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LETTER

Letter to the Editor

A BeppoSAX observation of the Crab Pulsar (PSR B0531+21)

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Abstract. The Crab Pulsar (PSR B0531+21) was observed by the four Narrow Field Instruments onboard the Italian-Dutch satellite BeppoSAX in August and September 1996, during the Science Verification Phase. The fine time resolution (15 μs) and high statistics provided phase histograms of very good quality over the entire energy band (0.1–300 keV) covered by BeppoSAX payload. In this letter we present a detailed study of the variations in the light curve shape with energy and evaluate the spectral index difference between the main features.

Key words: stars – stars: neutron – pulsar: individual – X-rays: stars

1. Introduction

The Crab pulsar (PSR B0531+21) is the only rotation powered pulsar observed in almost every energy band of the electromagnetic spectrum. Its pulse profile is characterized by a double peak structure with a phase separation of 0.4. The relative intensity, height and width of the two peaks varies with energy: in particular, the first peak (P1), dominant at low energies, becomes smaller than the second one (P2) in the soft γ rays. The enhancement of the *bridge* between these peaks – hereafter named Interpeak (Ip) region – as function of energy is also well evident. The broad energy band (0.1–300 keV) covered by the BeppoSAX instruments permits to study, with a very high statistical accuracy, the shape of the pulse profile in an energy range in which the greatest changes occur. In this paper we present some results of the first BeppoSAX observation of this source: in particular we study the energy dependence of the P2/P1 and Ip/P1 ratios and the shape of the first peak.

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2. Observation and Data Reduction

The Crab Nebula and its pulsar were observed by the Narrow Field Instruments (NFI's) onboard BeppoSAX (Boella et al. 1997a) 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 (Parmar et al. 1997), the Medium Energy Concentrator Spectrometer (MECS) having three units operating in the 1–10 keV (Boella et al. 1997b), the High Pressure Gas Scintillation Proportional Counter (HPGSPC) operating in the 4–120 keV (Manzo et al. 1997) and the Phoswich Detector System (PDS) with four units operating in the 15–300 keV energy band (Frontera et al. 1997). The LECS and MECS are both imaging instruments. The latter has an the effective area about three time larger than that of the former in the overlapping band. The angular resolution is about 1.2' at 6 keV for both instruments. The HPGSPC and PDS are collimated instruments with a field view of 1^o; and 1.3^o respectively; the PDS is more sensitive than the HPGSPC which has better energy resolution. During the observations all instruments operated in direct mode (single photon informations were telemetred to ground), the collimated instruments were pointed to the source using the standard 96 s stay collimator mode.

Data reduction was performed with the standard procedures and selection criteria to avoid the South Atlantic Anomaly, solar, bright Earth and particle contaminations[1]. 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 LECS and MECS events were reduced using the SAXDAS v.1.1.0 package and selecting only

[1] see http://www.sdc.asi.it/software/cookbook as a reference about the data analysis software and reduction procedures.

