DIFFUSE GALACTIC CONTINUUM EMISSION

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ABSTRACT

Some of the most important questions about the diffuse continuum emission from the Galaxy are briefly discussed, based mainly on pre-Compton Observatory results but including new information from COMPTEL. 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.

INTRODUCTION

This paper reviews some of the important issues for the interpretation of the diffuse Galactic continuum. It does not attempt to include the latest Compton Observatory results since these are presented in various papers from the instrument teams at this conference. However recent new results from COMPTEL are included since these do not appear elsewhere.

Since we certainly do not yet understand the diffuse emission in all its detail, I will concentrate on what seem to be the most important issues upon which the interpretation depends. There are 4 key questions to which we don't yet have final answers: the rôle of molecular hydrogen, the point-source contribution, the cosmic-ray gradient and the electron spectrum. Many other topics such as the Galactic centre, local clouds, and spectral variations are important but will not be discussed here. A useful recent review of the diffuse emission is given by Bloemen (1993).

SOURCE CONTRIBUTION

The source contribution is unknown, and has generally been presumed rather small; quantitative estimates are very difficult. 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 et al. (this conference) have studied this issue using EGRET data. 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. Up to now the fit to COS-B has not indicated the need for any non-gas component beyond the 10% level. 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, once sufficient pulsar spectra have been measured.

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THE ROLE OF MOLECULAR HYDROGEN

The analysis of COS-B data (Lebrun et al. 1983, Bloemen et al. 1984, 1986, Strong et al. 1988) was based on fitting to HI and CO surveys; in the final analysis the Galaxy was divided into Galactocentric rings and the emissivity q(R) assumed to be a function of radius only. The other parameter was the apparent conversion factor from CO to H_2, X_γ . I use here the notation X_γ to emphasize that it is not necessarily the same as the non-gamma value (X_{CO}) because of the possibility (for example) that the cosmic-ray density is different between cloud and intercloud medium. An important feature of this analysis was that both the shape of q(R) and X_γ could either be energy dependent or constrained to be energy-independent. The main limitation of this analysis was the assumption of cylindrical symmetry for the emissivity (but not for the gas itself, which was based on survey data).

An important conclusion of the full Galactic plane work (Strong et al. 1988) was that it is possible to separate not only the HI and CO-related components, but also to distinguish q(R) from 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.

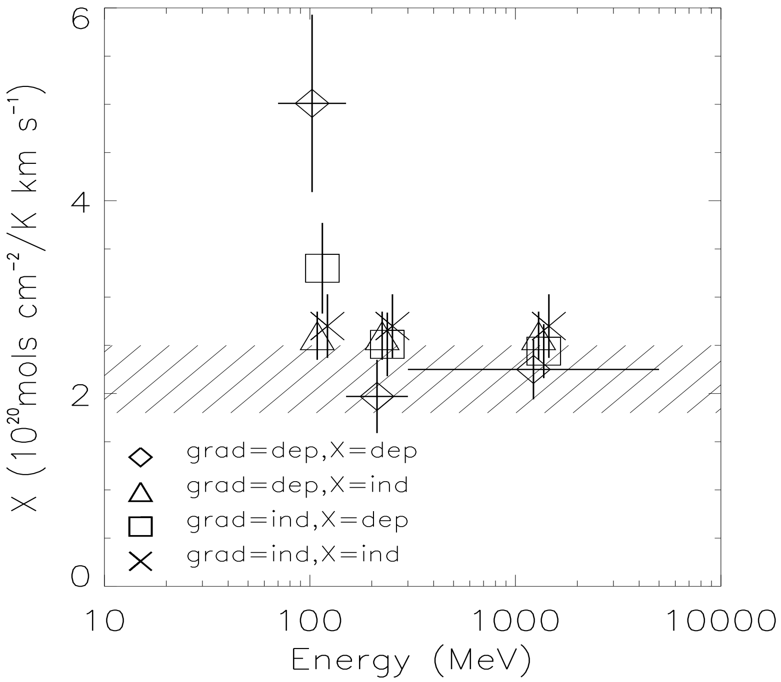

Fig 1 COS-B estimates of X_γ (Strong et al. 1988). The symbols refer to different constraints on the energy dependence of the shape of the gradient q(R) and X_γ ; dep: parameter is energy dependent, ind: parameter constrained to be energy independent. The hashed line indicates the approximate range of X_{CO} found from non-γ-ray studies of molecular clouds in the inner Galaxy.

