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Time delay between radio and gamma-ray pulsed emissions of the Crab pulsar.

J.L. Masnou[1], B. Agrinier[2], E. Barouch[2], R. Comte[2], E. Costa[3], J.C. Christy[2], G. Cusumano[8], G. Gerardi[4], C. Gouiffes[2], D. Lemoine[5], P. Mandrou[6], E. Massaro[7], G. Matt[7], T. Mineo[8], M. Niel[6], J.F. Olive[6], B. Parlier[2], L. Perret[1,10], B. Sacco[8], M. Salvati[9] and L. Scarsi[8]

FIGARO Collaboration

[1]UPR176, CNRS, DARC, Observatoire de Paris, Section de Meudon (France)
[2]Service d'Astrophysique, DAPNIA, CES, Saclay (France)
[3]Istituto di Astrofisica Spaziale, CNR, Frascati (Italy)
[4]Istituto di Fisica, Università di Palermo (Italy)
[5]UA173, CNRS, DAEC, Observatoire de Paris, Section de Meudon (France)
[6]CESR, CNRS, Université P. Sabatier, Toulouse (France)
[7]Istituto Astronomico, Università "La Sapienza", Roma (Italy)
[8]Istituto di Fisica Cosmica e Appl. Informatica, CNR, Palermo (Italy)
[9]Osservatorio Astrofisico di Arcetri, Firenze (Italy)
[10]EUROPA, Université de Paris 7 (France)

ABSTRACT

Gamma-ray emission has been detected for six radio pulsars. Two of them (Crab and Vela) are known from the first gamma-ray satellite and balloon missions, and four more have been discovered with the Compton Observatory (CGRO). In this contribution, we review the main characteristics of these objects and present new results from the FIGARO II experiment on the phase shift between the radio and the gamma-ray (0.15-4 MeV) pulses emitted by Crab pulsar.

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2. High energy gamma-ray isolated pulsars.

Table 1 displays the main gamma-ray pulsars characteristics (Thompson, 1993, Fierro et al., 1993) in the high-energy gamma-ray range. The last column lists the efficiencies computed as the ratio of the gamma-ray luminosity observed between 0.1 and 5000 MeV to the rotational energy loss with the arbitrary assumption that gamma-rays are emitted inside a solid angle of one steradian. The gamma-ray luminosity has been computed by integration below a single power-law or a series of adjacent power laws when necessary.

Table 1

Pulsars observed in the high-energy gamma-ray range

Pulsar	Period (s)	Age (yr)	Luminosity 0.1-5000 MeV ergs/s	Spectral index	Efficiency
PSR B0531+21 Crab	0.033	1300	$2.0\ 10^{35}$	-2.15	0.005
PSR B1509-58	0.150	1550	$1.9\ 10^{35}$	-1.8	0.01
PSR B0833-45 Vela	0.089	11000	$2.3\ 10^{34}$	-1.89	0.003
B1706-44	0.102	17000	$3.7\ 10^{34}$	-1.72	0.01
Geminga[1]	0.237	340,000	$2.6\ 10^{33}$	-1.46	0.08
PSR B1055-52	0.197	530,000	$9.7\ 10^{33}$	-1.18	0.3

[1] Assuming a distance of 250 pc (Halpern and Ruderman, 1993)

The four new gamma-ray pulsars are B1509-58, B1706-44, B1055-52 and Geminga. B1509-58 is the third radio pulsar to have been detected in the gamma-ray range after Crab and Vela pulsars with BATSE (60 keV-2 MeV, Wilson et al., 1991), OSSE (Ulmer et al., 1993), COMPTEL (Bennett et al., 1993). It had been detected beforehand with *Ginga* (Kawai et al., 1991) following its discovery in the X-ray range (Sewrd and Harnden, 1982). However it is not detected at high energy (i.e.with EGRET). B1706-44 has been detected by EGRET above 100 MeV.(Thompson et al., 1992) and B1055-52 above 300 MeV (Fierro et al., 1993, Kanbach et al., 1993). The gamma-ray source Geminga (PSR J0633+1746), listed as 2CG195+04 in the second COS-B catalogue (Swanenburg et al., 1981), has been identified as a X-ray pulsar by Halpern & Holt (1992) with the X-ray satellite ROSAT. The period of 237 ms has been confirmed in EGRET, COS-B, SAS-2, GAMMA 1 and FIGARO II observations (Bertsch et al., 1992, Mayer-Hasselwander et al., 1994, Bignami and Caraveo, 1992, Hermsen et al., 1992, Akimov et al., 1993, Massaro et al., 1993). Accurate Ephemeris have been derived from EGRET observations 1 & 2 by Mattox et al. (1993). The light curves of gamma-ray pulsars obtained (when they are detected) at radio, optical, X-ray or gamma-ray wavelengths show (Thompson, 1993, Mereghetti et al., 1993) that the geometry of the emission is quite complex, and varies from one object to the other. The pulsed emissions are in general not in phase at all wavelengths, Crab pulsar being a peculiar case of close simultaneity. Spectral variability is often observed, for example in the case of Geminga and Vela (Grenier et al., 1993). Crab, Vela and Geminga present double-peaked pulse profiles and the three other pulsars display a single broad pulse.

