INTEGRAL observation of the Crab pulsar

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Abstract

In this paper we present the timing and spectral analysis of several observations of the Crab pulsar with INTEGRAL. All these observations, when summed together provide an high statistics data set which can be used for accurate phase resolved spectroscopy of the pulsed emission over the energy range 3-350 keV. In particular, we present the light curves in several energy ranges and phase-resolved spectral analysis of the pulsed emission.

1 Introduction

The Crab pulsar (PSR B0531+21) can be 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 that is almost aligned in absolute phase over all wavelengths (Rots et al. 2000, Tennant et al. 2001, Kuiper et al. 2003).

In the X-ray range, the spectral energy distribution of the Crab pulsar profile changes with phase: the first peak (P1), dominant at low X-ray energies, becomes smaller than the second one (P2) at soft γ rays; moreover, in the same range, an enhancement with energy of the bridge between these peaks, usually called Interpeak (Ip), is also observed.
A first detailed study of the phase-resolved spectra has been performed by Pravdo et al. (1997), in the 5-200 keV energy interval, based on RXTE (PCA and HEXTE) data. They found a variation of the photon index as function of the pulse phase, with the interpeak region systematically harder that the main peaks. Similar results have been reported by Massaro et al. (2000) in the energy range observed by BeppoSAX (0.1-300 keV). In particular, a photon index difference of 0.14 ± 0.03 and 0.31 ± 0.07 is observed between the first

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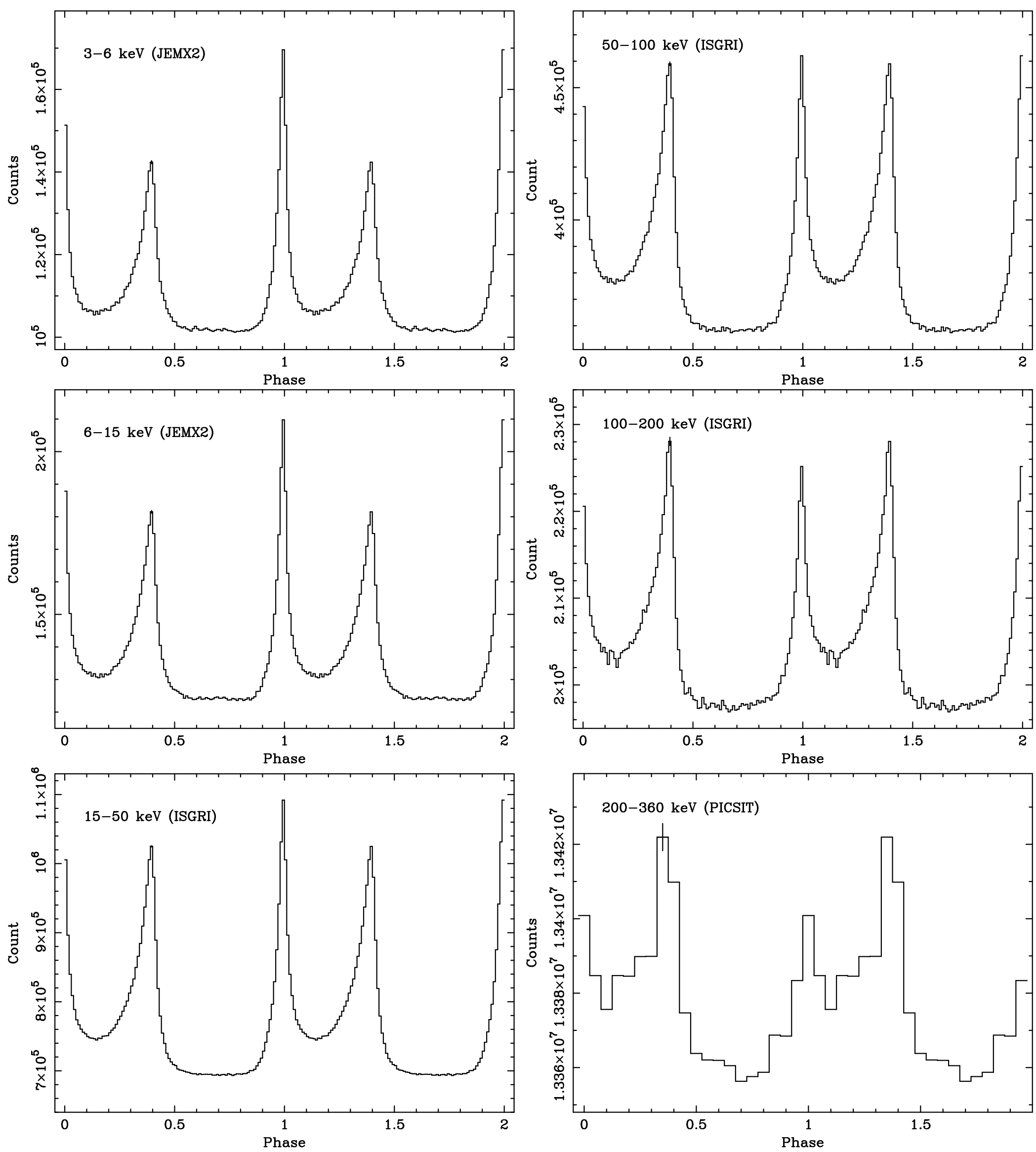

