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1975 J. Phys. A: Math. Gen. 8 617

(http://iopscience.iop.org/0305-4470/8/4/023)

J. Phys. A: Math. Gen., Vol. 8, No. 4, 1975. Printed in Great Britain. © 1975

Derivation of γ-ray emissivity in the Galaxy from satellite data

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Received 12 June 1974

Abstract. A method of deriving the γ-ray emissivity in the Galaxy by unfolding the longitudinal distribution of γ-ray intensity is proposed, and applied to the available data from the SAS-II and OSO-III instruments. The uncertainties in the analysis resulting from statistical errors in the data are estimated. A broad enhancement of emission 3–8 kpc from the Galactic centre is found. There is evidence for a drop in emissivity within 3 kpc of the centre, although the uncertainties in this region are very large.

1. Introduction

New results from the SAS-II satellite (Kniffen *et al* 1973, Fichtel 1974) have improved considerably our knowledge of the distribution of γ-ray intensity along the Galactic plane, providing higher resolution and better statistics than were available in the earlier OSO-III survey (Kraushaar *et al* 1972).

The correct interpretation of the γ-ray emission is important because it is related to the distribution and origin of cosmic rays in the Galaxy, and is the only method available for studying cosmic-ray protons on the Galactic scale (making the usual assumption that the γ-rays originate from π^0 mesons produced, in turn, in proton–interstellar gas nucleus interactions). In fact, if some other process is responsible for the γ-rays the present analysis, which gives the distribution of emissivity, is still correct.

At present, little information is available on the latitude distribution of gamma-rays near the plane, except that the 2σ width is probably smaller than 6° (Kniffen *et al* 1973) and possibly as small as 3° (Share *et al* 1974).

The fundamental problem is therefore to unfold the longitudinal distribution $j(l)$ of γ-ray line intensity to obtain the emissivity q (defined here as number of γ-rays with energy greater than 100 MeV emitted per cubic centimetre per second) as a function of position in the Galaxy. The resulting distribution can then be compared directly with the predictions of various theoretical models.

Models have been proposed by Strong *et al* (1973), Stecker *et al* (1974) and Bignami and Fichtel (1974); the first two propose enhanced cosmic-ray intensity in a ring between 3 and 6 kpc from the Galactic centre (associated with a region of larger magnetic field in the first model, and with large-scale Fermi acceleration in the second). The third model differs from this in assigning a large part of the emission to the Sagittarius arm at 8 kpc from the centre; this difference provides a basis for an observational distinction between the models.

It is therefore important to make a careful analysis of the uncertainty in the derived Galactic emissivity which results from statistical errors in the observations of $j(l)$. In particular, $j(l)$ becomes progressively less sensitive to emission at distances between 5 and 10 kpc from the sun, so that an analysis of the uncertainty in this region is essential.

In this paper a method of analysis is described in some detail and it is applied to the currently available satellite data. When new data become available the method can be used there too.

In the following paper by Dodds *et al* (1975), alternative models are used to explain the emissivity data derived in the present work.

2. Methods of analysis

Although there is not in general a unique solution for q for a given $j(l)$, the assumption of cylindrical symmetry about the Galactic centre does imply a unique solution $q(R)$, where R is the distance from the Galactic centre. This solution can be obtained as follows.

Divide the disc into annular rings, so that the ith ring corresponds to the ith bin of data, as indicated in figure 1. For data presented in bins of width Δl, the rings have inner and outer radii $R_0 \sin(i-1)\Delta l$ and $R_0 \sin i\Delta l$ respectively, where R_0 is the distance from the sun to the Galactic centre, taken as 10 kpc. The observed flux from the jth longitude bin is denoted by J_j. The emissivity in the Galactic plane is assumed to be constant for 15 kpc $> R > R_0$ (the nth ring), and zero for $R >$ 15 kpc. This is justified because the observed $j(l)$ in the range $90° < l < 270°$ does not show any large-scale deviation from a uniform distribution, and fits the assumption of uniform emissivity.