Fig 1 shows the derived value of X_γ as a function of energy (3 ranges) for various cases depending on whether the gradient and/or X_γ were allowed to be energy dependent. The two high-energy points were the basis of the value 2.3±0.3 10^{20} mols. $cm^{-2}/(K\ km\ s^{-1})$ quoted as best value and often used since by radio astronomers for cloud mass estimates. Note that X_γ seems to increase below 150 MeV; the alternative to this, an energy-dependence in the shape of q(R), was found less likely based on statistical tests, but this conclusion is at the limits of the data. A confirmation or otherwise of this effect by EGRET will be very important.

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≈ 11 kpc)
Digel, Bally, Thaddeus 1990	virial	4-14 (outer Galaxy: R≈ 13 kpc)
Carpenter,Snell,Schloerb 1990	virial, LTE	3.6** (outer Galaxy: R≈ 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 (preliminary)

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

Table 1. Recent published estimates of X_{CO}

Table 1 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). A new method is that based on soft-X-ray absorption in ρ Oph from ROSAT (Snowden 1993: preliminary result), which gives a value consistent with the other methods. Infrared survey data also supports a 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 certainly 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. 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 can probably be attributed to reduced cloud heating which might itself be influenced in part by cosmic-rays (Suchkov et al. 1993), adding an interesting twist to the problem.

EMISSIVITY GRADIENTS

Fig 2a shows the gradient from COS-B based on a fit to all energies and assuming that the gradient is energy-independent (but with X_γ energy dependent). 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.

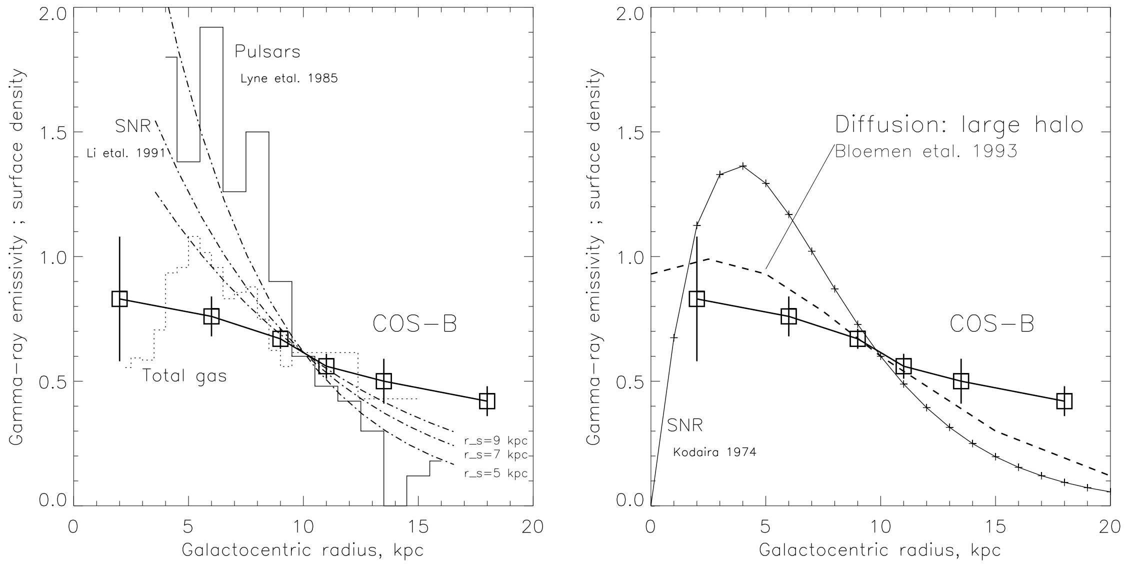

Fig 2 (a) Emissivity gradient from COS-B (squares: Strong et al. 1988) compared with various potential cosmic-ray sources. Upper histogram: pulsars, Lyne et al. (1985); dash-dot line: SNR, Li et al. (1991), various possible scale lengths; dotted histogram: surface density of total gas (HI & H_2) based 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.

