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The distribution of cosmic-ray sources in the Galaxy, γ-rays and the gradient in the CO-to-H$_2$ relation

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Abstract. We present a solution to the apparent discrepancy between the radial gradient in the diffuse Galactic γ-ray emissivity and the distribution of supernova remnants, believed to be the sources of cosmic rays. Recent determinations of the pulsar distribution have made the discrepancy even more apparent. The problem is shown to be plausibly solved by a variation in the $W_{\rm CO}$-to-$N({\rm H}_2)$ scaling factor. If this factor increases by a factor of 5–10 from the inner to the outer Galaxy, as expected from the Galactic metallicity gradient, we show that the source distribution required to match the radial gradient of γ-rays can be reconciled with the distribution of supernova remnants as traced by current studies of pulsars. The resulting model fits the EGRET γ-ray profiles extremely well in longitude, and reproduces the mid-latitude inner Galaxy intensities better than previous models.

Key words. gamma rays – galactic structure – interstellar medium – cosmic rays – supernova remnants – pulsars

1. Introduction

The puzzle of the Galactic γ-ray gradient goes back to the time of the COS-B satellite (Bloemen et al. 1986; Strong et al. 1988); using HI and CO surveys to trace the atomic and molecular gas, the Galactic distribution of emissivity per H atom is a measure of the cosmic-ray (CR) flux, for the gas-related bremsstrahlung and pion-decay components. However the gradient determined in this way is much smaller than expected if supernova remnants (SNR) are the sources of cosmic rays, as is generally believed. This discrepancy was confirmed with the much more precise data from EGRET on the COMPTON Gamma Ray Observatory, even allowing for the fact that inverse-Compton emission (unrelated to the gas) is more important than originally supposed (Strong et al. 2000). A possible explanation of the small gradient in terms of CR propagation, involving radial variations of a Galactic wind, was recently put forward by Breitschwerdt et al. (2002).

However the derivation of the Galactic distribution of SNR, commonly based on radio surveys, is subject to large observational selection effects, so that it can be argued that the discrepancy is not so serious. But other tracers of the distribution of SNR are available, in particular pulsars; the new sensitive Parkes Multibeam survey with 914 pulsars has been used by Lorimer (2004) to derive the Galactic distribution, and this confirms the concentration to the inner Galaxy. Figure 1 compares the pulsar distribution from Lorimer (2004) with a CR source distribution which fits the EGRET γ-ray data (Strong et al. 2000). If the pulsar distribution indeed traces the SNR, then there is a serious discrepancy with γ-rays. The distribution of SNR given by Case & Bhattacharya (1998) is not so peaked, but the number of known SNR is much less than the number of pulsars and the systematic effects very difficult to account for (Green 1996). But even this flatter distribution is hard to reconcile with that required for γ-rays. Another, quite independent, tracer of the SNR distribution is the 1809 keV line of ^{26}Al; whether this originates mainly in type II supernovae or masssive stars is not important in this context, since both trace star-formation/SNR. The COMPTEL ^{26}Al maps (Knödlseder et al. 1999; Plüschke et al. 2001) show that the emission is very concentrated to the inner radian of the Galaxy. The density of free electrons shows a similar distribution (Cordes & Lazio 2003). The ^{26}Al measurements are not subject to the selection effects of other methods; although they have their own uncertainties, they support the type of distribution which we adopt in this paper.

A major uncertainty in the models of diffuse Galactic γ-ray emission is the distribution of molecular hydrogen, as traced by the integrated intensity of the $J = 1$–0 transition of ^{12}CO, $W_{\rm CO}$. Gamma-ray analyses have in fact provided one of the standard

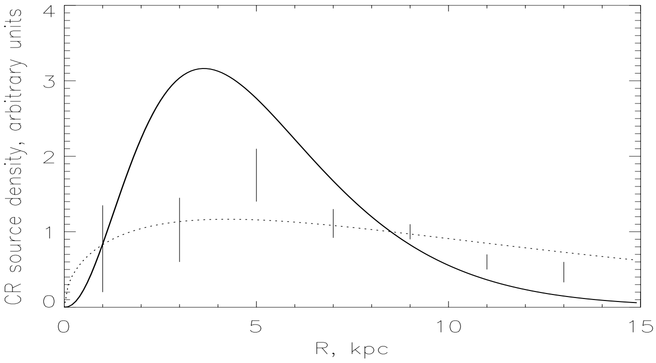

Fig. 1. CR source density as function of Galactocentric radius R. Dotted: as used in Strong et al. (2000), solid line: based on pulsars (Lorimer 2004) as used in this work, vertical bars: SNR data points from Case & Bhattacharya (1998). Distributions are normalized at R = 8.5 kpc.

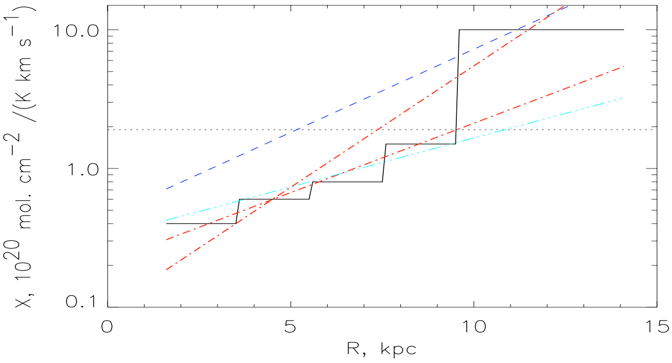

Fig. 2. X_{CO} as function of R. Dotted horizontal line, black: as used in Strong & Mattox (1996); Strong et al. (2000); solid line, black: as used for γ-rays in this work; dashed, dark blue: from Sodroski et al. (1995); dash-dot, red: using metallicity gradient as described in the text, $X_{CO} \propto Z^{-2.5}$ (Israel 2000), two lines for [O/H] = 0.04 and 0.07 dex/kpc; dash-dot-dot,light blue: using $X_{CO} \propto Z^{-1.0}$ (Boselli et al. 2002) and [O/H] = 0.07 dex/kpc. The values using metallicity are normalized approximately to those from the γ-ray analysis.

values for the scaling factor[1] $X_{CO} = N(H_2)/W_{CO}$; with only the assumption that cosmic rays penetrate molecular clouds freely, the γ-ray values are free of the uncertainties of other methods (e.g. those based on the assumption of molecular cloud virialization). However previous analyses, e.g. Strong & Mattox (1996), Hunter et al. (1997), Strong et al. (2000), have usually assumed that X_{CO} is independent of Galactocentric radius R, since otherwise the model has too many free parameters. But there is now good reason to believe that X_{CO} increases with R, both from COBE/DIRBE studies (Sodroski et al. 1995, 1997) and from the measurement of a Galactic metallicity gradient combined with the strong inverse dependence of X_{CO} on metallicity in external galaxies (Israel 1997, 2000). A rather rapid radial variation of X_{CO} is expected, based on a gradient in [O/H] of 0.04–0.07 dex/kpc (Hou et al. 2000; Deharveng et al. 2000; Rolleston et al. 2000; Smartt 2001; Andrievsky et al. 2002) and the dependence of X_{CO} on metallicity in external galaxies: $\log X_{CO} \propto -2.5$ [O/H] (Israel 1997, 2000), giving $X_{CO} \propto 10^{(-0.14\pm0.04)R}$, amounting to a factor 1.3–1.5 per kpc, or an order of magnitude between the inner and outer Galaxy[2]. A less rapid dependence, $\log X_{CO} \propto -1.0$ [O/H], was found by Boselli et al. (2002), which however still implies a significant $X_{CO}(R)$ variation. Boissier et al. (2003) also combine the metallicity gradient with $X_{CO}(Z)$ within individual galaxies, to obtain radial profiles of H_2, and give arguments for the validity of this procedure. Digel et al. (1990) found that molecular clouds in the outer Galaxy ($R \sim 12$ kpc) are underluminous in CO, with X_{CO} a factor 4 ± 2 times the inner Galaxy value. Sodroski et al. (1995, 1997) derived a similar variation ($\log X_{CO}/10^{20} = 0.12R - 0.34$) when modelling dust emission for COBE data. Pak et al. (1998) predicted the physical origin for a variation of X_{CO} with Z. Papadopoulos et al. (2002) and Papadopoulos (2004) discuss the physical state of this metal-poor gas phase in the outer parts of spiral galaxies (relatively warm and diffuse). Observations of H_2 line emission from NGC 891 with ISO (Valentijn & van der Werf 1999) indicate a massive cool molecular component in the outer regions of this galaxy, supporting the trend found in our Galaxy.

Figure 2 illustrates some of the possible X_{CO} variations implied by these studies. For the cases where metallicity is used to estimate X_{CO}, the values are normalized approximately to the values used in the present γ-ray analysis, since we are only interested in comparing the variations of X_{CO}. From the viewpoint of γ-rays, the effect of a steeper CR source distribution is compensated by the increase of X_{CO}. Thus we might expect to resolve the apparent discrepancy in the source distribution, and improve our understanding of the Galactic γ-ray emission. In this paper we investigate quantitatively this possibility. Note that the γ-rays include major contributions from interactions with atomic hydrogen and from inverse Compton scattering, both of which are independent of X_{CO}; this means that the X_{CO} variation has to be quite large to have a significant effect.

