THE ASTROPHYSICAL JOURNAL, 243:L69–L73, 1981 January 15

SECOND *COS B* CATALOG OF HIGH-ENERGY GAMMA-RAY SOURCES

B. N. SWANENBURG,[1] K. BENNETT,[2] G. F. BIGNAMI,[3] R. BUCCHERI,[4] P. CARAVEO,[3] W. HERMSEN,[1] G. KANBACH,[5] G. G. LICHTI,[2] J. L. MASNOU,[6] H. A. MAYER-HASSELWANDER,[5] J. A. PAUL,[6] B. SACCO,[4] L. SCARSI,[4] AND R. D. WILLS[2]
Received 1980 August 26; accepted 1980 October 10

ABSTRACT

A list of 25 high-energy ($E > 100$ MeV) gamma-ray sources detected by *COS B* is presented. Only four sources are identified with well-known objects. Of the remaining sources, 20 are at low galactic latitude, and they may represent a new galactic population. Their luminosity is estimated to be in the range $(0.4\text{–}5) \times 10^{36}$ ergs s^{-1}. It is seen that several hundred such sources may exist in the Galaxy. Their nature is not understood.

Subject headings: gamma rays: general

I. INTRODUCTION

The detection by *COS B* of 13 high-energy gamma-ray sources (Hermsen *et al.* 1977) has shown for the first time that copious gamma-ray emission is produced in numerous localized regions. The mysterious nature of those objects has persisted because of the lack of unambiguous identification, except for PSR 0531+21 and PSR 0833−45.

COS B has continued to operate successfully since its launch in 1975 August, and sufficient data have now been accumulated to permit a more systematic search for gamma-ray sources in the Galaxy. The results of the survey provide the basis for an unbiased investigation of the gamma-ray sources, which is the first requirement for the derivation of the main characteristics of this population.

II. OBSERVATION AND RESULTS

The characteristics of the instrument and the important features of the *COS B* mission have been described by Bignami *et al.* (1975) and Scarsi *et al.* (1977). The 32 observations, each typically of 1 month duration, used for this investigation were made in the period 1975 August to 1978 December. The region of the sky covered is shown in Figure 1. The angular resolution of *COS B* below 100 MeV is inadequate to maintain a sufficiently uniform source visibility throughout the Galaxy because of the complex structure of the galactic gamma-ray emission, particularly in the intense regions of the inner Galaxy (Mayer-Hasselwander *et al.* 1980). Therefore only events of measured energy above 100 MeV have been used in this search. The measured arrival directions of the gamma rays have been sorted into $0\overset{\circ}{.}5 \times 0\overset{\circ}{.}5$ bins. The resulting skymap was analyzed using a cross-correlation method in which the distribution of the photon arrival directions was correlated with the distribution expected for a point source. This latter distribution, the intrinsic point-spread function of the instrument, was determined by calibration and confirmed by the actual flight data for the strong source PSR 0833−45. A gamma-ray source is thus defined as a significant excess which has a spatial distribution consistent with the point-spread function. Pertinent aspects of the complete analysis have been presented by Hermsen (1980). Here it suffices to summarize its prime characteristics. The main advantage is that the presence in the data of the signature of a point source, i.e., the point-spread function, is exploited, yielding a favorable combination of sensitivity, positional accuracy, and low susceptibility to spurious effects. On the other hand, the method imposes certain limitations. For instance, the effective angular resolution is slightly degraded, which impacts on the ability to distinguish between a real point source and an extended region of emission and on the sensitivity in confused regions.

Preliminary results using this method have been presented by Willis *et al.* (1980). Rigorous application of selection criteria as described by Hermsen (1980) results in the catalog presented in this *Letter*. From extensive simulations, it was concluded that for the entire search not more than one spurious detection above the adopted selection threshold could be expected (Hermsen 1980).

The positions of the 25 detected gamma-ray sources are shown in Figure 1. Parameters of these sources, designated 2CG (*l-b*) following Hermsen *et al.* (1977), are given in Table 1. The error radii (~90% confidence level) have been derived using representative simulations. Although the profiles of all the sources are compatible with that expected for a point source, the angular extent of the sources may be up to 2°. Because the detector's sensitive area varies with energy, the

[1] Cosmic-Ray Working Group, Huygens Laboratorium, Leiden, The Netherlands.

[2] Space Science Department of the European Space Agency, ESTEC, Noordwijk, The Netherlands.

[3] Istituto di fisica cosmica del CNR, Milano, Italy.

[4] Istituto di fisica, Università di Palermo, Italy.

