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The distribution of γ-ray emissivity in the Galaxy

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Abstract. The longitude distribution of γ-ray intensity measured with the SAS-2 satellite has been unfolded to give the Galactic γ-ray emissivity. We find that the observations are consistent with either a cylindrically symmetric emissivity distribution, or a distribution uniform along spirals with tilt angles similar to those for spiral arms. The γ-ray distribution in the Galaxy seems to be more in accord with models based on the molecular hydrogen distribution than those based on spiral structure.

1. Introduction

The distribution of Galactic γ rays reported by Fichtel *et al* (1975) has attracted much theoretical interest in view of its relation to the structure of the Galaxy and the distribution of cosmic rays. Two principal types of interpretation have emerged.

(*a*) Models based on the spiral arm structure of the Galactic gas, in which cosmic ray density is assumed to vary as about the first power of the gas density (Bignami *et al* 1975, Paul *et al* 1975, Schlickeiser and Thielheim 1974).

(*b*) Models in which most of the γ-ray structure is attributed to the molecular hydrogen ring at Galactocentric radius $R \sim 5$ kpc (Dodds *et al* 1974, Stecker *et al* 1975, Stecker 1975).

Convincing arguments for each of these approaches are advanced by their respective proponents, and the longitude distributions predicted in the adopted detailed models are in each case in fair agreement with the SAS-2 data.

At present it would seem difficult to rule out either class of model on theoretical grounds or by using data apart from the γ-ray distribution. The question naturally arises: to what extent does the γ-ray data allow a distinction?

In an attempt to answer this question, we adopt the alternative approach to that of constructing models from which the longitude distribution $j(l)$ is calculated; instead, we unfold $j(l)$ to give a distribution of emissivity $\epsilon(R, \phi)$ (where R, ϕ are Galactocentric polar coordinates), by making some assumptions about the symmetry of this function. A similar analysis was made of the earlier SAS-2 results (Strong 1975), and this was used by Dodds *et al* (1975) to discuss the types of model described above; the increased angular resolution of the most recent data (5° in longitude compared to 10°) justifies a re-analysis. The technique is similar in essence to that used by Puget and Stecker (1974), Puget *et al* (1976) but differs in preserving all the information content of the original data—in other words, the data are represented in an alternative and revealing manner which is convenient for comparison with models for Galactic γ-ray production.

The two forms assumed here for $\epsilon(R, \phi)$ are that ϵ is independent of ϕ, that is, cylindrical symmetry and, since this is clearly inappropriate for the case of spiral structure, we consider the case of ϵ constant on spirals $R(\phi)$ based on Galactic spiral structure. The method first serves as a test for consistency of the assumed form of $R(\phi)$ with the data; provided this consistency is confirmed, the possibility of correlations with large-scale Galactic features can be discussed.

2. Analysis of data

2.1. Unfolding of data assuming radially symmetrical emissivity

Before unfolding, the longitude distribution $j(l)$ was corrected for the isotropic background. Analysis was restricted to the range $l = 0$–$180°$ because of the absence of SAS-2 data in the range $290° < l < 310°$. The method is that of Strong (1975).

The disc is divided into rings of constant relative emissivity W_i such that the ith ring corresponds to the ith bin of data. Analysis for $0° \leq l \leq 80°$ gives 16 rings. The region from here out to Galactocentric distance $R = 15$ kpc forms the 17th ring which is assumed to have constant emissivity because the observed flux is fairly uniform for $80° < l < 180°$. The emissivities are normalized to give $W_{17} = 1$. For $R > 15$ kpc, $W_i = 0$.

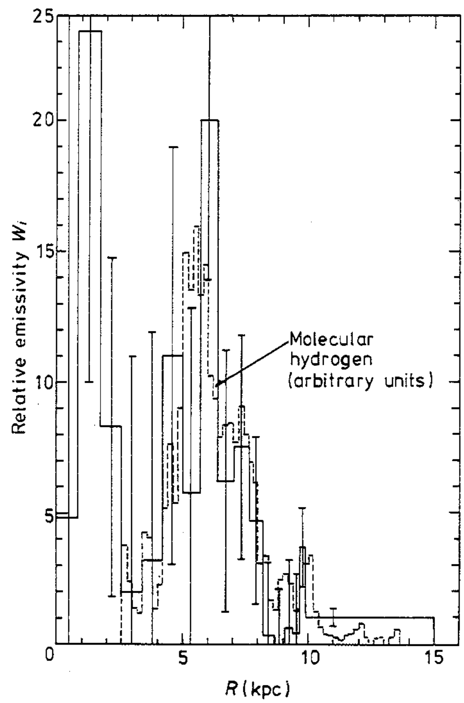

Figure 1. Results of unfolding for radial symmetry, using the SAS-2 data (Fichtel *et al* 1975) in the 0–85° longitude range corrected for the isotropic background, showing emissivity W_i against distance. The broken line is the molecular hydrogen distribution from Scoville and Solomon (1975).

Negative values of W_i are not corrected to zero in the analysis. The unfolding is sensitive to the Galactic plane thickness since the data as presented are integrated over the wide latitude range of $\pm 10°$. In the analysis a 'flat slab' model is used with a thickness of 230 pc and constant emissivity throughout this thickness is assumed. The use of a more elaborate model is not justified by the data at the present time. The errors in W_i due to the errors on the experimental data are calculated analytically. The resulting distribution from this analysis is shown in figure 1.

The unfolding procedure was also carried out for the longitude distribution first corrected for both the isotropic background and the contribution from nearby (< 1 kpc) gas as estimated by Puget *et al* (1975, 1976). The result is shown in figure 2. The similarity between figures 1 and 2 shows that the local contributions are reasonably uniform (as evident from Puget 1975, 1976) and so do not mask large scale structure.