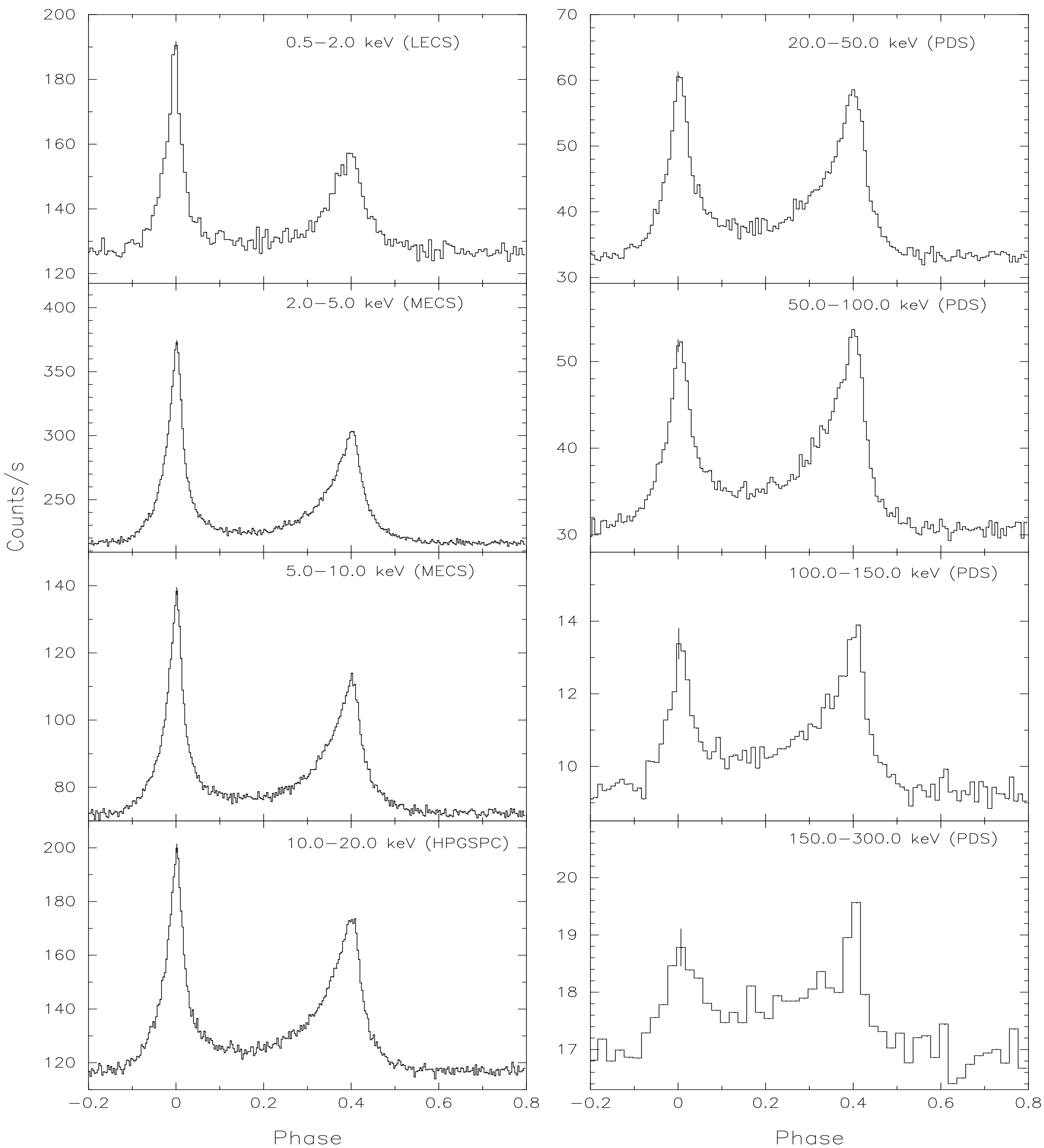

Fig. 1. Phase histograms of PSR B0531+21 (Crab) observed with the NFI's of BeppoSAX in eight energy ranges from 0.1 to 300 keV.

the photons within a circular region centered at the source of 16′ and 10′ radius respectively. The HPGSPC and PDS data were reduced using the XAS v.2.0.1 package.

3. Shape of the pulse profile

The UTC arrival times of all the selected events, after conversion to the Solar System Barycenter, were folded with the Crab pulsar period computed from the radio ephemeris (Lyne & Pritchard 1996). The adopted values of the pulsar frequency and frequency derivative were ν_o = 29.8861513101 Hz and $\dot{\nu} = -375733.90 \times 10^{-15}$ Hz s^{-1} at the reference epoch t_o = 24450310.5 JD (August 15).

The resulting phase histograms in eight energy bands from 0.5 to 300 keV are shown in Fig. 1, with a phase resolution ranging from 300 (0.11 ms) to 50 bins. The zero phase was taken, as usual, at the centre of P1. The well known double peaked structure is prominent in all the profiles with a very high statistical significance. It is also evident from Fig. 1 that the intensity of P2 and Ip with respect to that of P1 increases with energy (see the data base of Massaro et al. 1997 containing all X-ray published pulse profiles). Only few phase histograms

