ELSEVIER

Nuclear Physics B (Proc. Suppl.) 69/1-3 (1998) 265-268

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Phase resolved spectroscopy of Crab Pulsar (PSR B0531+21)

G. Cusumano[a], T. Mineo[a], A. Segreto[a], S. Piraino[a], A. Santangelo[a], F. Frontera[f], D. Dal Fiume[c], G. Zavattini[f], A. N. Parmar[d], F. Fiore[e], M. Guainazzi[e].

[a] IFCAI/CNR, Via Ugo La Malfa 153, I-90146, Palermo, Italy

[c] TESRE/CNR, via P. Gobetti 101, I-40129, Bologna, Italy

[d] Astrophysics Division, SSD of ESA, ESTEC, Post box 299, 2200 AG Noordwijk, The Netherlands

[e] BeppoSAX Science Data Center, c/o Nuova Telespazio, Via Corcolle 19, I-00131, Roma, Italy

[f] Dipartimento di Fisica, Universita' di Ferrara, Via Paradiso 12, 44100 Ferrara

The Crab Nebula and the Pulsar were observed from 31th to 1st of August and from 6th to 7th September 1996 with the Narrow Field Instruments (NFI's) on board of BeppoSAX, during the Science Verification Phase. The fine time resolution (15 μs) and the high statistic of the data provided phase histogram of very good quality and well suited for phase resolved spectroscopy over the entire energy band (0.1–300 keV) covered by BeppoSAX payload. We present some results of the phase resolved spectral analysis.

1. INTRODUCTION

Crab pulsar (PSR B0535+21) has been observed in almost every energy band of the electromagnetic spectrum and has been extensively studied in order to understand the physics of the emission mechanisms. The light curve, characterized by the well known double structure with a phase separation of 0.4, contains the bulk of the pulsar emission whose ratio to the nebula emission increases from a few percentage at 1 keV to more than 50% above 1 MeV ([4]) and references within). Moreover the relative intensity, height and width of the two main peaks varies with energies indicating spectral variations with the phase. The model generally used to describe the spectra of the pulsed and unpulsed components is a power law. However, a single power law has been find not to be the correct model to describe Crab pulsar spectra over the GRO wide energy band (50 keV – 10 GeV) ([9]). The authors show that a better fit can be achieved with broken power laws whose break energies are respectively 98 keV for first peak, 130 keV for for the second peak and 450 keV for the interpulse.

The intense and stable emission makes this source one of the best available candles for calibrating X-ray instruments. The total spectrum has been used by the hardware teams to verify and calibrate the BeppoSAX NFI's response matrixes.

In the following we studied separately the spectra of four main segments of the signal: the first peak (P1), the second peak (P2), the interpeak (Ip) and the off-pulse which is essentially identified with the nebular contribution.

2. OBSERVATIONS AND DATA ANALYSIS

The Crab Nebula and its pulsar were observed by the Narrow Field Instruments (NFI's) on board BeppoSAX ([1]) during the Science Verification Phase in two different runs in 1996 (August–September).

The NFI's consist of four coaligned instruments: the Low Energy Concentrator Spectrometer (LECS) operating in the energy range 0.1–10 keV ([8]), the Medium Energy Concentrator Spectrometer (MECS) having three units operating in the 1–10 keV ([2]), the High Pressure Gas Scintillation Proportional Counter (HPGSPC) operating in the 4–120 keV ([6]) and the Phoswich Detector System (PDS) with four units operating in the 15–300 keV energy band ([3]).

The total exposure time was 9690 s for the LECS, 33481 s for the MECS, (September 6-7) and 12487 s for the HPGSPC and 14130 s for the PDS (August 31-September 1). The background subtraction for the imaging instruments has been per-

0920-5632/98/$19.00
PII S0920-5632(98)00223-0

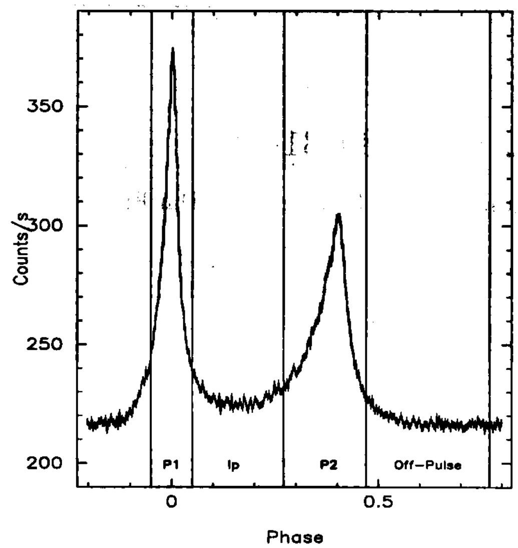

Figure 1. Crab phase histogram in the energy band 2–10 keV observed with the MECS

formed using blank sky spectra extracted from the same region of the detector field of view. PDS and HPGSPC background subtraction were performed by using the collimator off position data. The spectral analysis has been done using XSPEC 9.0 version and public response matrices available from August 31th were used.