It would be interesting to explain two trends which emerge from the small sample of 6 detected gamma-ray pulsars (Thompson, 1993, Fierro et al., 1993, see Table 1). These trends are not confirmed however through search of gamma-ray emission from other pulsars and are in any case biased by the quite diverse spectral behaviour from source to source and by the arbitrary choice of a uniform solid angle of outgoing radiation for all objects. The trends are the following ones:

1) The efficiency of conversion of rotational energy loss (assuming a moment of inertia $I=10^{45}$ g-cm^2) into integrated gamma-ray luminosity is significantly higher for the oldest pulsars such as Geminga and PSR B1055-52. More precisely, the trend predicted by Ozernoi and Usov (1977), Buccheri et al. (1978), Salvati and Massaro (1978), Massaro and Salvati (1978) and Ochelkov and Usov (1980) between efficiency and apparent age is confirmed in the sample of those six detected pulsars.

2) The average photon energy is significantly higher for the oldest pulsars. This is indicated also by the flattening of the spectral index with age (from -2.15 for Crab to -1.18 for PSR B1055-52).

However, these trends have not been confirmed when other radio pulsars, such as B0656-14 and B1929-10, are included in the search. They should have been detected if the above laws were universal. An unknown bias might affect the results. Under the usual assumption that the solid angle into which gamma-rays are emitted is identical for all pulsars, i.e. 1 steradian, neither the polar cap model with an expected correlation between the product Efficiency x $\dot{P}^{-1/3}$ (where $\dot{P}$ is the derivative of the period) and the apparent age (Harding, 1981), nor the outer gap model with an extinction limit in the log B-log P plot (Chen and Ruderman, 1993), allow firm predictions of gamma-ray pulsars observability.

The launch from Milo (Italy), during the summer 1995, of the high sensitivity (16 m^2 geometrical area) , high timing resolution new telescope FIGARO IV (Sacco et al., 1993), built to detect gamma-rays with energy above 50 MeV, will bring new elements about the nature of a number of low flux sources listed in the EGRET-CGRO catalog (Fichtel et al., 1994).

Dermer and Sturner (1994) propose (see also Ozernoi and Usov, 1977) a new polar cap model with the restriction that the rotation axis and the magnetic axis are quasi parallel, i.e. $\theta \approx \theta_{pc}$ where θ_{pc} is the angular extension of the polar cap. High-energy electrons (Sturner et al., 1994, Sturner, 1993, Sturner and Dermer, 1994) Compton-scatter up to gamma rays within a narrow cone the low energy thermal and non-thermal photons (from optical to soft X-rays) emitted near the polar cap. The effective gamma-ray luminosity is then much smaller than if computed assuming an emission spread out within one steradian. Gamma-ray pulsars are expected from this model for high values of $\dot{P}^{3/4}\,P^{-5/4}\,d^{-2}$ where d is the distance. A specific radio-gamma phase delay is predicted which depends upon θ as well as the gamma-ray pulsed profile.

