Pergamon

0273-1177(94)00041-7

Adv. Space Res. Vol. 15, No. 5, pp. (5)81–(5)84, 1995

0273-1177/95 $9.50 + 0.00

THE CRAB NEBULA AND PULSAR IN THE MeV ENERGY RANGE

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ABSTRACT

The imaging Compton Telescope COMPTEL is sensitive in the energy range 0.75 to 30 MeV. COMPTEL observed the Crab several times during the CGRO sky survey and CGRO Phase II. Both the Crab pulsar and nebula are detected over the entire COMPTEL energy range. The phase-averaged energy spectra of the Crab Pulsar and Nebula are presented. The combined observations provide sufficient statistics for a phase-resolved analysis of the Crab pulsar spectrum.

INTRODUCTION

COMPTEL, one of the four instruments aboard the Compton Gamma Ray observatory (CGRO), provided during its first 18 months of operation (Phase I of the CGRO-Mission) the first all sky survey in the low MeV range. In the subsequent 10 months selected objects of interest were observed (Phase II of the CGRO-Mission). COMPTEL has a field of view of 1 steradian and it has a positioning accuracy for strong sources better than 1°. A detailed instrumental description of COMPTEL is given by Schönfelder *et al.* /1/. This paper reports on results from the analysis of all available data on the Crab pulsar and nebula collected during Phase I and II. The results of the Phase II data analysis are published for the first time.

OBSERVATIONS AND ANALYSIS

During Phase II of the CGRO-mission the Crab was twice within 25° of the instrument z-axis. The details of these two observations are summarized in Table 1. The listed exposure numbers are specified for the 1 to 3 MeV energy range.

Table 1 COMPTEL observations of the Crab during Phase II of the CGRO-Mission

Obs. #	T_{start} dd-mm-yy	T_{end} dd-mm-yy	Pointing l (°)	Pointing b (°)	Crab View Angle	Exposure (10^6 cm^2·s)
213.0	23-03-93	29-03-93	182.6	-8.2	3.1°	2.33
221.0	13-05-93	24-05-93	187.5	-5.9	3.0°	3.94

A detailed analysis of the Phase I data (validation period, observation 0, 1, 36.0, 36.5 and 39) is described elsewhere /2/. For these Phase I Crab observations the exposure was 2.7 10^7 cm^2 s in the 1 to 3 MeV interval, a factor of about four more than in Phase II. Here we add Phase II data to these data sets.

Light curves are generated using contemporary Crab radio ephemerides /3/ by period folding of the photon arrival times after they were transformed to the solar system barycentre. The image reconstruction is performed in a three-dimensional dataspace, defined by the photon scatter direction between the two detector layers and the Compton scatter angle using either a Maximum Entropy method or a Maximum Likelihood method (/1/ and references therein). The latter determines the source flux with the associated statistical error. The pulsed flux is obtained from the total flux in the pulsed phase interval after subtraction of the unpulsed component. The unpulsed emssion is determined in the 'off'-phase interval (indicated in Figure 1).

RESULTS

The resulting light curve for the 0.75 to 10 MeV energy range for the combined data is shown in Figure 1. Above 10 MeV no statistically significant pulsed emission was detected by COMPTEL in the phase histogram.

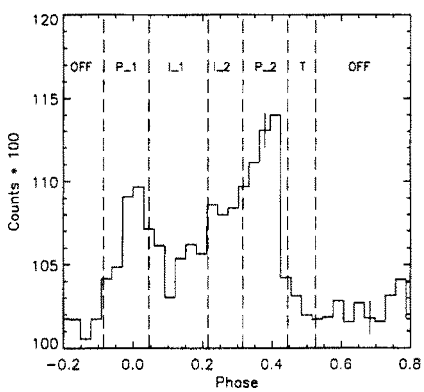

Fig. 1: The 33-bin Crab light curve for the energy interval 0.75-10 MeV. Indicated are the $\pm 1\sigma$ error bars.

