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Phase distribution of the 0.44 MeV feature in the Crab pulsar spectrum

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Abstract. — On 1990 July 9, the balloon-borne experiment FIGARO II (0.15 - 4 MeV) observed the Crab region. The light-curve of PSR 0531+212 shows, in addition to the well-known two-peak structures, evidence for extra structures at absolute radio phases 0.1, 0.3, and 0.45 around the energy 0.44 MeV. The phase-resolved spectroscopy confirms that an excess, compatible with a line-like feature, is present at these phase positions.

Key words: gamma-ray astronomy, pulsars, PSR 0531+21, Crab.

1. Introduction.

Among gamma-ray point sources, the Crab pulsar holds a unique position: It has been detected over the whole electromagnetic spectrum from radio wavelengths to gamma rays. The energy dependence of the Crab pulse profile provides an essential tool for investigating the complex phenomena involved in the pulsar mechanism. Observations of a narrow emission line near 400 keV in the total Crab spectrum were reported several times in the literature (see Owens 1991). However, positive detections and upper limits were not compatible, suggesting a variable phenomenon. Recently, a narrow emission feature has been detected in the second peak spectrum, with the FIGARO II experiment (Massaro *et al.* 1991). This line ($0.86 \pm 0.33 \times 10^{-4}$ ph/cm^2 sec at 0.44 ± 0.01 MeV) confirms the result obtained with the same experiment four years before (Agrinier *et al.* 1990). A further analysis of the FIGARO II 1990 data has shown that, between the main peaks, two extra structures appear at the absolute phases of 0.1 and 0.3 (the zero is taken at the center of the first radio peak) in the energy range (0.38-0.49) MeV (Massaro *et al.* 1992). This suggests that the 0.44 MeV emission has its own modulation over the pulsar period. To examine this phase distribution, we applied the Kernel density estimation method to the Crab light-curves in various energy ranges and computed the phase resolved spectra.

2. Observation and results.

FIGARO II (Agnetta *et al.* 1988) was launched from the Milo-Trapani base (Sicilia, Italia) on July 9, 1990, at 4:33 UT, for a transmediterranean flight. The tracking of the Crab began at 7:06 UT, slightly before reaching the ceiling (4.4 mbar at 7:42 UT). To the end of the Crab observation (14:30 UT), variation of the residual pressure was limited to 4% around the ceiling value. The total duration of useful data is 5.8 hours. The events were transmitted to the ground station and their arrival times were converted to UT with an accuracy of 20 microseconds. These times were then computed at the solar system barycenter using the JPL Ephemeris DE200 and folded with the pulsar parameters (Lyne & Pritchard, private communication). Thus, we obtained a sample $\Phi = (\phi_1, \phi_2, .., \phi_n)$ of n phases corresponding to the n photons falling in a given energy range. This sample is used to compute an estimation $f(\phi, \Phi)$ of the unknown density function of the phases $F(\phi)$. In the Kernel Density Estimation method

(KDE: De Jager *et al.* 1986) the estimation at any phase point (ϕ) is:

$$f\ (\phi, \Phi) = \frac{1}{nh} \sum_{i=1}^{n} \left(K \left(\frac{\phi - \phi_i}{h} \right) \right),$$

Where K is a weighting function and h a smoothing parameter obtained by minimizing the Mean Integrated Square Error (MISE) (De Jager 1987). We choose the Swanepoel kernel function

$$K(x) = \frac{1}{2}\ (\sin|x| + \cos x) \times \exp\ (-\ |x|),$$

which yields an optimal estimation for nearly all kinds of density distributions even if the first derivative F' is discontinuous (Swanepoel 1987).