[5] Max-Planck-Institut für Physik und Astrophysik, Institut für Extraterrestrische Physik, Garching-bei-München, West Germany.

[6] Service d'electronique physique, Centre d'etudes nucléaires de Saclay, Gif-sur-Yvette, France.

conversion from source counts to source flux depends on the assumed spectral shape. The flux values listed in Table 1 have been derived assuming E^{-2} differential photon spectra, because this slope is consistent with the average observed ratio of fluxes above 300 MeV and 100 MeV (see seventh column of Table 1). It can be seen that individual spectra deviate from this average (see also Wills *et al.* 1980), and therefore individual fluxes must be considered approximate (about $\pm 30\%$).

The CG sources (Hermsen *et al.* 1977) not appearing in the 2CG catalog, CG 176−7, CG 189+1, and CG 327−0, do not meet the presently adopted acceptance criteria. Their absence is either due to the higher threshold of statistical significance, to spatial extension of the enhancement, or to source confusion. It is noted that the flux reported by Hermsen *et al.* (1977) for CG 176−7 was in conflict with the upper limit derived by Hartman *et al.* (1979). Three of the four localized sources observed by *SAS 2* (Hartman *et al.* 1979) are among the brightest of the present catalog. However, the fourth one, identified with Cyg X-3 by Lamb *et al.* (1977) is not apparent in the *COS B* data. The Cygnus region has been observed by *COS B* three times (1975 December, 1977 June, and 1978 November). For each observation a timing analysis at the characteristic period of 4.8 hr has been performed with consistently negative results at the level reported by Bennett *et al.* (1977*b*) for the first observation.

Of the 21 sources which have been observed at least twice, 20 were visible in each observation. In one case (2CG 356+00) a source has been clearly seen only in one of four observations. This particular case presents a hint for time variability at the 99% confidence level. Also, it has been recognized that the flux from the region $79° \lesssim l \lesssim 84°$ and $|b| < 2°.5$ shows differences between the three observations of the Cygnus region, suggesting a contribution from variable sources. However, the structure in this region cannot be resolved into individual sources.

It is noted that, although the sources in the Cygnus region (2CG 075+00 and 2CG 078+01) and in the Carina region (2CG 284−00 and 2CG 288−00) are quoted in the catalog as individual entries, the corresponding structures could also be interpreted as extended features.

Only four sources of the catalog have been identified: 2CG 184−05 and 2CG 263−02 are identified with the Crab and Vela pulsars through their timing signature (Bennett *et al.* 1977*a*). The other two are identified because of the remarkable positional coincidences, 2CG 289+64 with 3C 273 (Swanenburg *et al.* 1978; Bignami *et al.* 1980) and 2CG 353+16 with the ρ Oph cloud complex (Mayer-Hasselwander *et al.* 1980; Bignami and Morfill 1980). For the remaining 21 sources, no unambiguous counterparts appear to exist at other wavelengths. With the exception of 2CG 010−31 all these sources lie close to the galactic disk.

III. DISCUSSION

These observations confirm the existence of a galactic population of gamma-ray sources. At first glance this population appears to be rather uniformly distributed in galactic longitude. The picture changes, however, if the selection effect introduced by the higher detection threshold in the brighter parts of the galactic gamma-ray plane is reduced by selecting only the stronger sources. The distribution of a sample of sources with fluxes greater than 1.3×10^{-6} photons cm^{-2} s^{-1} (Fig. 1, filled circles) shows a magnitude concentration toward the inner part of the Galaxy. This is particularly