Fig. 1. Crab phase histograms in six energy bands.

peak and the second peak, and between the first peak and the interpeak, respectively. Moreover, these authors found that the photon index relative to the same phase interval significantly increases with energy, and that the phase-resolved spectral distribution can be well modeled by a single curved power law with a slope variable with Log(E). Applying this model to three wider phase intervals, the first peak, the Interpeak and the second peak, a value of ~ 0.15 for the bending parameter has been measured in the three intervals (Massaro et al. 2001).

Kuiper et al. (2001) presented an exhaustive high-energy picture of the Crab pulsar from 0.1 keV up to 10 GeV by using the high energy γ-ray data from the CGRO satellite together with data obtained at X-ray energies from other observatories.

Table 1
Observation log for the data used in this analysis

Revolution	Start-Stop time	Exposure (ks)		
	(MJD)	JEM-X2	ISGRI	PICSIT
39	52677.2 - 52679.8	149.3	142.3	–
40	52680.2 - 52681.6	122.6	56.0	106.5
41	52683.2 - 52685.8	–	–	204.0
42	52686.4 - 52688.2	75.4	61.6	–
43	52689.6 - 52691.7	–	30.7	–
44	52692.2 - 52694.4	–	9.8	–
45	52695.2 - 52696.7	–	2.1	–
102	52866.3 - 52868.1	–	37.9	–
103	52868.6 - 52868.8		21.6	–
	Total	347.3	362.0	310.5

In this paper, we present the timing and spectral analysis of several observations of the Crab pulsar with JEM-X2, ISGRI and PICSIT on board INTEGRAL.

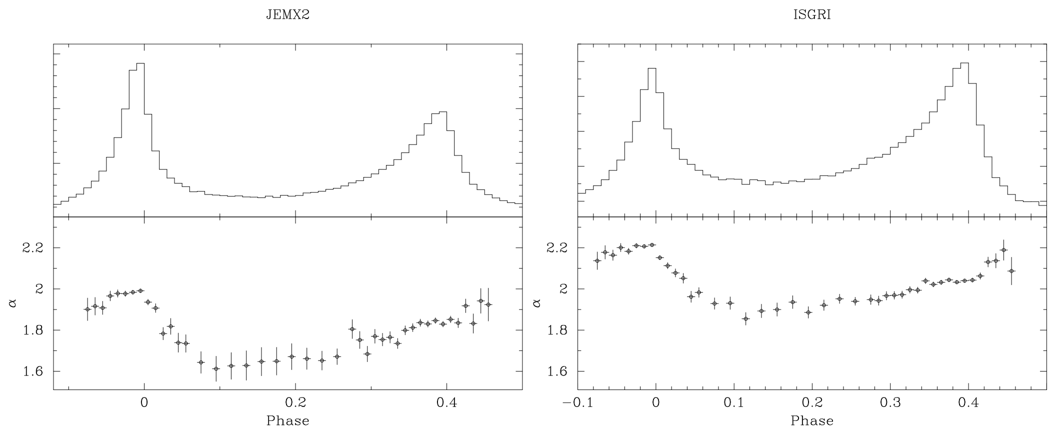

Fig. 2. Spectral index vs. phase measured by JEM-X2 in the energy range 3-20 keV and ISGRI in the energy range 20-350 keV fitting the two instruments separately