2. Data

The EGRET and COMPTEL data are the same as described in Strong et al. (2000, 2004a). The EGRET data consist of the standard product counts and exposure for 30 MeV–10 GeV, augmented with data for 10–120 GeV. The γ-ray point sources in the 3EG catalogue have been removed as described in Strong et al. (2000). The HI and CO data are as described in Moskalenko et al. (2002) and Strong et al. (2004a); they consist of combined surveys divided into 8 Galactocentric rings on the basis of kinematic information. Full details of the procedures for comparing models with data are given in Strong et al. (2004a) to which the reader is referred.

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[1] Units: molecules cm^{-2}/ (K km s^{-1}).

[2] The values given by Israel (1997, 2000) include the effects of the radiation field, implicitly containing the radiation field/metallicity correlation of his galaxy sample. X_{CO} is positively and almost linearly correlated with radiation field, so the dependence of X_{CO} for constant radiation field is even larger: $\log X_{CO} \propto -4$ [O/H] (Israel 2000). By adopting the coefficient –2.5 we implicitly assume the same radiation/metallicity correlation within the Galaxy as over his galaxy sample.

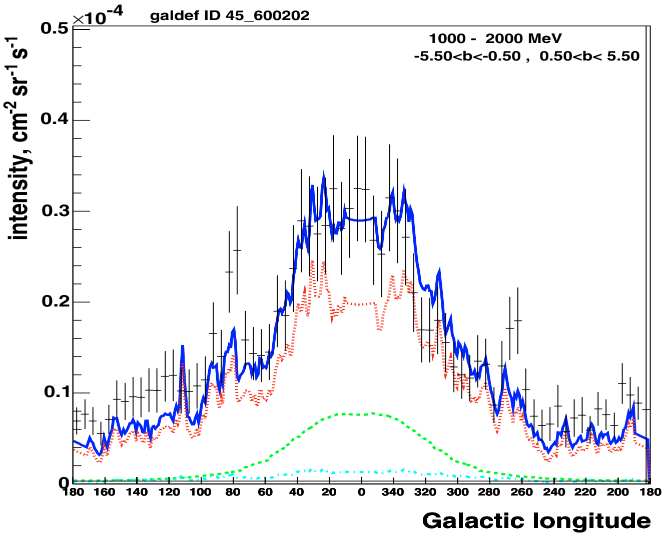

Fig. 3. Longitude profile of γ-rays for 1000–2000 MeV, averaged over $|b| < 5.5°$. Vertical bars: EGRET data; lines are model components convolved with the EGRET point-spread function: green: inverse Compton emission, red: π^0-decay, light blue: bremsstrahlung, dark blue: total.

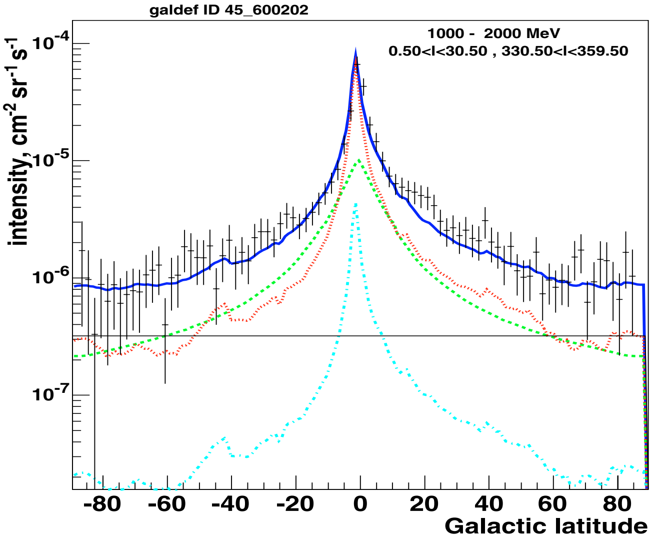

Fig. 4. Latitude profile of γ-rays for 1000–2000 MeV, averaged over $330° < l < 30°$. Data and curves as in Fig. 3. The extragalactic background is shown as a black horizontal line.

3. Model and method

We use the GALPROP program (Strong et al. 2000, 2004a) to compute the models. GALPROP was extended to allow a variable $X_{\rm CO}(R)$ to be input. The distribution of CR sources is assumed to follow that of pulsars in the form given by Lorimer (2004), as shown in Fig. 1. The other parameters, in particular the CR nucleon and electron injection spectral shape and propagation parameters, are taken from the "optimized model" of Strong et al. (2004a). As before the halo height is taken as $z_h = 4$ kpc, and the maximum radius $R = 20$ kpc. The isotropic background is as derived in Strong et al. (2004b). Since in this work we simply wish to demonstrate the possibility to obtain a plausible solution, we adopt a heuristic approach, adjusting $X_{\rm CO}(R)$ to obtain a satisfactory solution as shown in Fig. 2. The electron flux has been scaled down by a factor 0.7 relative to Strong et al. (2004a) to obtain an optimal fit.