3. RESULTS

Crab pulse profiles were obtained with the usual folding technique (after corrections to the Solar System Barycentre) based on the Jodrell Bank radio ephemeris ([5]). Figure 1 shows the light curve from 2.0-10.0 keV (MECS) with a phase resolution of 300 bins (0.11 ms). The well known double peaked structure is prominent with a very high statistical significance; also the interpeak region is clearly apparent. A detailed timing analysis of the NFI's data is reported in [7].

The phase boundaries we defined for P1, P2, Ip and the off-pulse interval, as reported in Fig. 1, are (-0.05,+0.05) for P1, (+0.27,+0.47) for P2, (+0.05,+0.27) for Ip and (+0.56,+0.80) for the off-pulse. We accumulated the spectra in each phase interval and, for the pulsed component, we subtract the off-pulse contribution. The energy ranges for the spectral analysis were 0.1–8.0 KeV for LECS, 1.6–10 keV for MECS, 6.2–50 keV for HPGSPC and 13–200 keV for PDS.

Each instrument spectrum was fitted independently with a single power law. Low energy absorption was introduced for LECS and MECS spectra and the absorbing column was fixed to the value obtained by LECS for the nebula spectrum (N_H=(3.24±0.02)$\times 10^{21}$ cm^{-2}). Table 1 reports the resulting spectral indexes together with the reduced χ^2. Errors are taken at the 90% confidence level for a single parameter when χ^2 is less than 2.0. Almost all fits gives acceptable χ^2, from what we conclude that the single power law well describe the source emission in each detector energy band. Local residuals mainly due to calibrations uncertainties are responsible for the high χ^2 in the HPGSPC and PDS nebula fits.

Moreover we studied the behaviour of the spectral index vs energy in the whole BeppoSAX energy band. The relative plot is shown in Fig. 2 where the energies associated to each point are the average over the relative detector energy band weighted with counts.

Only the nebula spectral indexes do not show any trend with energy being compatible with a constant. The average value is 2.14±0.03 where the error is manly due to systematic effects in the NFI's intercalibration. On the contrary, P1, P2 and Ip spectral indexes present significant variations with the energy and the differences in the detected values are bigger than the systematicities due to the intercalibration effects estimated for the nebula. Therefore for these spectra the single power law in the all the BeppoSAX range can be rejected with large confidence level.

We determined a better model for the pulsed components using the ratio spectra P1/Nebula, P2/Nebula and Ip/Nebula. These spectra, that are largely instrument independent, are obtained normalizing the detected counts to the nebula ones. If the input model of the two comparing

Table 1
Spectral indexes for the Crab components fitted with a single power law in several energy ranges.

Range		Nebula	P1	P2	Ip
0.1–8 keV	α	2.108±0.004	1.76±0.03	1.59±0.05	1.5±0.2
(LECS)	χ^2_{rid} (d.o.f.)	1.0 (742)	1.0 (742)	1.0 (742)	1.0 (742)
1.6–10 keV	α	2.144±0.003	1.80±0.01	1.67±0.02	1.52±0.06
(MECS)	χ^2_{rid}(d.o.f.)	1.2 (176)	1.3 (176)	1.0 (176)	0.9 (176)
6.2–50 keV	α	2.096±0.005	1.92±0.02	1.76±0.02	1.65±0.07
(HPGSPC)	χ^2_{rid} (d.o.f.)	1.6 (173)	1.20 (173)	1.0 (176)	1.03 (176)
13–200 keV	α	2.15	2.08±0.02	1.93±0.02	1.80±0.04
(PDS)	χ^2_{rid} (d.o.f.)	2.6 (56)	1.45 (56)	1.5 (56)	1.0 (56)

Table 2
Best fit coefficients for the spectral ratio

	α	β	χ^2 (d.o.f.)
P1/Nebula	0.50±0.01	0.136±0.006	1.2 (215)
P2/Nebula	0.61±0.01	0.125±0.006	1.1 (174)
Ip/Nebula	0.78±0.04	0.130±0.02	0.8 (47)