An alternative model which does not explicitly invoke gradients is described by Bertsch et al. (1993); 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. This model also fits the COS-B intensity distribution and a comparison with EGRET is given by Hunter et al. (this conference). From Fig 2a 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. It may indeed be hard to distinguish them even with EGRET data. If we adopt the conventional diffusive propagation model, with SNR as cosmic-ray sources, then it is hard to obtain the small gradient. Bloemen et al. (1993) have investigated this and find that for a source distribution based on SNR from Kodaira (1974) a very large halo (20 kpc) is required to smooth out the source distribution so that it agrees with the observed gradient (Fig 2b). 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. (1993). Webber et al. (1992) made a similar calculation and propose 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.

RESULTS FROM COMPTEL

An analysis similar to that described above for COS-B has been performed on the COMPTEL Phase I Sky Survey data; preliminary results based on early parts of the survey have already been published (Strong et al. 1993a,b). Here I report on some recent developments (Strong et al. 1993c). The main objectives are to get the emission spectrum, separate the atomic and molecular gas, and, since bremsstrahlung is presumably the most important process, to learn about the low energy electron spectrum. A gradient is not yet included (the effect should be small) but the value of X_γ may be fixed or left as a free parameter. Data from 25 observations were combined in the COMPTEL 3-D dataspace consisting of photon scatter vector and Compton scatter angle from the energy deposits in the upper and lower detectors. The background has been estimated using a set of high-latitude observations; only the shape (in dataspace) of the background is in this way determined, the absolute level is left as a free parameter to be determined in the fitting. The four standard energy ranges 0.75-1, 1-3, 3-10 and 10-30 MeV were used. The method used is a maximum-likelihood fit in dataspace using the COMPTEL response.

The basic result is that we detect the galactic emission; out of a total of 6 million events about 300 000 are attributed to the Galaxy, making it by far the strongest COMPTEL γ-ray source (about ten times the Crab, which is by far the strongest point source). Fig 3 shows the emissivity spectrum, combined with that from COS-B. Note that it is legitimate to combine COMPTEL and COS-B results since the model used was the same for both analyses. The COMPTEL emissivities depend on whether we fit X_γ or fix it at the canonical COS-B value; but the difference is significant only in the 10-30 MeV range. The emissivity values are consistent with those previously published, but are more reliable being based on a much larger data set.

It must be emphasized that we have no *proof* that all 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 the COS-B results (see section on point source contribution above).