Table 2 Ratio of second to first peak background subtracted counts in the Crab light curve for different energy intervals.

Energy (MeV)	P_2/P_1 Ratio
0.75-1	2.83 ± 1.25
1-3	1.64 ± 0.24
3-10	1.76 ± 0.60
1-10	1.67 ± 0.22

The COMPTEL light curve resembles much more that seen at hard X-rays by OSSE /4/ than that seen above 50 MeV by EGRET /5/. It has a significant interpulse emission and a more intense second peak compared to the first peak. The latter is also seen from the ratio of counts above background in the light curve (Table 2). The COMPTEL ratios are within the statistical errors consistent with ratios in the 50-340 keV energy band (~ 1.4) measured by OSSE /4/. They are systematically greater than the EGRET ones (~ 0.4) above 50 MeV /5/.

As indicated in Figure 1 the full period is divided into 6 phase intervals which are identical to the phase definitions used by Much *et al.* /2/. The pulsed phase stretches from the beginning of the first peak P_1 to the end of the trailer T. Although we determined the photon fluxes in smaller phase bins, we list in Table 3 and 4 the unpulsed flux and the pulsed flux, both averaged over the full period. For the combined data of Phase I and II we were able to split up the 1 to 10 MeV interval into smaller energy bins. Due to the low flux of the pulsed emission we could not split the 4-10 MeV range into smaller energy bands as done for the unpulsed emission.

We fitted the combined Phase I and II data with a single and a broken power law. The broken power law $I(E_\gamma) = 4.9 \cdot 10^{-5}(E_{MeV}/E_b)^{-\alpha}$ (α=1.83 if $E < E_b$ MeV, α=2.15 otherwise) describes the unpulsed COMPTEL data better than a single power law (Figure 2). The break energy is $E_b = 5.5^{+15.2}_{-4.3}$ MeV. A fit of a single power law to the phase-averaged pulsed COMPTEL data resulted in $I(E_\gamma) = 1.38 \cdot 10^{-4}(E_{MeV}/1.65)^{-2.35}$ (Figure 1). A broken power law did not improve the fit result. For both the pulsed and unpulsed spectrum, it is obvious from Figure 2 that model fits are only meaningful if all available high-energy data are considered simultaneously.

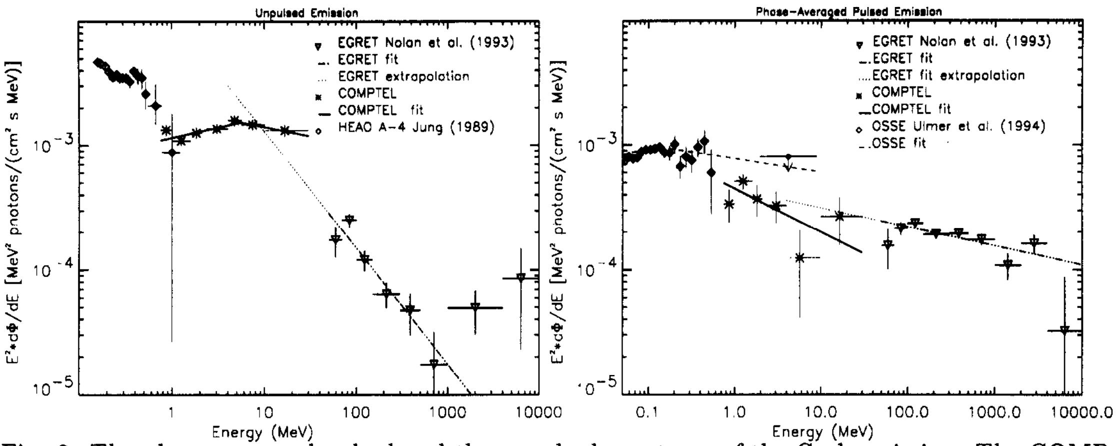

Fig. 2: The phase-averaged pulsed and the unpulsed spectrum of the Crab emission. The COMPTEL data displayed are for the combined observations of Phase I and II.