4. Results

Figures 3 and 4 show the longitude and latitude distributions for 1–2 GeV, compared to EGRET data. A rather rapid variation of $X_{\rm CO}$ is required to compensate the CR source gradient, but it is fully compatible with the expected variation based on metallicity gradients and the COBE result, as described in the Introduction. The longitude and latitude fits are good except in the outer Galaxy where the prediction is rather low. One possible reason for this is that the CR source density does not fall off so fast beyond the Solar circle as given by the adopted pulsar distribution, which has an exponential decay. Another possibility could be even larger amounts of H_2 in the outer Galaxy than we have assumed (see discussion in Introduction). We have chosen the range 1–2 GeV for the profiles since this is where the gas contribution and hence the effect of $X_{\rm CO}$ is maximal. An exhaustive comparison of profiles in all energy ranges is beyond the scope of this Letter, but in fact the agreement is good at all energies. The larger CR gradient in this model has another consequence: the predicted inverse-Compton emission in the inner Galaxy is more intense at intermediate latitudes where the interstellar radiation field is still high; this is precisely the region where previous models (Hunter et al. 1997; Strong et al. 2000, 2004a) have had problems to reproduce the EGRET data. Figure 5 shows the model spectrum of the inner Galaxy compared with EGRET data; the fit is similar to that of models (Strong et al. 2004a) with ad hoc source gradient and constant $X_{\rm CO}$. The prediction is rather high above 20 GeV, however the EGRET data are least certain in this range (Strong et al. 2004a).

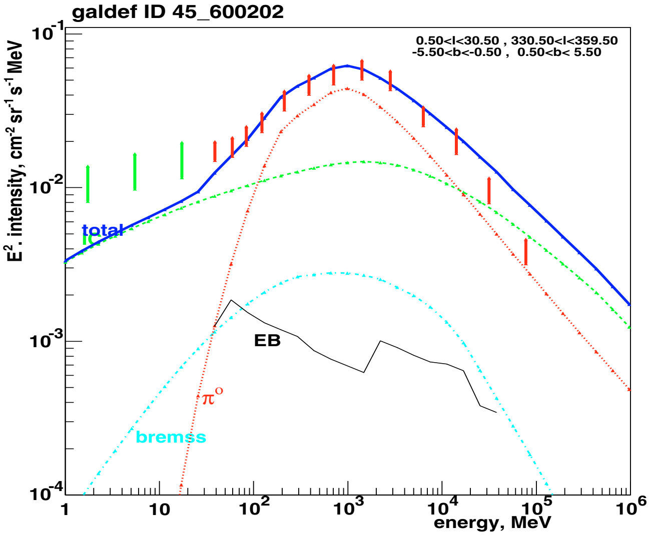

Fig. 5. Spectrum of inner Galaxy, $330° < l < 30°$, $|b| < 5.5°$. Vertical bars: EGRET data (red), COMPTEL data (green). Curves: predicted intensities; inverse Compton (green), π^0-decay (red), bremsstrahlung (light blue), extragalactic background (black), total (dark blue).

5. Discussion

We have shown that a good fit to the EGRET data is obtained with the particular combination of parameters chosen. We can however ask whether the pulsar source distribution combined with a constant $X_{\rm CO}$ could also give a good fit if we reduce the CR electron intensity, to supress the inner Galaxy peak from inverse Compton emission. This can indeed reproduce the longitude profile in the inner Galaxy, but fails badly to account for the latitude distribution, since it has a large deficit at intermediate latitudes. Some variation of $X_{\rm CO}$ is therefore required. The suggested variation of $X_{\rm CO}$ would have significant impact on the Galactic H_2 mass and distribution. Warm molecular hydrogen in the outer parts of spiral galaxies that is not traced by CO emission may be detectable by the Spitzer observatory in 28 μm vibrational emission. These issues will be addressed in future work.

6. Conclusions

Two a priori motivated developments allow us to obtain a more physically plausible model for Galactic γ-rays, simultaneously allowing a CR source distribution similar to SNR as traced by pulsars and an expected variation in the $W_{\rm CO}$-to-$N({\rm H}_2)$ conversion factor. Obviously the uncertainty in both the source distribution and $X_{\rm CO}$ are large so our solution is far from unique, but it demonstrates the possibility to obtain a physically-motivated model without resorting to an ad hoc source distribution. This result supports the SNR origin of CR. The resulting model also gives improved predictions for γ-rays in the inner Galaxy at mid-latitudes. We have therefore achieved a step towards a better understanding of the diffuse Galactic γ-ray emission. This result is important input to the development of models for the upcoming GLAST mission. This Letter is intended only to point out the potential importance of the effect. The next step will be a more quantitative analysis to derive $X_{\rm CO}(R)$ from the γ-ray data themselves.

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