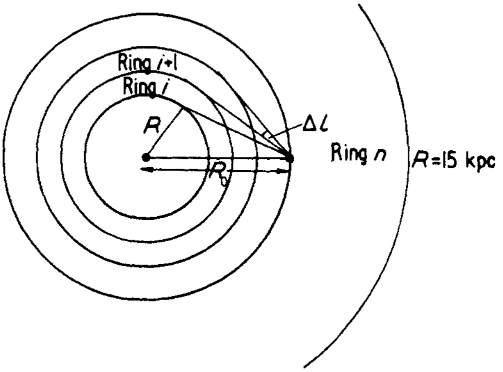

Figure 1. Illustration of geometry of method for unfolding the distribution of gamma-ray emissivity in the Galaxy.

For $R < R_0$, the ith ring has an emissivity in the plane equal to w_i times the emissivity for $R > R_0$. Then

$$J_j = \sum Q_{ij} w_i \tag{1}$$

where Q_{ij} is the contribution from the ith ring to the jth data bin for $w_i = 1$. This matrix can be calculated providing some assumption is made about the z dependence of the emissivity.

Equation (1) is a set of linear equations which can be solved for the w_i. Explicitly,

$$w_i = \frac{J_i - \Sigma_{k=i+1}^{n} w_k Q_{ki}}{Q_{ii}}, \qquad i < n \qquad R < R_0 \tag{2}$$

$$w_n = 1 \qquad\qquad 15 > R > R_0.$$

In this analysis, negative values of w_i can occur when the assumption of cylindrical symmetry is inadequate to represent the observations. An alternative procedure is to replace w_i by zero whenever equation (2) gives a negative value, thus forcing a physical solution. The resulting solution will then not reproduce the J_j exactly.

To investigate the probable errors in the derived distribution, a Monte Carlo method was used. A large number N of artificial data sets J_j^1 were generated from the J_i assuming a Gaussian distribution of errors with standard deviations taken from the quoted statistical errors on the experimental points. Each data set was then analysed using equation (2), giving N distributions of w_i^1. Finally the mean and standard deviation for each ring were obtained from the w_i^1.

It is important to note that since adjacent values of w_i are not independent, separate tests are required for analysis of errors in the shape of the distribution. To determine the significance of the apparent dip in emissivity towards the centre of the Galaxy, for example, we can use the w_i^1 to obtain an integral frequency distribution $P(>y)$ for the ratio $y = (w_1^1 + w_2^1)/2w_3^1$. In this way, confidence limits can be estimated for theories involving a decrease or increase in emissivity in the inner regions of the galaxy.

A similar type of inversion of the observations has been made by Puget and Stecker (1974), in which the problem was reduced to an Abel integral equation. However, this is not entirely satisfactory for a number of reasons:

(i) The contribution from nearby (within ~2 kpc) regions cannot be included in the inversion and must be treated separately. They assume $w = 1$ for $R = 8$–10 kpc.

(ii) A smoothing of the data is required to enable derivatives to be calculated, leading to a certain loss of the information content of the data.

(iii) The method does not readily allow the consequent errors in the determination of $q(R)$ to be estimated.

We consider that the method used here uses essentially all the information contained in the data, and allows an analysis of the errors involved.

3. Application of the method to the data currently available

At present, the SAS-II data only cover the region 340°–40° around the Galactic centre, and a limited region in the anti-centre. For the remaining longitude ranges, we use the OSO-III results (Kraushaar *et al* 1972), normalizing these to the SAS-II data to give the same sum over all bins for which SAS data are available. The normalizing factor is 0·8. (This method is not satisfactory but is the best available; no doubt the indicated errors are underestimates.)

In each case the 'isotropic' component was subtracted. The resulting distribution is shown in figure 2.