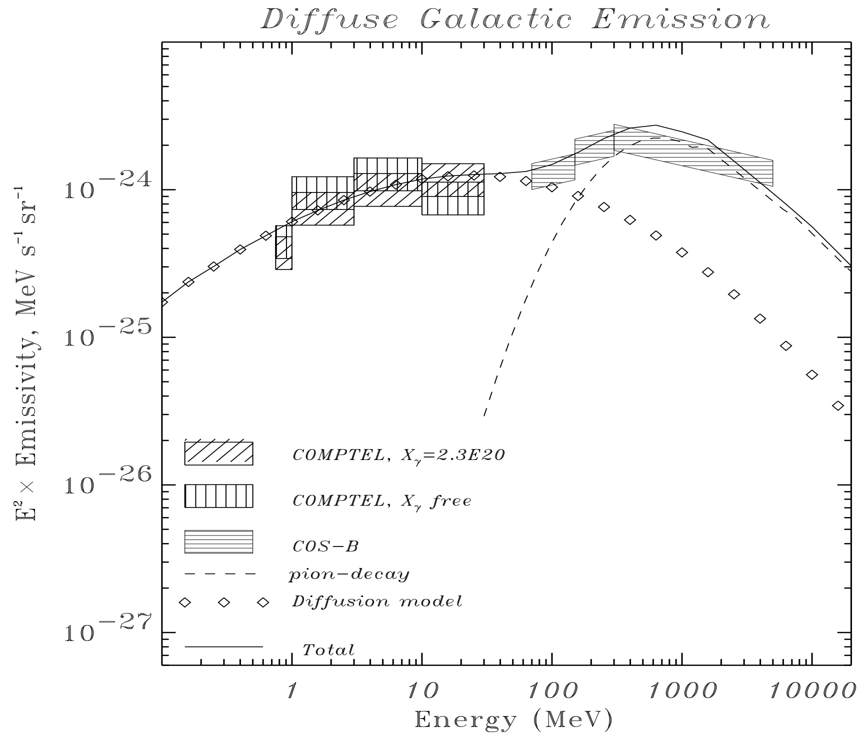

Fig 3 γ-ray emissivity from COMPTEL and COS-B. Slanted shading: COMPTEL, X_γ fixed at 2.3 10^{20} mols. cm^{-2}/(K km s^{-1}) ; vertical shading: COMPTEL, X_γ free; horizontal shading: COS-B, X_γ free (Strong et al. 1988). Model predictions: dashed line: π^o-decay (Dermer 1986); diamonds: bremsstrahlung from electron spectrum based on electron spectrum shown in Fig 4; solid line: π^o-decay + bremsstrahlung.

THE EMISSIVITY SPECTRUM FROM COSMIC RAY INTERACTIONS AND THE COSMIC-RAY ELECTRON SPECTRUM

The observed emissivity spectrum shown in Fig 3 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) 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.

The low-energy electron spectrum is strongly modulated by ionization losses, so that the computed spectrum depends critically on the propagation parameters. Computations of the electron spectrum using the 'leaky-box' model have been performed by Skibo and Ramaty (1993a,b,c), Skibo (1993), and Strong et al. (1993a). The leaky-box electron spectra imply lower bremsstrahlung emissivities at low energies than the values derived from the COMPTEL analysis. This could be explained if there is a significant point-source contribution at low energies. Note that recent work taking into account He and ionized H in the ISM indicates higher values of grammage than the conventional 6-8g cm^{-2} (Soutoul et al. 1990, Ferrando et al. 1991: 14.4βg cm^{-2} below a few GV; for a critical discussion see Ferrando 1993). This would reduce the predicted low-energy spectrum still further and reinforce the need for some additional γ-ray component such as point sources. [1]

