proc. 23rd ICRC, Calgary, **2**, 132
Skibo, J.G., Ramaty, R., Purcell W.R. 1995, Proc. 24th ICRC, Rome, **2**, 219
Skilling, J., Strong, A.W. 1976, A&A, **53**, 253
Snowden. S. 1993, private communication
Sodroski, T.J. 1991, ApJ, **366**, 95
Sodrowski, T.J. et al. 1995, ApJ, **452**, 262
Solomon, P.M. et al. 1987, ApJ, **319**, 730
Solomon. P.M., Barrett. J.W., 1991, in IAU Symp. 146, Combes, F., Casoli, F., (eds), 235
Stecker F. W. 1988, ApJ, *Cosmic Gamma Rays, Neutrinos and Related Astrophysics*, ed Shapiro M. M. and Wefel J.P., (Dordrecht:Reidel), 85
Strong, A.W., 1995 Proc. Capri Workshop 'Imaging in High-Energy Astronomy'
Strong, A. W., Skilling, J. 1977, ESA SP-124, 147
Strong, A.W., Youssefi G, 1995, Proc. 24th ICRC, Rome, **3**, 48
Strong, A. W. et al. 1985, Proc. 19th ICRC, La Jolla, **1**, 333
Strong, A. W. et al. 1988, A&A, **207**, 1
Strong, A. W. et al. 1993a, in 'Compton Gamma Ray Observatory', St. Louis, AIP Conf. Proc. **280**, 35
Strong, A. W. 1994, in 'The Second Compton Symposium', College Park MD 1993, AIP Conf. Proc. **304**, 463
Strong, A. W. et al. 1994, A&A, **292**, 82
Strong, A. W. et al. 1995, Proc. 24th ICRC, Rome, **2**, 234
Sreekumar, P. et al. 1992, ApJ Lett **400**, L67
Sreekumar, P. et al. 1993, Phys. Rev. Lett. **70**, 127
Taira T et al. 1993 Proc 23rd ICRC, **2**, 128

Thompson, D.J. et al. 1995, ApJ Supp. **101**, 259
Thompson, D.J., Fichtel, C.E. 1982, A&A, **109**, 352
Suchkov, A., Allen R.J., Heckman, T. M. 1993, ApJ **413**, 542
Webber, W.R. 1983, in 'Composition of Origin of Cosmic Rays', ed. Shapiro, M. M., pub. D. Reidel, p. 83
Webber, W.R., Lee, M.A., Gupta, M. 1992, ApJ, **390**, 96
Wolfire, M.G., Hollenbach, D., Tielens, A.G.G.M. 1993, ApJ **402**, 195
Youssefi G, Strong A. W.,1991 Proc 22nd ICRC **1**, 129