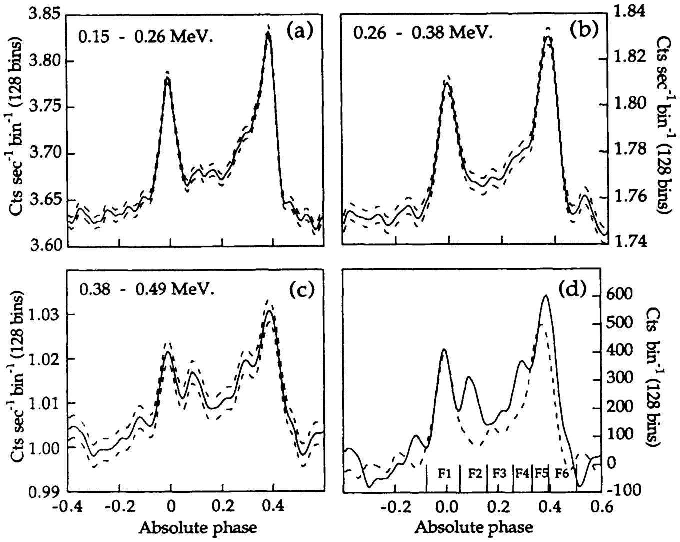

FIGURE 1. a-c) Kernel density estimation of the Crab light curves in different energy bands. The parameter h is (a) 0.079, (b) 0.123 and (c) 0.139 rad. The dotted lines are $\pm 1\sigma$ confidence interval. d) Comparison between the 0.38-0.48 MeV estimate (solid line) and the template curve (dotted line : see text).

The estimated light curves in three energy intervals (0.15-0.26) MeV, (0.26-0.38) MeV, and (0.38-0.49) MeV, are plotted Figure 1. The two low-energy estimations are nearly identical, with a symmetric first peak and an asymmetric second peak showing a broad leading side. On the other hand, the (0.38-0.49) MeV estimation clearly shows additional peak-shaped structures, around phases of 0.1 and 0.3. To illustrate these differences, we built up a template light curve by considering all the events in the two energy ranges adjacent to the interesting one. The (0.28-0.38) + (0.49-0.65) MeV estimation has the same smoothing parameter as the (0.38-0.49) MeV estimation, so the two light curves have same phase resolution. The template curve was normalized to the first peak area of the (0.38-0.49) MeV estimation and compared with it (Fig. 1d). Contrary to the first peak zone, for which the two light curves can be superposed, we are so able to recognize 3 phase intervals, centered at 0.1, 0.3, and 0.45 (interval F2, F4, F6, see definitions in Tab. 1) showing an excess of the (0.38-0.49) MeV estimation above the normalized template. The existence of the two first excesses confirms a previous analysis by Massaro *et al.* (1992), obtained by fitting the interpeak phasogram shape with an analytical expression: these structures resist to the KDE estimation. The third structure consists in a broadening of the second peak trailer.

TABLE 1. *Phase definition of the considered intervals.*

F1	F2	F3	F4	F5	F6
[-0.08 , 0.05]	[0.05 , 0.157]	[0.157,0.257]	[0.257 , 0.33]	[0.33 , 0.393]	[0.393,0.503]
Peak 1	"Anomaly 1"	Part of Interpulse	"Anomaly 2"	Part of peak 2	"Anomaly 3"

We derived the pulsed spectra by substracting the background counts : $\Delta\ \phi_{\mathrm{bkg}} =$ (0.503, 0.92) from those in selected phase bins. The net spectrum was then fit to models with a maximum likelihood procedure using a transfer matrix including both the residual atmosphere and the instrument. Various spectra, for different combinations of the 6 phase intervals were examined (see Tab. 2). The single power law : (model 1 : $N(E) = A \times 10^{-3} \times (E/0.3\ \mathrm{MeV})^{-\gamma}$ ph/cm^2 sec MeV), is a good representation of the peak 1 spectrum ($F1$), of the total pulsed ($F1$ to $F6$), and of the sum ($F1 + F3 + F5$). On the contrary, when one considers the combination ($F2 + F4 + F6$), the fit is not satisfactory ($\chi^2(9) = 16.15$) and shows a clear excess in the (0.38-0.49) MeV range (2.95σ). A possible explanation is a narrow line superposed on the continuum spectrum. Using a four-parameter model which includes the energy position (E_o) and the amplitude (L) of the Dirac function-like line (model 2 : $N(E) = A \times 10^{-3} \times (E/0.3\ \mathrm{MeV})^{-\gamma}$ ph/cm^2 sec MeV $+\ L \times 10^{-4} \times \delta\ (E - E_\mathrm{o})$ ph/cm^2 sec), the χ^2 value ($\chi^2(7) = 5.67$) becomes acceptable. The intensity of the fitted line is $3 \pm 1 \times 10^{-4}$ ph/cm^2 sec at $E_\mathrm{o} = 0.44 \pm 0.01$ MeV.