2 Observation and Data reduction

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL; Winkler et al. 2003) observed the Crab nebula and pulsar for calibration purposes several times from February 2003 (rev. 39) to August 2003 (rev. 103). In this paper, we present the analysis of the data obtained by JEM-X (Lund et al. 2003) and IBIS (Ubertini et al. 2003). JEM-X consists of two identical coded-aperture mask telescopes with a geometrical area of 500 cm^2 and Microstrip Gas Chamber (MSGC) at the focal plane that operates in the energy range

3-35 keV. IBIS is a coded aperture telescope composed by two detection layers: ISGRI (Lebrun et al. 2003) and PICSIT (Di Cocco et al. 2003). ISGRI is a large CdTe gamma-ray camera operating in the range 15 keV–1 MeV, with a geometrical area of 2621 cm^2 and an energy resolution of $\sim$8% at 60 keV. PICSIT is composed by 64×64 Caesium-Iodide (CsI) scintillation pixels working in the energy intervals 175 keV – 10 MeV. The time resolution is 90μs and 150μs for IBIS and JEM-X, respectively; the INTEGRAL absolute timing accuracy, as estimated by Kuiper et al. (2003) from Crab data, is about 40μs. PICSIT detector cannot be routinely configured in photon-by-photon mode due to the tight telemetry budget. For timing studies, observers can select the spectral-timing mode in which spectra are accumulated on board in four energy bins with an integration time of 1 ms.

Observations with a maximum off-axis angle of 2 deg. were selected for the analysis. For JEM-X, we considered data from only one of the two units (JEM-X2); for PICSIT, we selected observation intervals with time resolution of 1 ms. Moreover, to increase the statistics of PICSIT light curve, data from rev. 0041, with an off-axis of 9.6 deg., were also included. Table 1 summarizes the log of the observations used in this analysis together with the time exposures. Standard reduction procedures have been applied to data and photon list files have been generated with the standard pipeline (INTEGRAL OSA v3.0). In particular, we created for JEM-X2 and ISGRI a list of photons selecting only events falling in pixels illuminated by the Crab, increasing the signal-to-noise ratio. PICSIT data were accumulated in four light curves, one for each available energy channel.

JEM-X2 and ISGRI response matrices are also provided by the standard software; in particular, matrices provived with OSA v4.1 has been used for spectral analysis. No response matrix is available at the moment for PICSIT; data from this detector has not been included in the spectral analysis.

3 Timing and Spectral Analysis

Arrival times were converted to the Solar System Barycentre and folded with proper Crab ephemerides. Our data set spans several months and for each observation we used contemporary radio ephemeris provided by Jodrell Bank radio telescope (UK) that continously monitors this pulsar.

The resulting phase histograms in six energy bands from 3 keV to 360 keV are shown in Fig. 1 with a phase resolution ranging from 0.01 (0.33 ms) to 0.03 (1.1 ms). The well-known double peaked structure is prominent in all the profiles with a high statistical significance.