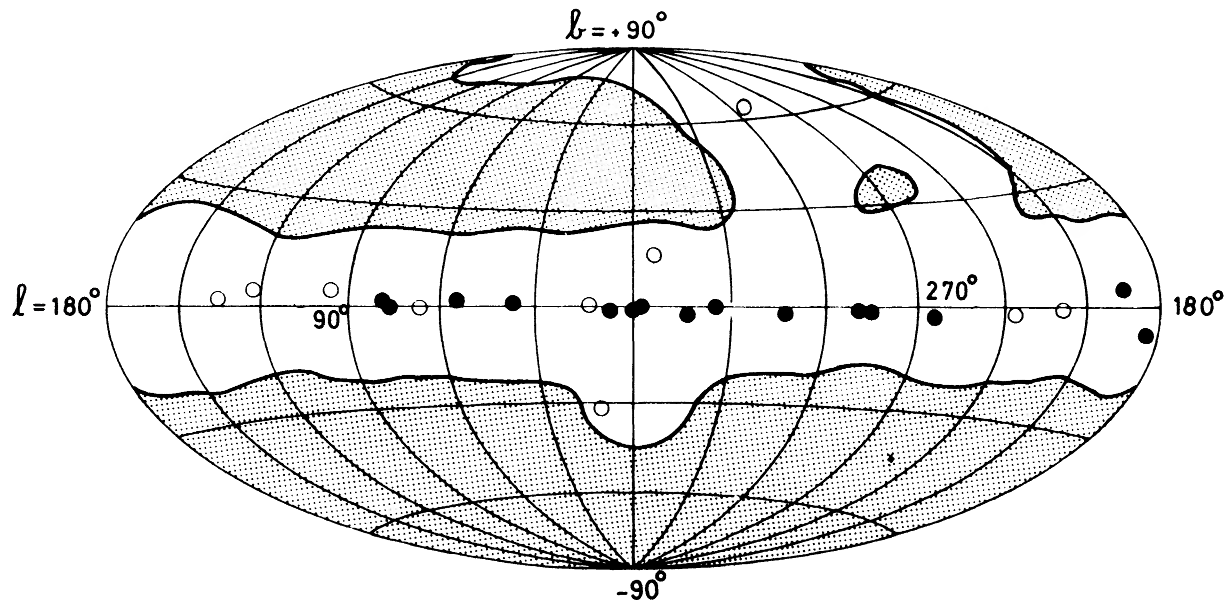

FIG. 1.—Region of the sky searched for gamma-ray sources (*unshaded*) and sources detected above 100 MeV by spatial analysis. The filled circles denote sources with measured fluxes $\geq 1.3 \times 10^{-6}$ photons cm^{-2} s^{-1}. Open circles denote sources below this threshold.

TABLE 1

THE 2CG CATALOG OF GAMMA-RAY SOURCES

Source Name	No. of Observations	Position l (degrees)	Position b (degrees)	Error Radius (degrees)	Flux[a] $E>100$ MeV (10^{-6} photons $cm^{-2}\ s^{-1}$)	Spectral[b] Parameter	Comments	CG Source (Hermsen *et al.* 1977)	Identification	References
2CG 006−00.....	3	6.7	−0.5	1.0	2.4	0.39±0.08		...	...	...
2CG 010−31.....	1	10.5	−31.5	1.5	1.2	...		...	...	...
2CG 013+00.....	4	13.7	+0.6	1.0	1.0	0.68±0.14		...	...	...
2CG 036+01.....	3	36.5	+1.5	1.0	1.9	0.27±0.07		...	...	...
2CG 054+01.....	3	54.2	+1.7	1.0	1.3	0.20±0.09		...	...	...
2CG 065+00.....	4	65.7	0.0	0.8	1.2	0.24±0.09		CG 64+0	...	...
2CG 075+00.....	5	75.0	0.0	1.0	1.3	...	could be an	CG 75−0	...	...
2CG 078+01.....	5	78.0	+1.5	1.0	2.5	...	extended feature	CG 78+1	...	...
2CG 095+04.....	3	95.5	+4.2	1.5	1.1	...		...	...	...
2CG 121+04.....	3	121.0	+4.0	1.0	1.0	0.43±0.12		CG 121+3		
2CG 135+01.....	3	135.0	+1.5	1.0	1.0	0.31±0.10		CG 135+1	...	...
2CG 184−05.....	4	184.5	−5.8	0.4	3.7	0.18±0.04		CG 185−5	PSR 0531+21	Kniffen *et al.* (1974)
2CG 195+04.....	3	195.1	+4.5	0.4	4.8	0.33±0.04	γ195+5	CG 195−4	...	Thompson *et al.*(1977)
2CG 218−00.....	3	218.5	−0.5	1.3	1.0	0.20±0.08		...	...	...
2CG 235−01.....	2	235.5	−1.0	1.5	1.0	...		...	...	...
2CG 263−02.....	4	263.6	−2.5	0.3	13.2	0.36±0.02		CG 263−2	PSR 0833−45	Thompson *et al.*(1975)
2CG 284−00.....	1	284.3	−0.5	1.0	2.7	...	could be an	...	...	...
2CG 288−00.....	1	288.3	−0.7	1.3	1.6	...	extended feature	...	...	...
2CG 289+64.....	2	289.3	+64.6	0.8	0.6	0.15±0.07		CG 291+65	3C 273	Swanenburg *et al.*(1978); Bignami *et al.* (1980)
2CG 311−01.....	2	311.5	−1.3	1.0	2.1	...		CG 312−1	...	...
2CG 333+01.....	3	333.5	+1.0	1.0	3.8	...		CG 333+0	...	...
2CG 342−02.....	5	342.9	−2.5	1.0	2.0	0.36±0.09		...	...	...
2CG 353+16.....	4	353.3	+16.0	1.5	1.1	0.24±0.09		...	ρ Oph	Mayer-Hasselwander *et al.* (1980)
2CG 356+00.....	1	356.5	+0.3	1.0	2.6	0.46±0.12	prob. variable	...	...	...
2CG 359−00.....	3	359.5	−0.7	1.0	1.8	...		...	...	...