The matrix Q_{ij} was calculated assuming constant emissivity in the z direction in the disc, with a thickness of 230 pc; at this stage a more elaborate treatment, though straightforward, seems unjustified. The integration in Galactic latitude was over the range $b = -10°$ to $+10°$. The number of rings, n, was 10. Overall normalization was

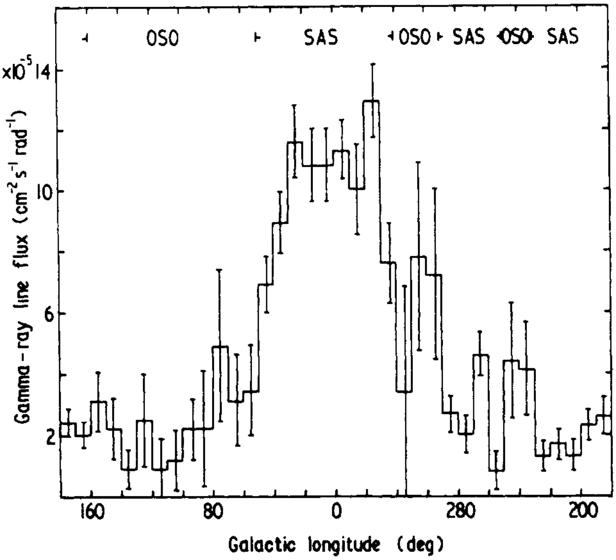

Figure 2. Flux of γ-rays around Galactic plane, from SAS-II and OSO-III results.

obtained by requiring that the mean intensity in the 90°–270° range was consistent with emission from the $R > R_0$ ring with $w_{10} = 1$.

In order to test the consistency of the cylindrical symmetry assumption, the data for l = 0–90° and 270°–360° were analysed separately. Using N = 300, both 'unforced' and 'forced' treatments were carried out, as described in § 2, and the results are shown in figure 3(*a*–*d*), together with the corresponding distributions $P(>y)$.

4. Discussion and conclusions

The evaluation of w_i by this method depends mainly on the observations in the range l = 270°–0°–90°. The SAS-II coverage is complete only in the 320°–40° range, so that OSO-III observation must be used in the remaining regions if we are not to resort to interpolation.

In the 0–90° band, the combined data are reasonably consistent with the hypothesis of cylindrical symmetry, since for this case, figure 3(*a*) shows that mainly positive values of w_i are obtained using the 'unforced' solution. The situation is less satisfactory in the 270°–360° band, figure 3(*c*), where negative values of w are found for rings 2 and 5 (although the 1σ upper limits are positive in each case). The reason for this behaviour is the rather high OSO-III values in the 290°–310° region. The cylindrical symmetry assumption is clearly unjustified in this region, and we must await the corresponding SAS-II observations for a new assessment to be made.

Concentrating therefore on the 0–90° region, we observe:

(i) The enhancement of emissivity in the 3·5–5 kpc region is confirmed, but the error on the magnitude of the enhancement is rather large, with $w_3 = 10 \pm 4$. Further, there is not much evidence that the peak is as narrow as this, and it could be rather flat over the range R = 3–8 kpc. We do not agree with the rather small error estimates, and narrow peak given in the equivalent analysis shown in figure 3 of Puget and Stecker (1974).

