PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

A Statistical Study of the Distribution of $\gamma $-ray Sources

P. A. Riley

Phil. Trans. R. Soc. Lond. A 1981 **301**, 529-531
doi: 10.1098/rsta.1981.0129

Phil. Trans. R. Soc. Lond. A **301**, 529–531 (1981)
Printed in Great Britain

A statistical study of the distribution of γ-ray sources

By P. A. Riley

Department of Physics, The University, Science Laboratories, South Road, Durham DH1 3LE, U.K.

Data from the COS-B satellite have enabled discrete sources of cosmic γ-rays to be identified. We wish to estimate the contribution that such sources make to the γ-ray luminosity of the Galaxy (see Protheroe *et al.* 1979; Rothenflug & Caraveo 1980). Since only the brightest, and hence relatively near, sources are known, only the contribution of sources to the local γ-ray emissivity can be determined from them. The distances to most of the sources in the second COS-B catalogue (Hermsen 1980) are not known so that neither their mean luminosity, $\bar{L}$, nor their surface density, σ, on the galactic plane can be determined accurately. The latitude distribution of sources indicates that their distance from the Sun, r, is much greater than their distance from the galactic plane, z. We can therefore calculate the product $\sigma\bar{L}$ without knowing the distances of the sources. This may be seen as follows.

Since $z \ll r$ we may approximate the number of sources with flux S or greater that lie in the longitude interval Δl and the latitude range $-\theta < b < +\theta$ by

$$N(>s) \approx \int_s^\infty \int_0^\infty (L/8\pi s^2)\,\lambda(L)\,\sigma\,((L/4\pi s)^{\frac{1}{2}})\,H((L/4\pi s)^{\frac{1}{2}}\sin\theta)\,\mathrm{d}L\,\mathrm{d}s\,\Delta l, \tag{1}$$

where $\sigma(r)$ is the surface density of sources, $\lambda(L)$ is the source luminosity distribution and $H(z)$ is the proportion of sources lying within a distance z of the plane. If σ is roughly constant out to the limit of visibility of sources, then (1) simplifies to

$$N(>s) \approx (\sigma\bar{L}/8\pi s)\,\Delta l, \tag{2}$$

enabling an estimate of $\sigma\bar{L}$ to be made.

Another way of exploiting the plane geometry of the situation is to plot $s^{-\frac{1}{2}}$ against l. The number of sources per unit area on such a plot is proportional to $\sigma\bar{L}$. Using (1) and making the change of variable $t = s^{-\frac{1}{2}}$ we obtain

$$4\pi N(t_1 < t < t_2)/A_t \approx \int_{t_1}^{t_2} t \int_0^\infty L\lambda(L)\,\sigma\,((L/4\pi)^{\frac{1}{2}}t)\,H((L/4\pi)^{\frac{1}{2}}t\sin\theta)\,\mathrm{d}L\,\mathrm{d}t \Big/ \int_{t_1}^{t_2} t\,\mathrm{d}t, \tag{3}$$

where $A_t = \frac{1}{2}\Delta l\,(t_2^2 - t_1^2)$ is the area on the t against l plot. The right-hand side of (3) is simply $\langle\sigma\rangle\,\bar{L}$, $\langle\sigma\rangle$ being a weighted average of the surface density in the direction being considered.

The 22 sources in the second COS-B catalogue with $|b| < 15°$ have been used for an analysis by these methods. Plots of lg N against lg s for the centre $(-60° < l < 60°)$ and anti-centre $(60° < l < 300°)$ regions show that sources in the anti-centre region follow an $N \propto s^{-1}$ relation while those in the centre do not (cf. Rothenflug & Caraveo 1980). The steeper $N(>s)$ curve for the centre region indicates a varying source density in that direction and also that the relation $N \propto s^{-1}$ for the anti-centre sources is unlikely to be due to a very flat luminosity function $\lambda(L)$. A plot of $s^{-\frac{1}{2}}$ against l is shown in figure 1. The region corresponding to $s > 1.3 \times 10^{-6}\ \mathrm{cm^{-2}\,s^{-1}}$ has been divided into six equal areas, as shown in table 1. If the source density were constant the numbers in each area would be equal, to within statistical errors. It is seen in table 1 that the numbers of sources in the 'near' regions and in the 'far-local' region are consistent with each other, while the numbers in the 'far-centre' and 'far-anti-centre' regions provide some evidence for a source gradient toward the centre. The former four regions may be used to calculate the local value of $\sigma\bar{L}$, by using equation (3):

$$\sigma\bar{L} = (7.0 \pm 2.5) \times 10^{-4}\,\mathrm{ph}\ (E > 100\,\mathrm{MeV})\,\mathrm{cm^{-2}\,s^{-1}}.$$