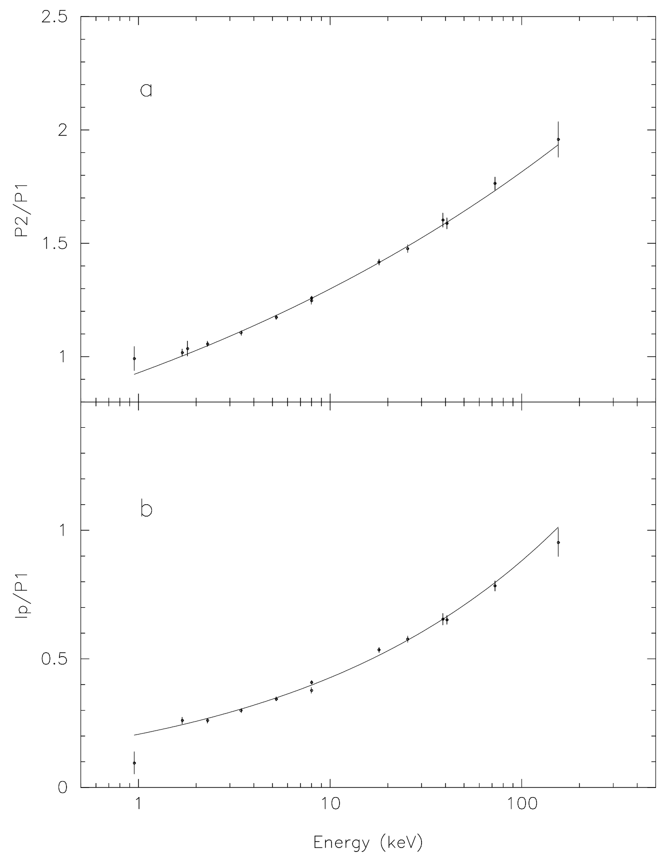

Fig. 2. The P2/P1(a) and Ip/P1 (b) ratios vs energy (keV). The lines are the power law best fits.

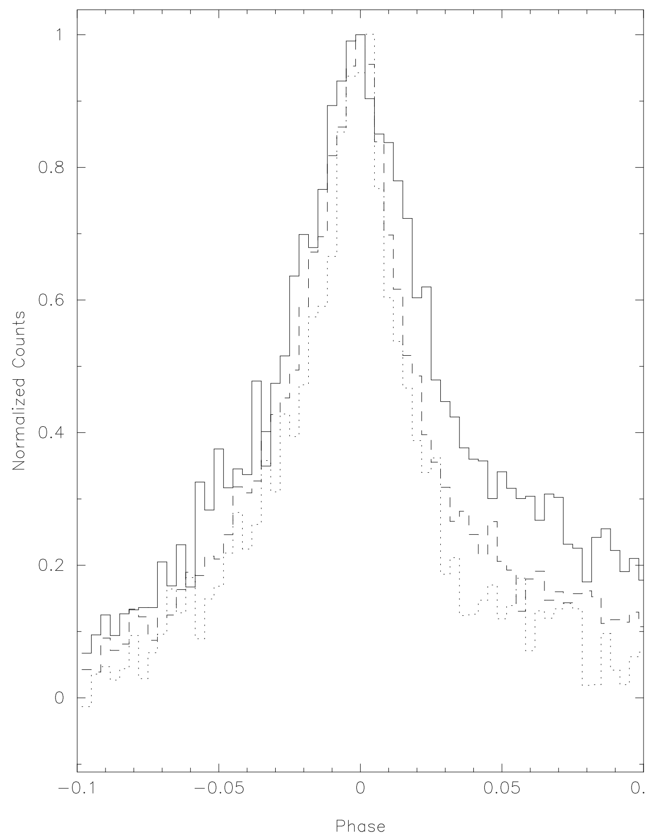

Fig. 3. The profile of P1 in three energy intervals 1.3–2.6 keV (dotted line), 12–28 keV (dashed line) and 52–105 keV (solid line).

with a comparable resolution in this energy range have been published. Becker & Aschenbach (1995) report a pulse profile observed by ROSAT between 0.1 and 2.5 keV in 333 bins, which is practically coincidents with the correspondent one in Fig. 1, confirming the stability of the pulse shape in this band. Ulmer et al. (1994) give a 256 bin pulse profile in the energy band 90–130 keV; again no significant difference with the correspondent one in the BeppoSAX data is evident.