The volume emissivity for γ rays above 100 MeV is given by $\epsilon_i = 9{\cdot}4 \times 10^{-26} W_i \text{ cm}^{-3} \text{ s}^{-1}$ and the surface emissivity by $6{\cdot}5 \times 10^{-5} W_i \text{ cm}^{-2} \text{ s}^{-1}$. This provides (using figure 1) a total Galactic emission of $1{\cdot}3 \times 10^{42} \text{ s}^{-1}$ above 100 MeV.

2.2. *Unfolding of the data assuming constant emissivity along spiral sections*

The method is similar to that described in § 2.1, and again analysis has been restricted to the range $l = 0$–$180°$. The circular annuli are now replaced by spiral sections so that the ith spiral corresponds to the ith bin of data. The equation used for the spiral field is that

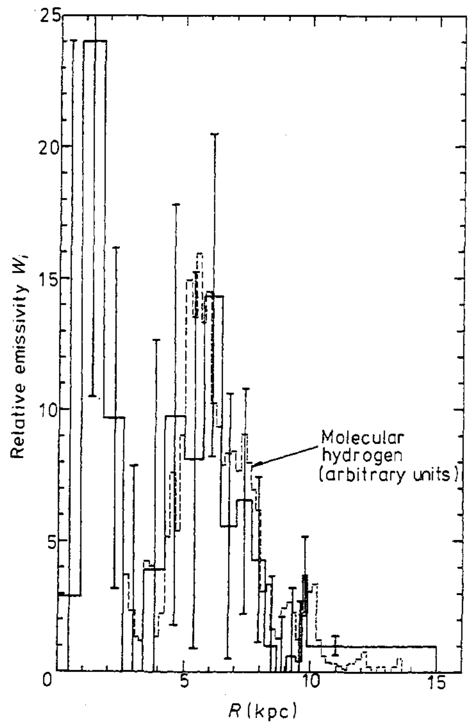

Figure 2. Results of unfolding for radial symmetry, using the SAS-2 data corrected for both the isotropic background and the contribution from nearby (< 1 kpc) gas as estimated by Puget *et al* (1975, 1976). Note how similar this is to figure 1. The broken line is the molecular hydrogen distribution from Scoville and Solomon (1975).

given by Burton (1971), based on 21 cm observations of the Sagittarius and Scutum arms. This is a spiral of the form $R \propto e^{\phi \tan(t)}$ with $\tan(t) = t_1 R + r_0$ with the condition that $t = 8°$ at $R = 5$ kpc and $t = 5°$ at $R = 10$ kpc.

Figure 3 shows the result of this analysis when both the isotropic background and nearby contribution are first subtracted from the data. Emissivities are given for points along the radius vector joining the sun to the Galactic centre. The Scutum and Sagittarius spiral arms lie in the shaded regions.

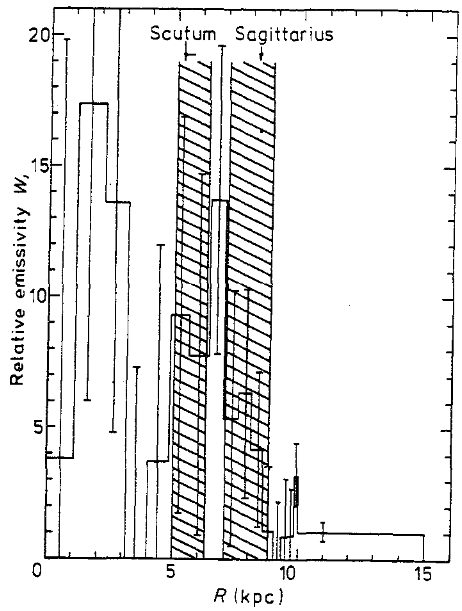

Figure 3. Results of unfolding of the SAS-2 data corrected for both the isotropic background and the contribution from nearby (< 1 kpc) gas as estimated by Puget *et al* (1975, 1976), assuming constant emissivity along spiral sections. Emissivities along the radius vector joining the sun to the Galactic centre are shown. The Scutum and Sagittarius neutral hydrogen spiral arms lie in the shaded regions.

3. Discussion and conclusions

The distributions W_i shown in the figures indicate that the data are consistent with either the cylindrical or the assumed spiral symmetry in $W(R, \phi)$; in fact the two analyses lead to very similar results and it is not possible to distinguish the models on this basis alone.

The main peak (apart from the Galactic centre) is in bin 8 ($35° < l < 40°$), corresponding to $5{\cdot}7 < R < 6{\cdot}5$ kpc in figures 1 and 2. The reason for the apparent dichotomy between the two classes of model is now clear; this peak lies about 0·5 kpc outside the main H_2 peak (which coincides with the Scutum arm) and is about 1·5 kpc interior to the Sagittarius arm. This lack of clear-cut correlation with either feature (which may well be purely a result of poor statistics, as the error bars show) explains why either class of model can give about the same degree of success in reproducing $j(l)$.

However, from figure 3 we can draw the conclusion that there is no evidence from the γ-ray data for a region of low emissivity corresponding to the Scutum–Sagittarius interarm region—indeed the main peak occurs here. On the other hand the apparent fairly steady increase in emissivity is well matched by the molecular hydrogen (figures 1 and 2). We would therefore tentatively conclude that the present data indicate that the predominant factor determining the γ-ray structure is the molecular hydrogen distribution (with perhaps some increase in cosmic ray intensity), rather than a collective effect of correlated increases in gas and cosmic rays in spiral arms.

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