[a] Assuming E^{-2} spectra.

[b] Intensity ($E > 300$ MeV)/Intensity ($E > 100$ MeV), assuming E^{-2} spectra calculating both intensities.

true since *this* sample is considered to be complete in the region $90° < l < 270°$, whereas it may not be complete in the central region of the Galaxy owing to confusion and the high level of background radiation.

The lack of identification of sources and, hence, the lack of knowledge about their distances prohibits the calculation of individual luminosities. Nevertheless, estimates for the average luminosity follow directly from limits on typical distances as derived from the observed longitude and latitude distribution.

Under the assumption of a rather symmetric galactic distribution of sources, the absence of a strong concentration in longitude close to the galactic center, say within $\sim 30°$, implies an upper limit to the typical distance of about 7 kpc. On the other hand, the confinement in latitude leads to a lower limit. Inside the solar circle scale heights of various populations are known to be independent of distance (e.g., Guibert, Lequeux, and Viallefond 1978). Accordingly, the sample of sources defined by $300° < l < 60°$ has been selected to estimate this lower limit. The average deviation from $b = 0°$ for this sample is $1\overset{\circ}{.}1$. Assuming that the minimum scale height observed among galactic populations, i.e., that of young objects and their tracers, of ~ 40 pc (Guibert *et al.*) also represents a lower bound for gamma-ray sources, their typical distance is not less than 2 kpc. In addition, selection effects and the inaccuracy in measured positions have to some extent blurred the inherent latitude distribution. Therefore this value should be regarded as an extreme limit. Conversely, it is noted that the 7 kpc upper limit on source distances derived above restricts the maximum scale height to 130 pc. Using the derived range of distances of 2–7 kpc and the average source flux and spectrum, the average luminosity of this sample of sources, taking $\langle E \rangle = 250$ MeV, is in the range of $(0.4\text{–}5) \times 10^{36}$ ergs s^{-1}, assuming their emission is isotropic. Considering the fact that scale heights tend to increase outside the solar circle, it is stressed that the latitude distribution of the 11 unidentified sources in the range $60° < l < 300°$ $(<|b|> = 1\overset{\circ}{.}7)$ is compatible with a similar distance range. Although their average intensity is slightly lower, one may conclude that the average luminosity of all unidentified sources falls in the same range as derived above. Luminosities in this range are not exceptional in themselves. One should consider, however, that the absence of strong (e.g., $\gtrsim 3$ *Uhuru* counts) X-ray counterparts implies that $\tilde{L}_\gamma$ (>100 MeV) $> 10 L_x$ (2–10 keV), and from a similar argument L_γ (>100 MeV) $\gg L_{\rm radio}$.

Reliable estimates for the total number of sources in the Galaxy require special assumptions on their galactocentric distribution (Bignami and Caraveo 1980), their luminosity function (see, e.g., Bignami, Caraveo, and Maraschi 1978; Rothenflug and Caraveo 1980), and the emission mechanism (isotropic or beamed) and are not attempted here. It is evident from geometrical considerations that this number exceeds 100. A reasonable upper limit is 1000 in order not to conflict with the limits imposed by the total gamma-ray luminosity of the Galaxy (Caraveo and Paul 1979).

The question as to the nature of these objects remains difficult to address, particularly owing to the lack of identifications. Because of the large error boxes, identification of the sources in the absence of a timing signature can best be attempted on a statistical basis. This, however, requires that a sample of the population of candidate objects can be selected which is sufficiently complete to distance of 2–7 kpc and which in addition contains a small enough number of objects to make the correlation significant. Such investigations should be supplemented by the formulation of at least rudimentary source models, which reproduce the average characteristics of the population such as luminosity, distribution, and the total number in combination with the absence of copious X- and radio emission. The astrophysical difficulties which must be overcome in the formulation of source models, as summarized, for instance, by Swanenburg (1979), are significantly amplified as a direct consequence of the high luminosity inferred from the present result.

Members of two classes of well-known galactic objects have been associated with sources of gamma-ray emission, i.e., molecular clouds in Orion (Caraveo *et al.* 1980) and the ρ Oph cloud complex (2CG 353+16) by positional coincidence and the pulsars PSR 0531+21 and PSR 0833−45 by their timing signature. It is questionable whether either of these classes can be considered as typical representatives of the main population of gamma-ray sources. To be visible beyond 2 kpc individual molecular clouds would have to be irradiated by a flux of cosmic rays much greater than the local value. Similarly the output in gamma-rays from a typical radio pulsar would have to be stretched much beyond that observed in Crab and Vela.

G. G. L. acknowledges the receipt of an ESA fellowship. J. L. M. thanks the Centre national de la recherche scientifique for support.

REFERENCES

Bennett, K., *et al.* 1977*a*, *Astr. Ap.*, **61**, 279.
Bennett, K., Bignami, G. F., Hermsen, W., Mayer-Hasselwander, H. A., Paul, J. A., and Scarsi, L. 1977*b*, *Astr. Ap.*, **59**, 273.
Bignami, G. F., *et al.* 1980, *Astr. Ap.*, in press.
Bignami, G. F., *et al.* 1975, *Space Sci. Instr.*, **1**, 245.
Bignami, G. F., and Caraveo, P. 1980, *Ap. J.*, **241**, 1161.
Bignami, G. F., Caraveo, P., and Maraschi, L. 1978, *Astr. Ap.*, **67**, 149.
Bignami, G. F., and Morfill, G. E. 1980, *Astr. Ap.*, **87**, 85.
Caraveo, P. A., *et al.* 1980, *Astr. Ap.*, in press.
Caraveo, P. A., and Paul, J. A. 1979, *Astr. Ap.*, **75**, 340.
Guibert, J., Lequeux, J., and Viallefond, F. 1978, *Astr. Ap.*, **68**, 1.
Hartman, R. C., Kniffen, D. A., Thompson, D. J., Fichtel, C. E., Ögelman, H. B., Tümer, T., and Özel, M. E. 1979, *Ap. J.*, **230**, 597.
Hermsen, W. 1980, Ph.D. thesis, University of Leiden.
Hermsen, W., *et al.* 1977, *Nature*, **269**, 494.
Kniffen, D. A., Hartman, R. C., Thompson, D. J., Bignami, G. F., Fichtel, C. E., Tümer, T., and Ögelman, H. 1974, *Nature*, **251**, 397.

Lamb, R. C., Fichtel, C. E., Hartman, R. C., Kniffen, D. A., and Thompson, D. J. 1977, *Ap. J.* (*Letters*), **212**, L63.
Mayer-Hasselwander, H. A., *et al.* 1980, *Proc. 9th Texas Symp. Relativistic Astrophysics* (*Ann. NY Acad. Sci.*, **336**, 211).
Rothenflug, R., and Caraveo, P. A. 1980, *Astr. Ap.*, **81**, 218.
Scarsi, L., *et al.* 1977, Proc. 12th ESLAB Symp., Frascati, Italy (ESA SP-124, p. 3).
Swanenburg, B. N. 1979, in *Stars and Star Systems*, ed. B. E. Westerlund (Dordrecht: Reidel), p. 1.
Swanenburg, B. N., *et al.* 1978, *Nature*, **275**, 298.
Thompson, D. J., Fichtel, C. E., Hartman, R. C., Kniffen, D. A., and Lamb, R. C. 1977, *Ap. J.*, **213**, 252.
Thompson, D. J., Fichtel, C. E., Kniffen, D. A., and Ögelman, H. B. 1975, *Ap. J.* (*Letters*), **200**, L79.
Wills, R. D., *et al.* 1980, *COSPAR Symp. on Non-Solar Gamma Rays, Advances in Space Exploration*, Vol. **7**, ed. R. Cowsik and R. D. Wills (London: Pergamon), p. 43.

K. Bennett and R. D. Wills: Space Science Department of the European Space Agency, ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands

G. F. Bignami and P. Caraveo: Istituto di fisica cosmica del CNR, via Bassini 15, 20133 Milano, Italy

R. Buccheri, B. Sacco, and L. Scarsi: Istituto di fisica, Università di Palermo, via Archirafi 36, 90134 Palermo, Italy

W. Hermsen and B. N. Swanenburg: Cosmic-Ray Working Group, Huygens Laboratorium, Wassenaarseweg 78, 2300 RA Leiden, The Netherlands

G. Kanbach, G. G. Lichti, and H. A. Mayer-Hasselwander: Max-Planck-Institut für Physik und Astrophysik, Institut für Extraterrestrische Physik, 8086 Garching-bei-München, West Germany

J. L. Masnou and J. A. Paul: Service d'electronique physique, Centre d'etudes nucléaires de Saclay, S.E.O., B.P. 2, F-91 Gif-sur-Yvette, France