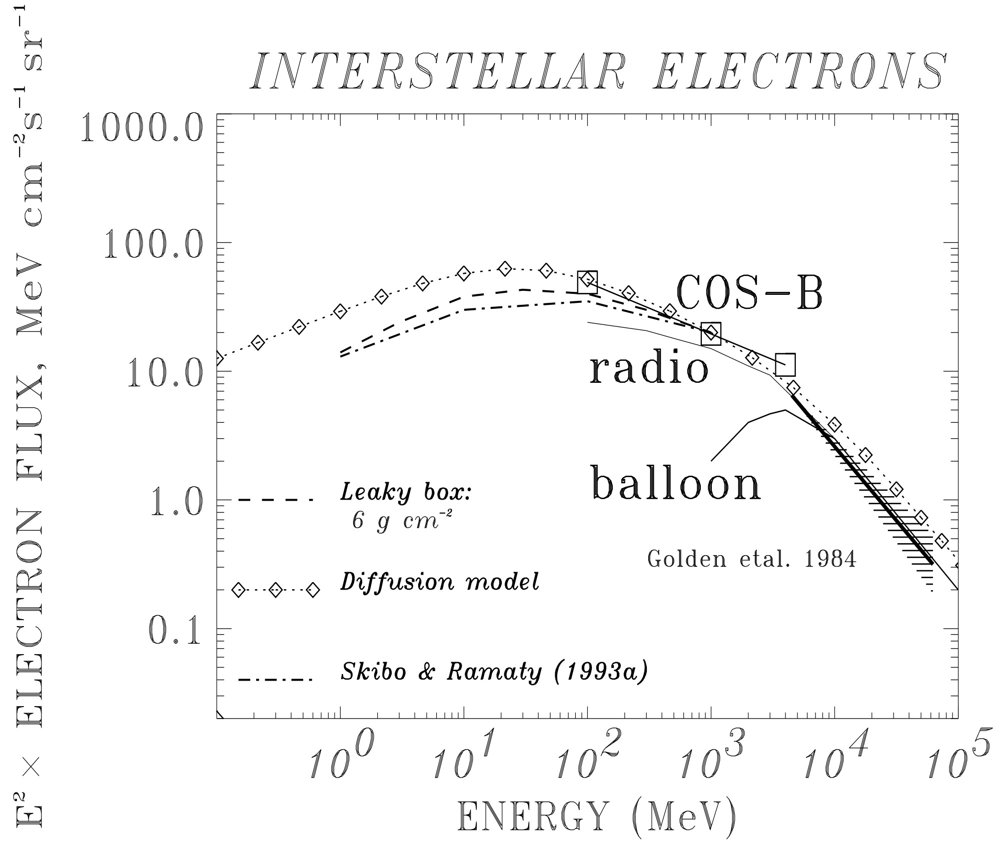

Fig 4 Electron spectrum: horizontal shading: balloon measurement (Golden et al. 1984); continuous lines: balloon measurements (showing effect of solar modulation) and extrapolation based on radio (Webber 1983); squares: derived from COS-B γ-rays (Strong 1985); diamonds: diffusive energy loss model (see text) with parameters chosen to give consistency with COMPTEL γ-ray emissivities. Dashed line: leaky-box model (Strong et al. 1993a); dash-dot line: leaky box model (Skibo and Ramaty 1993a).

If however the emission *is* mainly from bremsstrahlung, we can compute the electron spectrum required to produce it. Using a diffusive halo model with appropriate parameters we obtain the electron spectrum shown in Fig 4 and the cor-

[1] Skibo and Ramaty (1993c) and Skibo (1993) obtain a much lower spectrum, in part because they adopt the new higher grammage.

responding bremsstrahlung emissivity in Fig 3 (for details of the calculation see Strong and Youssefi 1993). This spectrum would however imply either a grammage lower than the values mentioned above, or a steepening of the electron injection spectrum at low energies.

Skibo and Ramaty (1993a,b,c) point out that the low energy electrons 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 (about 1/3 using the spectrum presented here) although the *ambient* electron spectrum has much less energy content due to the large energy losses.

Fig 4 also illustrates the fact that the interstellar electron spectrum above 1 GeV deduced from γ-rays may be more intense by a factor of about 2 relative to the directly measured near-Earth spectrum, as discussed in Strong (1985); the spectrum shown is normalized to the value at 1 GeV deduced in that work from COS-B data.

COSMIC-RAYS IN MOLECULAR CLOUDS

A new COMPTEL result is a determination of X_γ from the model fitting (Fig 5). It is encouraging that we get a value comparable on average with COS-B and X_{CO} from independent methods - this gives confidence that the emission really is related to the gas. More speculatively (since the errors are still large) there is a suggestion of an energy dependence, in particular the low X_γ at low energies. Note however that the 10-30 MeV COMPTEL point is consistent with the larger value found by COS-B in the 70-150 MeV range.

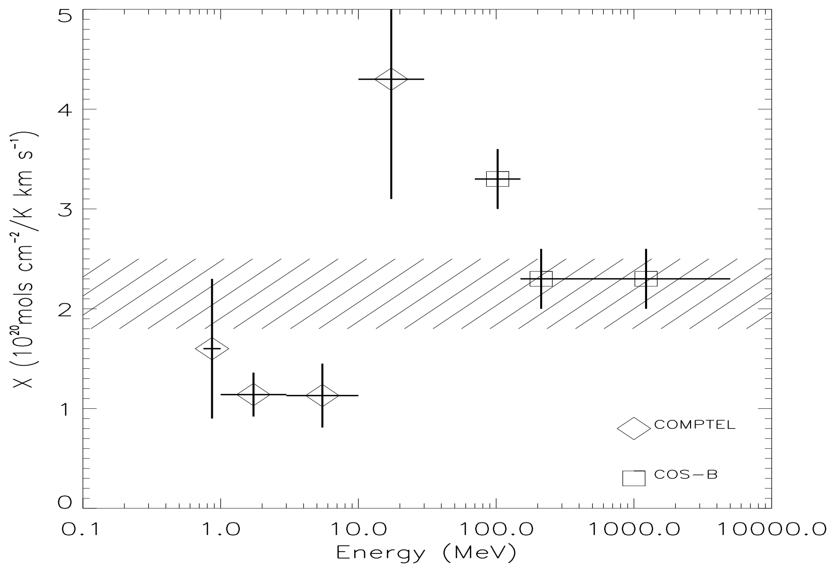

Fig 5 Estimates of X_γ from COMPTEL and COS-B. The hashed line is as in Fig 1.