The total γ-ray luminosity of the Galaxy has been determined by Strong & Worrall (1976) and Caraveo & Paul (1979) as being 1.4×10^{41} ph ($E > 100$ MeV) $\mathrm{s^{-1}}$. If cosmic γ-ray sources are

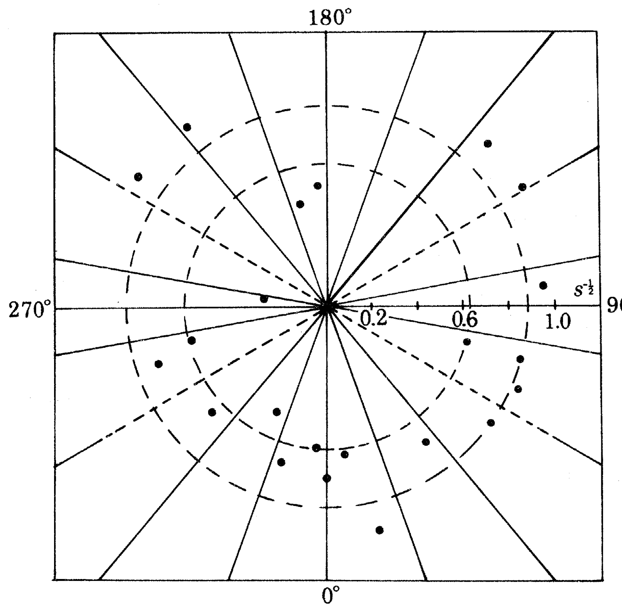

FIGURE 1. Plot of $s^{-\frac{1}{2}}$ against l for the 22 sources of the second COS-B catalogue with $|b| < 15°$. The division into six areas for analysis is shown. The COS-B catalogue is thought to be complete for $s > 1.3 \times 10^{-6}\ \mathrm{cm^{-2}\,s^{-1}}$ in the region $90° < l < 270°$.

TABLE 1. THE NUMBER OF SOURCES IN THE REGIONS OF THE $s^{-\frac{1}{2}}$ AGAINST l PLOT SHOWN IN FIGURE 1

	near ($s > 2.6 \times 10^{-6}$)	far ($1.3 \times 10^{-6} < s < 2.6 \times 10^{-6}$)
centre ($-60 < l < +60°$)	2	6
local ($60 < l < 120 < l < 300°$)	2	3
anticentre ($120 < l < 240°$)	2	0

distributed similarly to supernova remnants (Kodaira 1974) or pulsars (Manchester 1979), the local value of $\sigma\bar{L}$ implies a galactic luminosity due to discrete sources of $(0.53 \pm 0.18) \times 10^{41}$ $\mathrm{s^{-1}}$, roughly 40% of the total luminosity. Discrete sources such as those found by the COS-B experiment thus appear to contribute about 40% of the total γ-ray luminosity of the Galaxy above 100 MeV. Not all the discrete sources are necessarily star-like, however, owing to the poor angular resolution of the COS-B telescope. The figure of 40% is then an upper limit to the contribution of star-like sources to the total luminosity. The work reported by Issa & Li Ti-pei in this symposium suggests that at least 30% of the discrete sources are due to clouds of molecular hydrogen irradiated by cosmic rays. The upper limit to the contribution of star-like sources is then about 30%.

References (Riley)

Caraveo, P. A. & Paul, J. A. 1979 *Astron. Astrophys.* **75**, 340–344.
Hermsen, W. 1980 Ph.D. thesis, University of Leiden.
Kodaira, K. 1974 *Publs astr. Soc. Japan* **26**, 255–261.
Manchester, R. N. 1979 *Aust. J. Phys.* **32**, 1–7.
Protheroe, R. J., Strong, A. W., Wolfendale, A. W. & Kiraly, P. 1979 *Nature, Lond.* **277**, 542–543.
Rothenflug, R. & Caraveo, P. A. 1980 *Astron. Astrophys.* **81**, 218–222.
Strong, A. W. & Worrall, D. M. 1976 *J. Phys.* A **9**, 823.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES