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ANN ARBOR, MI 1990

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PREFACE

High energy γ-ray astronomy has undergone an astonishing growth in the last decade. Following closely after the initial SAS-2 and COS-B satellite maps of the γ-ray sky came reports of point-sources of photons at the highest energies. In some cases these coincided with objects in satellite and x-ray catalogs. The inferred luminosities of these objects would be enormous, but the mechanisms responsible for ultra-high energy emission proved difficult to quantify. For the first time there was the possibility of identifying discrete sources of some, perhaps all, high-energy cosmic rays. The unusual character of some reports spurred the interest of the high-energy physics community because new particles or new physics were needed to explain the observations.

Many new efforts were undertaken during the 1980s to clarify the situation. There is now a body of data on astrophysical γ-rays spanning ten decades of energy. The second generation of detectors are now taking data with even more ambitious devices planned or coming into operation. The gap between satellite and ground based observations will soon be much narrower with the launching of the GRO instrument.

The purpose of the conference was to present a forum for a unified discussion of all aspects of γ-ray astronomy. It provided a unique opportunity for the diverse community of observers to coordinate their efforts across the boundaries of different energy regimes. The focus of the meeting was γ-ray astronomy as a single discipline. The timing placed it midway between the Adelaide and Dublin ICRC's.

The success of the meeting was insured by the wide response from the world γ-ray astronomy community. The organizers acknowledge with gratitude the efforts of Joan Britton and the University of Michigan Extension Service staff for their smooth operation of the meeting. We especially thank Beth Demkowski, Tina Clark, and Laura Phillips, from the University of Michigan Physics Department, for long hours and dedication to detail in handling a chaotic flux of physicists and their schedules, papers, and problems. We are grateful to the Physics Department of the University of Michigan for financial and moral support, and to the United States Department of Energy, the National Science Foundation, and the University of Michigan for funding.

James Matthews
Ann Arbor, Michigan
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ABSTRACT

COS-B has surveyed about 9 steradians of the sky along the entire Galactic plane and with some excursions at high latitudes. Using a likelihood analysis to search for point-like excesses above the diffuse gamma radiation born in the interstellar medium, 12 sources have been detected with high statistical significance to a flux level of about 10^{-7} γ cm^{-2} s^{-1} between 300 MeV and 5 GeV. A list of 24 candidate sources has also been compiled which require confirmation at GeV or other energies. Only two sources have been clearly identified, namely the Vela and Crab pulsars. No other VHE candidate has been firmly seen by COS-B in the GeV range.

A striking analogy exists between Vela and Geminga in the 50 MeV-5 GeV range. They behave similarly, both in their variability over a time-scale of months and in their unusual hard spectrum, suggesting that Geminga be a Vela-type pulsar. Both sources are good candidates for detection by telescopes sensitive at a few hundred GeV.

THE COS-B 300 MeV - 5 GeV γ-RAY SOURCES

The 2CG-catalogue of γ-ray sources [1] was compiled before detailed knowledge was available on the fine-scale structure of the diffuse Galactic γ-rays. The structure is dominated by the clumpy molecular-hydrogen distribution. Therefore, some entries in that catalogue could be due to e.g. distant dense clouds. Since then, the molecular content of the Galactic disc was mapped in CO, and Strong et al. [2] produced a good quantitative fit to the large-scale γ-ray distribution along the Milky Way knowing the interstellar matter (ISM) content from the HI and CO surveys and using a small galactocentric gradient of the gas emissivity. This gradient is interpreted as a small variation in the density of the cosmic rays pervading the ISM. γ-ray features which are not explained by this model are due to compact objects or to active sites of enhanced cosmic-ray density. The adopted definition for a point-source is now: excess emission above the instrumental background and the diffuse radiation born in the ISM, having a spatial distribution consistent with the instrumental point-spread function.

We present here results from a new search for sources performed on all available COS-B data between 300 MeV and 5 GeV using a maximum-likelihood method. The analysis at lower energies (70 - 150 MeV, 150 - 300 MeV) is in progress and will be published together with the full details of the analysis [6].

THE SOURCE ANALYSIS

COS-B performed between August 1975 and April 1982 sixty five observations of about one month duration each. The ~9 steradians of sky area searched in the present analysis is shown in an exposure map in Figure 1. The maximum exposure of 4.82 10^8 cm^2 s was achieved in the complex Cygnus region. An exposure of about 10^7 cm^2 s was reached for single observations at the selected maximum radius of 20° from the telescope axis. Observations toward LMC and SMC have not been used because of disturbances by γ-rays from the Earth.

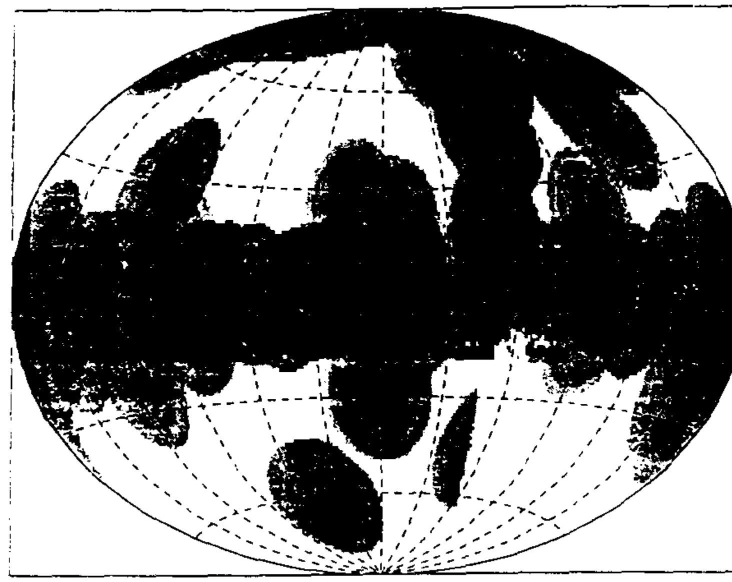

Fig. 1. Greyscale outline of the exposure used for the analysis

The diffuse γ-ray sky between 300 MeV and 5 GeV was constructed from the results of Strong et al. [2] in a grid containing ~27000 bins of equal area (1 deg²) to cover the viewed sky area indicated in Figure 1. The likelihood analysis tests the presence of point sources in addition to the ISM (see [4]). So, the log-likelihood ratio $\lambda(l_s,b_s)$ provides a continuous scale of the weight of evidence for a point source at l_s,b_s. In a classical interpretation, 2λ is distributed as χ_n^2 under the null hypothesis, with n the number of free parameters that are added to the null hypothesis of only diffuse γ radiation from the ISM. This method will show point-like sources as well as more extended excesses. We have tried to differentiate between these possibilities by simultaneously fitting more than one source and by considering how well the ISM-plus-sources model fits the data.

Each recorded γ incidental direction is treated individually (the events are not sorted in sky bins) in order to increase the sensitivity of the search and to make a more sensitive test in the case of nearby sources. Furthermore, the analysis is performed for each observation separately to look for time variability. In the case of overlapping observations, the λ-values of the single observations are summed, giving a skymap of the statistic $\Sigma\lambda$ that tests the overall evidence for emission in excess of the ISM radiation.

As a source detection threshold for a single observation, we have selected λ_1=7.5, such that we expect less than one spurious source in the whole search. Indeed, for all single observations together, we tested a sky area of ~77000 deg², while the effective solid angle of the PSF(E > 300 MeV) is a circle ~1.75° in radius. The estimated number of independent trials becomes then about 8000, predicting less than one spurious detection for $\chi_1^2 = 2\lambda = 15$ (only one degree of freedom for the optimization of the source flux).

Sources are also accepted for inclusion in the source list if $\Sigma\lambda$ in the overall map is considered to be of sufficient significance: for ~2800 independent trials, less than one spurious detection corresponds to $P(2\Sigma_n\lambda > \chi_n^2) \times 2800 < 1$. n is in this case the number of observations, since for each individual observation the flux has been treated as a free parameter.

Finally, when more than one source have to be included in the tests simultaneously, the global maximum Λ_{tot} provides the degree of evidence that the ISM model is incomplete. Then an individual λ_{source} can be obtained for an individual source from the difference in all n observations between the global maximum and the maximum-likelihood reached when the flux of the source of interest is set to 0.

The source detection threshold expressed in flux values is not uniform over the whole survey. It depends on the exposure and on the intensity and clumpiness of the underlying ISM emission.

Table I *COS-B SOURCES 300 MeV - 5 GeV*

l°	b°	N_{obs}	Λ_{tot}	λ_{source}	Flux	Comment	λ_{1obs}	flux
76.0	0.4			27.6	3.7	constant		
78.2	2.0	8	86.0	34.5	4.5	constant		
82.8	3.2			11.4	1.2	variable	9.3	4.4
135.0	1.4	5	22.2	12.6	2.5	constant		
139.2	-0.8			8.8	1.0	constant		
184.6	-5.8	6	450.0	125.5	7.3	constant		
195.1	4.2			350.6	14.2	constant		
263.5	-2.5	6		873.2	41.7	constant		
322.2	-1.7	3		11.7	3.0	variable	11.7	6.4
343.1	-2.9			23.9	3.9	variable	18.3	7.7
347.1	-1.9	7	60.0	8.7	0.5	variable	8.6	6.2
357.6	-1.2			25.7	4.3	variable	14.9	10.2

Fluxes in units of 10^{-7} γ cm^{-2} s^{-1}.

DISCUSSION

The features that passed our detection thresholds are given in Table 1. Due to the improved background treatment in this analysis, the positions of confirmed 2CG-sources may have changed, particularly in complex regions. The list contains constant as well as variable sources, the latter being seen predominantly in one observation as can be judged from the high λ_{1obs}-values. Of the 12 entries 8 are confirmations of 2CG-sources and the variable source at l= 82.8° and b= 3.2° has been reported earlier [4]. The only extragalactic object firmly seen by COS-B, 3C273, is only seen below 300 MeV because of its steep spectrum.

Many of the local maxima in Figure 2 reach high $\Sigma\lambda$-values. These are in fact good candidate γ-ray sources but need confimation by GRO measurements or detections at TeV energies. Our detection threshold might in fact be conservative. We treat the n observations as n free parameters, not considering that the individual weak excesses in many cases happen to coincide and build a nice source profile; e.g. at l= 75.0° and b= -8.5°. Therefore, we list in Table 2 all candidate sources with $\Sigma\lambda>6.5$. The quality of their structure and the accuracy of their position can be judged from the contours in Figure 2.

In some of the multiple source structures an extended excess can not be excluded, however there is sufficiently strong evidence for the presence of double/triple source structures in the cases listed in Table 1.

For the Cygnus region, we performed tests for additional sources, e.g. Cyg X-3. Confirming the findings of Hermsen et al. [7], no evidence for emission from Cyg X-3 was found (time-average flux between 300 MeV and 5 GeV < 10^{-7} γ cm^{-2} s^{-1}). In fact, the data supports the presence of a source at l= 80.7°, b= -1.2° (reported earlier [8]) with a λ_{source}= 11.1 for 8 observations and λ_{1obs}= 6.6 in observation 22 which are neither

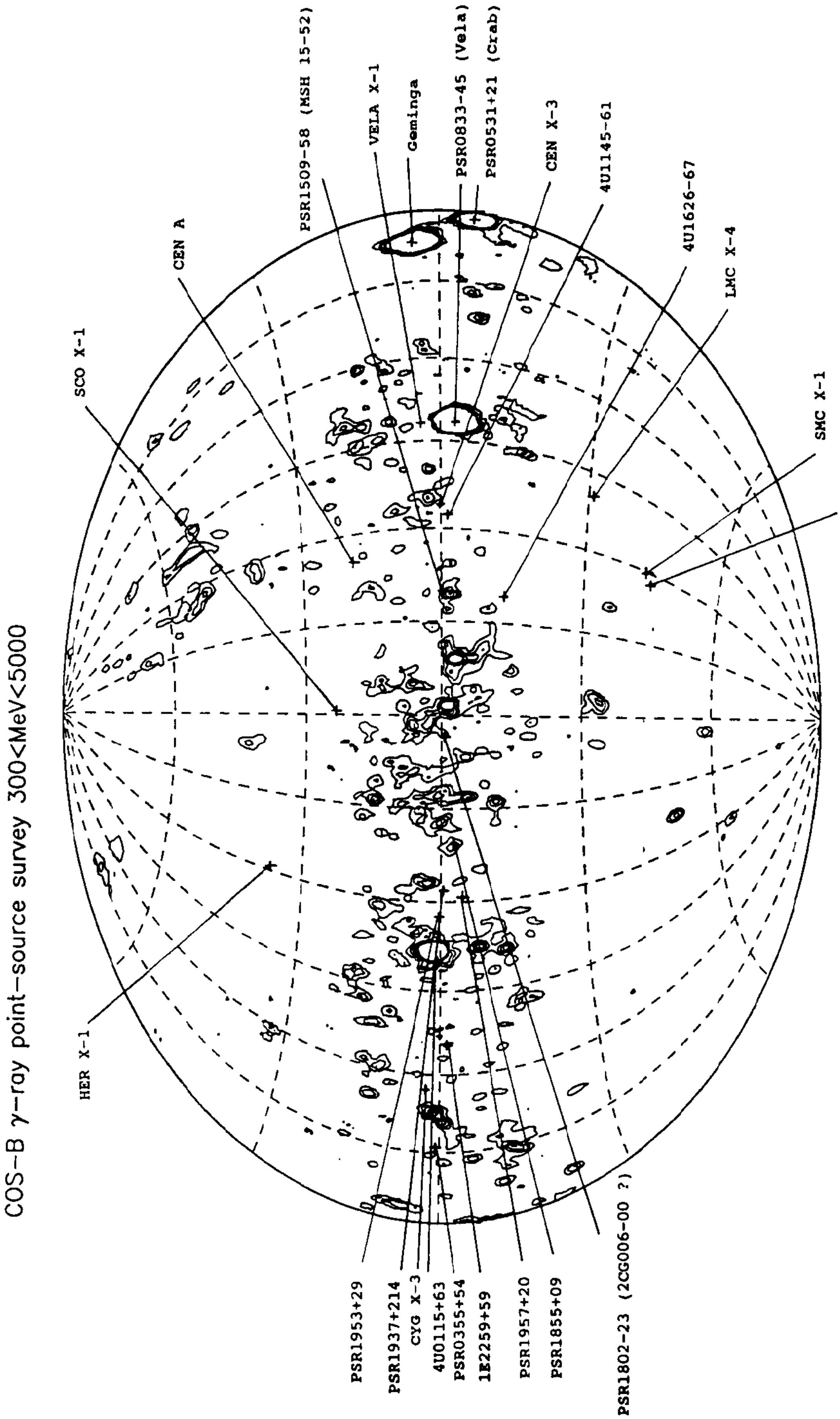

Fig. 2. Map of the statistic $\Sigma\lambda$, in galactic coordinates centered around l=b= 0°, giving the weight of evidence of a localized γ-ray excess. Contour values start from 2 with steps of 2.

good enough for inclusion in Table 1, but sufficiently interesting to underline for future measurements.

Table II *COS-B SOURCE CANDIDATES 300 MeV - 5 GeV*

l°	b°	N_{obs}	$\Sigma\lambda$	l°	b°	N_{obs}	$\Sigma\lambda$
1.0	2.0	7	8.0	75.0	-8.5	8	11.5
3.0	3.0	6	7.3	75.9	-13.3	7	9.3
3.0	6.0	6	8.4	150.7	-12.7	4	8.8
24.0	-1.0	7	6.1	179.9	-6.4	6	8.7
26.1	1.0	5	7.5	223.1	-7.5	4	7.1
26.2	-6.0	5	8.6	240.7	16.6	3	6.9
27.5	-11.9	5	7.6	270.8	-16.7	3	6.9
27.8	14.9	5	8.1	289.8	2.9	3	6.6
34.1	0.0	5	7.7	304.0	51.6	4	6.7
44.9	-50.9	1	6.8	338.0	-1.0	5	6.9
53.5	2.9	5	7.7	350.0	6.0	6	7.5
70.4	5.7	8	7.0	354.3	-33.5	2	6.8

The results in Table 1 should be compared with the findings of Mayer-Hasselwander and Simpson [7] (M-HS), who analysed the same data but with a cross-correlation method. The comparison can be made sofar for the range 300 MeV - 5 GeV: of the 9 new sources, other than 2CG confirmations, reported above 300 MeV by M-HS, 7 appear in Table 1 with mostly small differences in position. Indeed, our approach, in contrast to M-HS, used no binning and fitted multiple sources to the data simultaneously. Of the two remaining sources, one feature appears in Table 2 (l= 75.0°, b= -8.5°) and is indeed a very interesting candidate, as was discussed above. The only missing source in our lists is in the Carina region (2CG284-00, in M-HS at l= 285.2°, b= -1.8°). In an earlier likelihood analysis [8], a double structure was reported with sources at l= 284.7°, b= -1.8° and l= 286.8°, b= 0.6°. In the present work, only less significant features are visible in all energy ranges.

Table 1 contains 5 entries more than the list of M-HS: i) 3 variable sources which could not be seen by M-HS for they did not analyse single observations, ii) 2 sources in complex regions where multiple source structures had to be fitted (a triple source structure in the Cygnus region and double sources near l= 135° and near l= 345°).