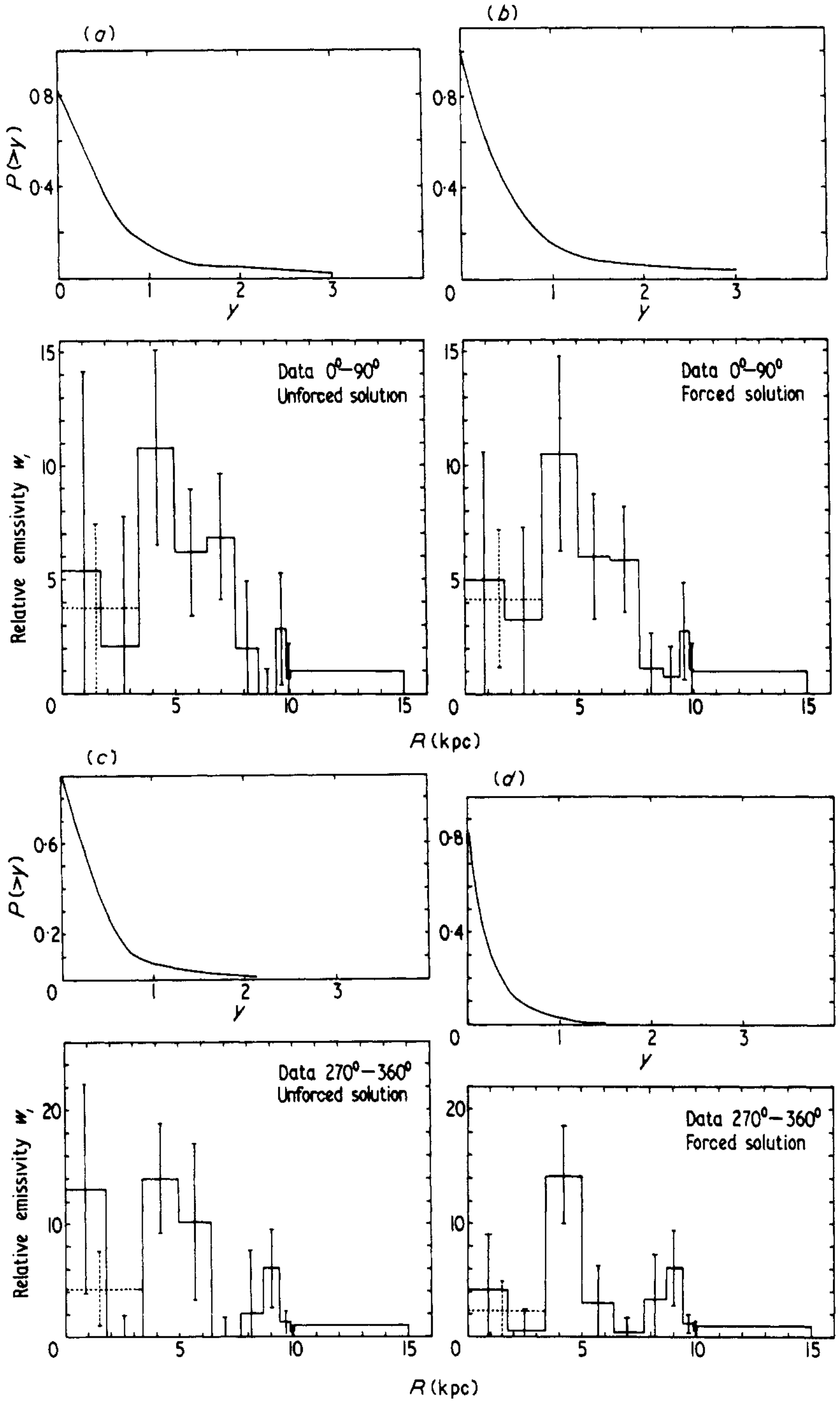

Figure 3. (*a*)–(*d*). Results from unfolding procedure, using data in 0–90° and 270°–360° ranges, showing 'unforced' and 'forced' solutions. The distribution $P\ (>y)$ for each case is also shown. The broken line is the result of combining the first two longitude bins before unfolding.

(ii) There is good evidence for a decrease of emissivity in the region $R < 3{\cdot}5$ kpc, as shown by the $P(>y)$ plots. From figure 3(*a*), there is only a 15 % probability of the ratio y being greater than 1·0, and 60 % probability that $y < 0{\cdot}5$.