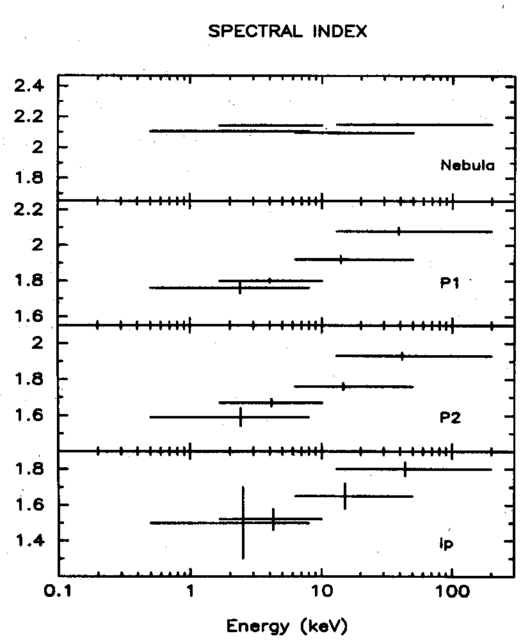

Figure 2. Spectral indexes as function of the energy measured by the NFI's independently

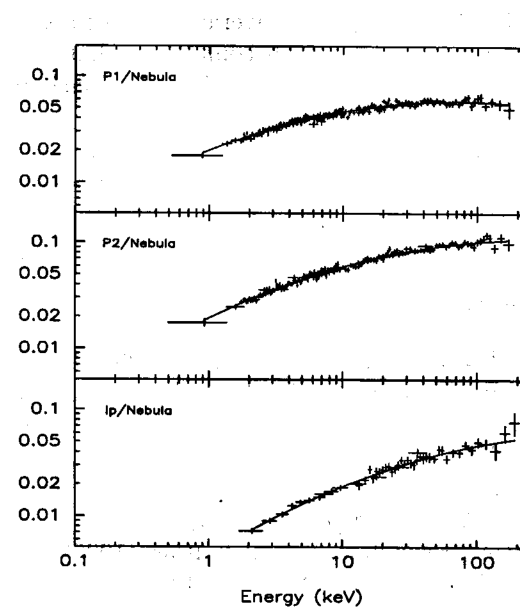

Figure 3. P1/Nebula P2/Nebula and Ip/Nebula ratio spectra. The continuum lines are the best fitting function.

spectra are both power laws, they are expected to be power laws with normalizations given by the count ratios at 1 keV and spectral indexes given by the differences of the two comparing ones. Fig. 3 shows the spectra over the whole BeppoSAX energy band.
We fitted the normalized counts with the following function (a parabola in the log-log plot):

$$Y = A\ E^{-(\alpha+\beta\ logE)}$$

where A α and β are the free parameters and E the energy in keV. The formula is simply related to the input model for the pulsed components ($\Phi_p(E)$) by the relation

$$\Phi_p(E) = Y \times \Phi_n(E)$$

where $\Phi_n(E) = A_n\ E^{-\alpha n}$ is the nebula emission spectrum. Table 2 shows the α and β best values together with the reduced χ^2. Errors are taken at the 90% confidence level for a single parameter. All fits produce acceptable values of χ^2.

We also compared these results with the ones obtained with the standard analysis (Table 1). The spectral indexes of the new model defined as $\partial\ log\Phi_p(E)/\partial\ logE$, have average values in each energy range and for each component that well agree with the previous results. We then conclude that the nebula is well described by a single power law in the 0.1-200 keV range, while a more complex model is required for the pulsar component being the single power law only a good approximation in small ranges.

REFERENCES

1. G. Boella, et al., *A&A Sup.*, 122, 299 (1997).
2. G. Boella, et al., *A&A Sup.*, 122, 327 (1997).
3. F. Frontera, et al., *A&A Sup.*, 122, 357 (1997).
4. F.K. Knight, *ApJ*, 260, 538, (1982).
5. A.G. Lyne, & R.S. Pritchard, http://www.jb.man.ac.uk/pulsar, (1996).
6. G. Manzo, et al., *A&A Sup.*, 122, 341 (1997).
7. T. Mineo, et al., *A&A Letters*, 327, L21 (1997).
8. A.N. Parmar, et al., *A&A Sup.*, 122, 309 (1997).
9. M.P. Ulmer, , et al., *ApJ*, 432, 228 (1994).