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). Morfill (1982) pointed out that secondary electrons may be enhanced in clouds since they are produced inside and may be to some extent trapped; there may also be first-order Fermi acceleration due to the incoming waves. The process works only up to 300 MeV electron energies since this corresponds to 50 MeV proton momentum where ionization losses become too small to drive the process. This could lead to an excess around 100 MeV. Dogiel and Sharov (1990) investigated CR enhancement due to acceleration of primaries by turbulence in clouds together with the resulting secondary production. There is clearly much scope for interesting theoretical work here, especially with the prospect of new information from the Compton Observatory instruments.

HIGH LATITUDES

Estimates of the components of the diffuse spectrum at the Galactic pole are shown in Fig 6, compared to the SAS total intensity from Thompson and Fichtel (1982). It is now known that the distribution of warm ionized gas dominates at high z and contributes about 1/3 of the column density at the pole (Reynolds 1991, 1993). The HII may explain the disagreement between observed and predicted diffuse emission at intermediate latitudes (Bloemen 1989).

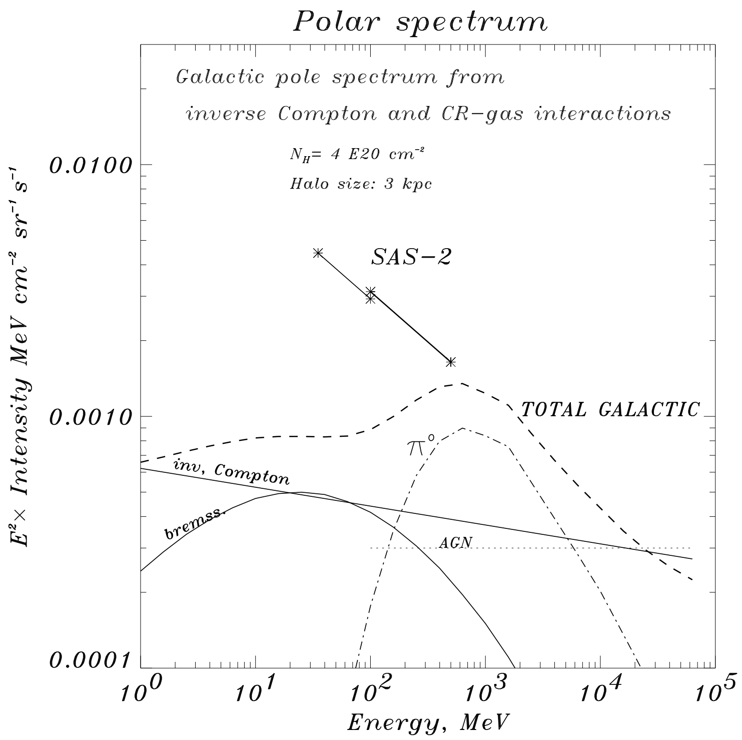

Fig 6 The components of γ-ray emission at the Galactic poles. The gas contributions are estimated using the emissivities derived from COS-B and COMPTEL, for the total gas column density towards the Galactic pole (HI+HII). The bremsstrahlung emissivities are from Fig 3. The inverse-Compton estimate is very approximate for the reasons given in the text. Dashed line is the total from Galactic processes. Horizontal dotted line: estimated AGN contribution (Stecker et al. 1993). SAS-2 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. I want to emphasize that the ISRF is very 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. We can be rather sure that in the plane it contributes not more than 10%. At high-latitudes the situation is different. Fig 4 shows a rough estimate of the spectrum expected at the galactic pole, using a halo half-thickness of 3 kpc. 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 above 10 GeV because of its very flat spectrum.

CONCLUSIONS

Among the most important questions for the Compton Observatory 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 magnitude and energy-dependence of point-source contribution and the determination of the electron spectrum over the whole 1 MeV - 10 GeV range. Another important goal is the identification of the inverse-Compton component. With the intense effort now being concentrated on the Sky Survey data, new answers can be expected soon.

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