The experimental phase-averaged spectrum (normalized counting rate) is compared in Figure 2 with the expected spectrum according to models 1 and 2, obtained by convolving the two models with the instrumental response and atmosphere transfer. Note the full compatibility between the width of the feature and the energy resolution of the experiment ($\Delta E =$ 60 keV *FWHM* at 440 keV).

The three "anomalous" intervals that we have summed, are chosen because the (0.38-0.49) MeV Crab light curve shows excesses over the template. Thus, the spectral analysis must not be used to examine the reality of the three excess zone. This last point is achieved with the KDE

TABLE 2. *Model 1 and 2 best fit parameters (see text). Excess is the normalized difference in the (0.38-0.48) MeV range between data and model.*

	Phase	F1	F1 F3 F5	F1 to F6	F2 F4 F6
	A	3.21 ± 0.24	7.38 ± 0.44	12.5 ± 0.72	4.57 ± 0.86
	Index γ	2.55 ± 0.25	2.40 ± 0.19	2.46 ± 0.20	3.02 ± 0.65
1	χ^2 (9)	6.15	3.85	7.45	16.16
	P(>χ^2)	0.725	0.921	0.592	0.063
	Excess	-0.05	-0.21	1.75	2.95
	A	-	-	11.8 ± 0.90	4.37 ± 0.6
	Index γ	-	-	2.67 ± 0.24	3.19 ± 0.5
2	L	-	-	3.15 ± 1.75	2.97 ± 1.0
	E0	-	-	0.448	0.438
	χ^2 (7)	-	-	3.05	5.67
	P(>χ^2)	-	-	0.880	0.578

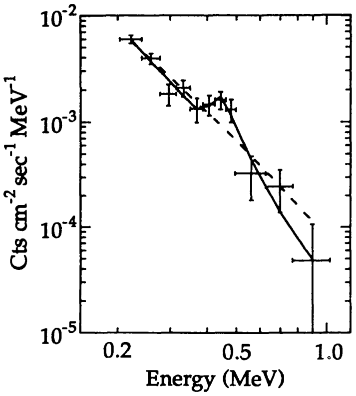

FIGURE 2. ($F2+$ $F4+$ $F6$) best fit spectra (model 1: dashed line, model 2: solid line) convolved by experimental response, compared with experimental FIGARO count rates (points).

analysis : confirming previous work (Massaro *et al.* 1992), secondary narrow structures, inexplicable with statistical fluctuations (otherwise they would have been smoothed by KDE procedure), were present in the (0.38-0.49) MeV Crab light curve during the FIGARO II observation. With the same data, a narrow emission feature ($0.86 \pm 0.33 \times 10^{-4}$ ph/cm^2 sec at 0.44 ± 0.01 MeV) has been detected in the second peak spectrum (Massaro *et al.* 1991). We propose that this spectral feature is not limited to the second peak, but appears in three phase regions $F2$, $F4$ and $F6$.

The reported flux of the feature ($3 \pm 1 \times 10^{-4}$ ph/cm^2 sec at $E_o = 0.44 \pm 0.01$ MeV) is about three times higher than the first value reported by Massaro *et al.* (1991). In their analysis, the phase interval was limited to (0.27-0.47) and included only a fraction of "anomalies 2 and 3". The choice of a much wider phase interval and in particular the "anomaly 1" which gives a relevant contribution, would naturaly produce a higher line flux. The excess is concentrated in very narrow phase regions. In particular, this is the reason why the "anomaly 1" (0.1 phase width) did not contribute significantly to the P1 + IP spectrum (0.32 phase width) obtained with the same data in Massaro *et al.* (1991).

3. Conclusion.

The present analysis suggest that the 0.44 MeV excess in the Crab pulsar spectrum has its own phase variation, independent of the classical double-peaked light-curves. This FIGARO result is the first observation of such structures. Preliminary results of the OSSE experiment on board CGRO (Johnson *et al.* 1992) did not show similar features. If the phenomenon is transient, or even slightly variable in phase position or energy, experiments which require observation times longer than a few hours to achieve a sensitivity equivalent to FIGARO, will not detect it. A possible interpretation of these excesses is a gravitationally redshifted positron annihilation line close to the pulsar surface (Bednarek *et al.* 1992). It is generally admitted that the low energy gamma ray continuum is emitted far from the surface, in the outer magnetosphere. So it would not be surprising to observe different light curve for the annihilation radiation.

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