Table 3 Crab pulsed and unpulsed fluxes in the COMPTEL standard energy intervals for observations 213, 221 and the combination of all Crab observations in Phase I and II. The quoted 1σ errors are statistical only. Upper limits are 2 σ.

Obs.	unpulsed photon fluxes (10^{-4} ph / (cm^2 s))			
#	0.75-1 MeV	1-3 MeV	3-10 MeV	10-30 MeV
213.0	4.26 ± 1.51	10.10 ± 1.60	4.22 ± 0.73	1.02 ± 0.35
221.0	4.05 ± 1.21	10.73 ± 1.29	3.59 ± 0.58	0.67 ± 0.22
Phase I+II	4.43 ± 0.42	8.11 ± 0.44	3.62 ± 0.21	0.88 ± 0.09
Obs.	phase-averaged pulsed photon fluxes (10^{-4} ph / (cm^2 s))			
#	0.75-1 MeV	1-3 MeV	3-10 MeV	10-30 MeV
213.0	< 2.37	1.86 ± 1.26	< 1.12	< 0.82
221.0	1.11 ± 0.96	2.53 ± 1.02	0.91 ± 0.46	< 0.68
Phase I+II	1.12 ± 0.33	2.63 ± 0.35	0.36 ± 0.17	0.18 ± 0.07

We generated phase-resolved spectra for the combined Phase I and II data. Although in the majority of the cases COMPTEL data themselves cannot be used to determine the spectral slope of the phase-resolved spectra, they can be used together with the EGRET data /5/ to constrain the spectral behaviour. Only the spectrum of the second peak can be described with a simple power law with a spectral index of $\alpha = (-2.13 \pm 0.21)$. The spectrum of the first interpulse phase interval is consistent with a simple power law from 1 MeV to 1 GeV For the other three phase-resolved spectra, first peak, second interpulse and trailer, we conclude from the COMPTEL data that the EGRET power law spectra do not extrapolate to the COMPTEL energy range. These conclusions are in agreement with the results from the analysis of the Phase I data /2/.

SUMMARY

The spectrum of the unpulsed emission exhibits a remarkable bump in the low energy γ-range. As pointed out by Arons /6/, this can be explained within a relativistic magnetohydrodynamic model by a time variable shock structure causing higher γ-ray energy emitting particles to pile up at energies where they preferentially emit MeV photons. Except for the second peak, the combined phase-resolved spectra of EGRET and COMPTEL are not consistent with single power laws,

Table 4 Crab pulsed and unpulsed photon fluxes for the finer binning of the 1 to 10 MeV range.

Energy range (MeV)	unpulsed photon fluxes (ph / (cm^2 s))	phase-averaged pulsed photon fluxes (ph / (cm^2 s))
1.0-1.6	$(4.08\pm0.32)\cdot10^{-4}$	$(1.92\pm0.26)\cdot10^{-4}$
1.6-2.1	$(1.88\pm0.20)\cdot10^{-4}$	$(0.55\pm0.16)\cdot10^{-4}$
2.36-4.0	$(2.36\pm0.21)\cdot10^{-4}$	$(0.57\pm0.16)\cdot10^{-4}$
4.0-10.0	-	$(0.18\pm0.12)\cdot10^{-4}$
4.0-5.6	$(1.14\pm0.11)\cdot10^{-4}$	-
5.6-10.0	$(1.15\pm0.11)\cdot10^{-4}$	-

therefore calculations of phase-resolved spectra in the context of the standard pulsar models are encouraged.

ACKNOWLEDGEMENTS

R. Much acknowledges receipt of a research fellowship from the European Space Agency. The COMPTEL project is supported by the German government through DARA grant 50 QV 90968, by NASA under contract NASA-26645 and by the Netherlands Organization for Scientific Research (NWO).

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