A detailed phase resolved spectral analysis was performed by selecting spectra in 43 phase intervals 0.01 wide between phase -0.1 and 0.46. The off-pulse level, computed from the interval (+0.60,+0.80), was subtracted from the phase re-

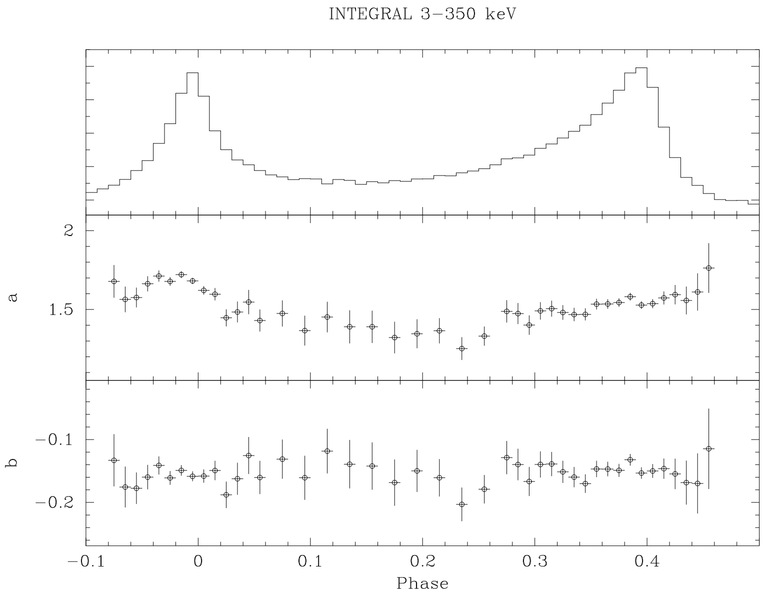

Fig. 3. Best fit parameters a and b measured fitting simultaneously JEM-X2 and ISGRI with the curved model of Eq.1 vs. phase

solved spectra. Energy channels are uniformly rebinned in agreement with the response matrix. JEM-X2 spectral analysis was performed in the energy range 3-20 keV where the response matrix has been tested (Lubinski et al 2004); ISGRI spectra were fitted in the range 20-350 keV due to the lack of detection at higher energies.

All spectra were modeled separately with a single power law. All fits gave acceptable χ^2 and the best fit spectral indices are shown in Fig. 2 vs. phase together with the light curves. The same phase dependence is clearly apparent in each plot: the first peak has the softest spectrum, whereas the hardest emission is produced in the interpeak phase region. Moreover, comparing JEM-X2 and ISGRI results, we note that spectral indices are clearly increasing with energy over all the phase intervals, in agreement with BeppoSAX results (Massaro et al. 2000). We moreover fitted JEM-X2 and ISGRI spectra simultaneously with the curved model:

$$F(E) = K\,E^{-(a+b\,Log(E))} \tag{1}$$

where a corresponds to the photon index at 1 keV and b measures the curvature of the spectral distribution. The resulting best fit values of the two parameters in the 43 phase bins are shown in Fig. 3. The bending parameter b is statistically compatible with a single value over all phase interval as indicated by Massaro et al. (2001) over 3 wider phase intervals. The fit with a constant gave a value of 0.15±0.02, where the error represents the spread around the average.

4 Conclusion

INTEGRAL observations of the Crab pulsar provided a high-statistical data set for a study of the spectral and phase distribution over a wide X-ray energy interval. The detected spectral distribution changes along with phase and the spectral indices clearly increase with energy in all the phase intervals. Moreover, fitting JEM-X2 and ISGRI spectra simultaneously with a curved model we find that this model well describes the spectral emission over all phase intervals, and that the curvature parameters is compatible with a single value (0.15 ± 0.02).
The interpretation of the spectral variation of the pulsed emission with phase in terms of a consistent physical model is not simple. A first step in this direction is the understanding if such complex behavior is due to the fact that we are observing photons emitted in different regions of the magnetosphere and likely by different emission mechanisms. Massaro et al. 2000 proposed that X-ray pulse profile of the Crab can be explained by the superposition of two components with different phase and energy distribution. One of the components has the same profile observed in the optical while the other presents a maximum at phase 0.4 with essentially the spectrum of the interpeak spectrum. The origin of these two components within the magnetosphere and the nature of the emission mechanism is an open problem. Kuiper et al. 2001 from a coherent study of the pulsed emission from 0.1 keV to 10 Gev indicate the outer magnetospheric gap accelerator as the most successful model in explaining the complex high energy characteristics of the Crab pulsar.

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