Besides the Crab and Vela pulsars, all the sources listed in Table 1 require identification. Geminga can tentatively be identified as a γ-ray pulsar on spectral grounds (see below). The Wolf-Rayet star HD193793, emitting variable non-thermal radio and infra-red emission, and being exceptionally bright in X-rays [9] has been proposed for the source at l= 82.8°, b= 3.2°. In a similar way, the peculiar WO star ST3, with a very high-velocity wind interacting with the nearby molecular cloud G75.77+.34, has been proposed [10] for the source at l= 76.0°, b= 0.4°.

Figure 2 is a useful finding chart for GeV γ-ray sources. It is of particular interest to verify detections at other wavelengths because a much lower detection threshold can be applied when the position is a priori known . For this purpose we have indicated in Figure 2 the positions of a sample of possible TeV sources. Most of these positions do not coincide with a COS-B feature.

Radio pulsars seem to be promising GeV-TeV sources. Besides the Vela and Crab pulsars, PSR 1802-23 was discussed [11] in relation to

2CG006-00 (not confirmed, but a small excess is visible in Figure 2). A possible timing signature has been reported [12] from the 1.6 ms pulsar PSR 1957+20 from an analysis of Potchefstroom TeV and COS-B >100 MeV data (chance probability 2 10^{-3} and 10^{-3}). They did not detect a DC flux, nor is a feature visible in Figure 2, however, preliminary results at 70-150 MeV and 150-300 MeV indicate small excesses at the source position. Of the remaining pulsars for which possible TeV emission has been reported, also PSR 1855+09 and PSR 1509-58 are on top of, or close to excesses in Figure 2. Finally, PSR 1951+32, the Crab-like 39.5 ms pulsar in CTB 80, has been observed in the COS-B data [13] at a significance level of 10^{-3}. In Figure 2 no excess is visible toward this source near the complex Cygnus region, but the preliminary maps below 300 MeV show a clear excess [3]. Therefore, this source is a most interesting target for repeated TeV observations.

Because of their proximity in energy, the firm and candidate sources in Tables 1 and 2 are promising targets at TeV energies. Particularly interesting might be the variable source at l= 322.2°, b= -1.7° which virtually reveals itself only above 300 MeV; a confirmation would be highly desirable.

THE SPECTRAL PROPERTIES OF GEMINGA AND VELA INTERPULSE

Geminga is the second brightest source in the GeV sky, but it has eluded a clear identification since its discovery in 1975 [14]. A recent, detailed study of its spectral properties in the γ-ray range sheds new light on this issue; the hard and variable spectrum from Geminga strongly recalls one component of the Vela pulsed emission, suggesting that Geminga might be a Vela-type pulsar.

COS-B looked at Geminga five times between 1975 and 1982 (periods 0, 14, 39, 54 and 64). Each observation lasted typically one month. The energy distribution of the emission between 50 MeV and 5 GeV has been analysed using the maximum-likelihood method developed to describe the Vela pulsar emission [15]. The analysis treats the photons individually. They are not binned spatially, nor in energy, to take full account of the modest spectral and angular resolutions of the COS-B detector. The large field-of-view of COS-B includes the diffuse galactic emission, the point-source of the Crab pulsar and nebula, and the point-source Geminga supposed to be in the direction l= 195.1° and b= 4.2° [16]. The stable spectra of the Crab pulsar and its nebula have been directly taken from [17], while independent power-law spectra have been fitted simultaneously for the instrumental background, the galactic emission, and for Geminga during each observation independently.

Masnou et al. [16] measured an average Geminga spectrum between 50 MeV and 5 GeV (in 7 bins) from the first four COS-B observations. It was consistent with an $E^{-1.8}$ power-law between 100 MeV and 3.2 GeV, but flattened and steepened slightly ($\leq 2\sigma$) below and above these limits. Therefore, the likelihood analysis has been applied to test the low-energy break; two-power-law distributions, covering the whole 50-5000 MeV range with two independent indices below and above a given threshold, have been fitted to the Geminga emission. Different break energies from 100 MeV to 400 MeV have been tested. A second break at high energy could not be included because the scarce photons arising from Geminga above 3 GeV cannot constrain the fits. The detailed results have been fully described in [18].

THE VARIABLE SPECTRUM OF GEMINGA

To study the time-average behaviour of Geminga, the output of all five observations have been combined and break energies of 140, 200 and 290 MeV tested. According to the maximum-likelihood values, the fit