The variation of pulse shape with energy is usually quantified by means of the intensity ratios between the two main features P2/P1 and Ip/P1. To evaluate these ratios in different energy bands we first subtracted the average off-pulse level from the content of each bin of the considered profiles. The phase intervals used were (−0.05,+0.05) for P1, (+0.27,+0.47) for P2, (+0.05,+0.27) for Ip and (+0.47,+0.77) for the off-pulse. Notice that the counts in the last intervals are mainly due to the nebular emission for the imaging instruments, while they contain also the environmental background for the collimated instruments. The resulting P2/P1 and Ip/P1 values are plotted in Fig. 2; the energy of each point corresponds to the mean value weighted with the total count rate of each energy channel and therefore the energy dependence on the pulsar spectrum and on the effective area were taken into account. A quantitative description of these behaviours can be derived by fitting a single power law to each data set. The resulting exponents would then correspond to the spectral index differences between the selected phase intervals. A very good fit was obtained for P2/P1 which gave an exponent equal to 0.145 ± 0.032 with a reduced χ^2 of 0.63 (12 d.o.f), whereas that of Ip/P1 was 0.315 but with $\chi^2_r = 2.01$ (11 d.o.f.). In the latter case, however, the χ^2 excess is mainly due to the first point where the Ip flux is particularly low. If this point is excluded from the fit, the resulting exponent is 0.313 ± 0.069 (practically coincident with the previous one), with a $\chi^2_r = 1.6$ (10 d.o.f). We conclude that the spectral slope of the Ip region is flatter than P2 which in turn is flatter than P1. A possible interpretation of such a behaviour will be discussed in the next section.

We investigated also the shape of P1. Massaro et al. (1997) have already shown on the basis of literature data that in the hard X rays and low-energy γ rays the P1 profile is larger than in the soft X rays and γ (> 30 MeV) ranges. The high statistical quality of the present data allows to check if this trend can be found in the 0.1–300 keV range. In Fig. 3 we plotted in detail the P1 profile measured in the following three energy bands 1.3–2.6, 12–28 and 52–105 keV; all the plots have been normalized by setting the peak height at zero phase equal to unity. The increasing peak width with energy is clearly apparent; this broadening can be quantified by evaluating the phase width of P1 at the normalized level 0.5: for the three profiles shown in Fig. 3 we found 0.038, 0.049 and 0.054. Notice that this effect is more evident on the trailing side because of the Ip contribution, but also on the leading side the higher energy profiles lie outside the inner ones. We stress that it is the first time that such effect is so clearly evident.

4. Discussion

The broad band and the high throughput of the NFI's onboard BeppoSAX provided a good set of phase histograms of PSR B0531+21 particularly useful to study the energy dependence of the pulse shape. Using the energy dependence of P2/P1 and Ip/P1 intensity ratios, we evaluated the difference of the spectral indices of P2 and Ip with respect to that of P1.

It has been already suggested (Hasinger 1984) that the change of the profile shape can be due to the onset of a pulsed component, characterized by a broad phase distribution (hereafter named BPC) different from the one responsible of the radio-optical(Percival et al. 1993) and high energy γ-ray profiles (Nolan et al. 1993) (hereafter ROGC), which are characterized by rather similar P2/P1 and Ip/P1 ratios. The present results establish valuable constraints on the spectral energy distribution of the additional BPC. The fact that the spectral index of P2 is intermediate between that of P1 and Ip can be naturally explained in this framework: the P2 spectrum should be, in fact, produced by the superposition of the hard BPC (essentially that of the Ip region, where the emission associated with the ROGC is negligible) with the softer one of the ROGC. In the same way we can explain the broadening of P1 because the BPC also contributes to P1 with a low intensity pedestal, increasing with energy, which is added to the narrow peak of the ROGC. The phase extension of the BPC, therefore, should not be limited to the Ip and P2 intervals but it must underlie P1 too. A more detailed model of these components, based not only on the present data but also on those of further BeppoSAX observations and of other instruments in different energy bands, is necessary to disentangle their relative contributions and to understand the emission processes and the locations in the pulsar magnetosphere.

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