(iii) The model of Bignami and Fichtel (1974) (see the following paper) requires that the emissivity increases by a factor 25 in spiral arms over the interarm regions. The distribution of emissivity derived here shows no such increase in the Sagittarius arm, which they take to lie between $R = 7{\cdot}3$ and 8·5 kpc. In fact, bin 6 ($R = 7{\cdot}7$–$8{\cdot}7$ kpc) has an enhancement $w_6 = 2 \pm 2{\cdot}9$ (figure 3(*a*)) or $w_6 = 2{\cdot}1 \pm 5{\cdot}6$ (figure 3(*c*)) for the 0°–90° and 270°–360° data respectively. Hence there seems to be conflict with the observations in this region, although the analysis does depend on the use of OSO-III data for $l > 50°$, so that the definite conclusion is not possible until SAS-II data are available in this range.

(iv) As pointed out by Stecker *et al* (1974), the correlation with the distribution of HII regions is good. Figure 4 shows the distribution of giant HII regions from Mezger (1970), plotted with the emissivity from figure 3(*a*).

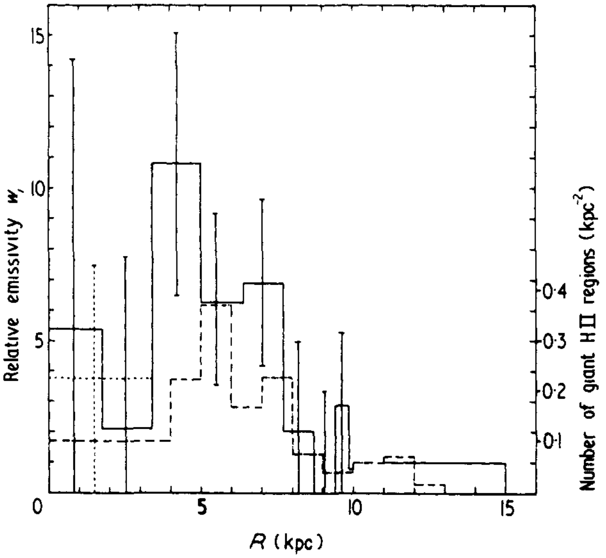

Figure 4. Comparison of distribution of emissivity in the Galaxy from figure 3(*a*) (full line) with the distribution of giant HII regions from Mezger (1970) (chain line).

This last point, and other possible correlations, is taken up in the following paper.

For the future, the identification and subtraction of point sources and 'hotspots' and an improvement in both statistical accuracy and precision of γ-ray directions should allow a more reliable analysis of the Galactic plane diffuse γ-rays to be made. Data on the latitude distribution will give additional information on the distance to the important emission regions, and perhaps resolve some of the present ambiguities.

Acknowledgments

The author wishes to thank the Science Research Council for its support.

Drs F W Stecker and C E Fichtel are thanked for useful discussions and for making available information prior to publication.

Acknowledgment is made of helpful discussions with Mr D Dodds, Dr J Wdowczyk and Professor A W Wolfendale.

References

Bignami G F and Fichtel C E 1974 *Astrophys. J. Lett.* **189** L65–7

Dodds D, Strong A W, Wolfendale A W and Wdowczyk J 1975 *J. Phys.* A: *Math. Gen.* **8** 624–35

Fichtel C E 1974 *Phil. Trans. R. Soc.* A **277** 365–79

Kniffen D A, Hartmann R C, Thompson D J and Fichtel C E 1973 *Astrophys. J. Lett.* **186** L105–9

Kraushaar W L, Clark G W, Garmire G P, Borken R, Higbie P, Leong C and Thorsos T 1972 *Astrophys. J.* **177** 341–63

Mezger P G 1970 *Proc. IAU Symp. No* 38, *Basel, Switzerland* ed W Becker and G Contopoulous (Dordrecht: Reidel)

Puget J L and Stecker F W 1974 *Astrophys. J.* **191** 323–8

Share G H, Kinzer R L and Seeman N 1974 *Astrophys. J.* **187** 45–56

Stecker F W, Puget J L, Strong A W and Bredekamp J H 1974 *Astrophys. J. Lett.* **188** L59–61

Strong A W, Wdowczyk J and Wolfendale A W 1973 *Gamma-Ray Astrophysics* ed F W Stecker and J L Trombka (Washington: Government Printing Office) p 259