Radio pulsars are loosing their energy by emission of electromagnetic radiation and the first deceleration parameter n or braking index describes the regular ordinary decrease in frequency $\nu' = -K\nu^n$. An accurate radio study of PSR B1509-58 by Kaspi et al. (1994) leads to a value of $n = 2.837 \pm 0.001$, smaller than the expected dipolar value of 3.000, alike Crab ($n = 2.509 \pm 0.001$) and B0540-69 ($n = 2.02 \pm 0.01$). We recall here that B1509-58 is the second youngest X-ray pulsar. There is controversy around the possible association with the supernova remnant G320.4-1.2 (MSH15-52) due to the age difference. This pulsar has a very high period derivative and it is remarkable that the value of the frequency third derivative, measured by Kaspi et al. (1993), $\nu''' = (-1.02 \pm 0.25)\ 10^{-31}\ s^{-4}$, is consistent with the value expected by the standard model $-0.9338\ 10^{-31}\ s^{-4}$.

For Geminga, n has been found much higher than 3 (Hermsen et al., 1992) with however a very large uncertainty ($n = 31 \pm 18$) but the effective value is probably lower after Doppler correction from the high velocity of this closeby pulsar (Bisnovatyi-Kogan and Postnov, 1993).

A possible interpretation (Dermer and Sturner, 1994) of low values ($n<3$) of the braking index n is that the magnetic moment is close to alignement with the rotation axis of these pulsars. Strong particle winds are then expected, providing also the clue for gamma-ray emission. Non-thermal optical emission has recently been discovered by Caraveo et al. (1994) for four pulsars: B1509-58, B0540-69, Crab (B0531+21) and Vela (B0833-45). Usov (1992) has shown that, for sufficiently high value of the magnetic field ($B > 4.4 \times 10^{12}$ Gauss), electric field would not be screened by electron-positron pairs generated above the polar caps, and high gamma-ray efficiency (Shabad and Usov, 1982) would be expected. It is probably already the case for B1509-58: $B \sim 1.5 \times 10^{12}$ Gauss.

The Crab pulsar is a peculiar object among other compact sources since it has been constantly claimed that, down to a 0.5 ms accuracy, pulses are locked on the same phase at all wavelengths. Furthermore, from the 1990 FIGARO II observation, additional minor features have been found at phases 0.1, 0.3 and around the second pulse, with pulsed line emission centered around 440 keV (Massaro et al., 1991a, Olive et al., 1992). Those additional features represent several beams. More detailed analysis of FIGARO observations is in progress. Sensitive observations performed independantly are high resolution spectroscopic data from the Gamma Ray Imaging Spectrometer (GRIS, Bartlett et al., 1993). No very narrow pulsed line has been found; this implies that the width of the 440 keV line emission is broader than ~10 keV in order to be in agreement with FIGARO II observations.

3. Delay between radio and gamma-ray emissions of the Crab pulsar.

In order to check if a small residual phase difference could remain between radio and gamma-ray pulses, we have analysed the 1986 and 1990 observations of the Crab pulsar performed with the balloon-borne gamma-ray experiment FIGARO in the low energy gamma-ray range. We present below a summary of our results. FIGARO (an acronym for French Italian GAmma Ray Observatory) detector is a squared array of 9 NaI(Tl) tiles, 5 cm thickness with a total geometrical area of 3600 cm^2. The energy ranges were respectively (0.17-6) MeV in 1986 and (0.13-3.75) MeV in 1990. A full description of the telescope can be found in Agnetta et al. (1989). Two launches were performed from the Milo airport (Trapani, Italy, latitude 38°00' N and longitude 12°35' E) on 1986 July 11 and on 1990 July 9. The arrival time of each event has been transformed into the solar system barycentric (SSB) system using the Jet Propulsion Laboratory (JPL) ephemeris code DE200 (Standish, 1982). Corrections due to pulsar proper motion have been neglected (Lemoine, 1991). The phase $\phi(t)$ of each gamma-ray has been computed according to the usual expression,

$$\phi(t) = \nu\,(t-t_o) + \nu'\,\frac{(t-t_o)^2}{2} + \nu''\,\frac{(t-t_o)^3}{6} \qquad (1)$$

where t is the gamma-ray arrival time and t_o the reference radio arrival time at infinite frequency. ν, ν' and ν'' are the radio parameters from the Jodrell Bank Ephemeris (1993). Figure 1 displays the light-curve obtained in the full energy range for the 1990 flight. The profile shows clearly an outstanding second pulse, as it is well known into this energy range, in contrast with profiles obtained at lower or higher energies. The light-curve obtained from the 1986 flight is very similar but slightly more noisy. In order to obtain an unbiased absolute phase of the first pulse and of the phase difference between the two pulses, a Kernel estimator (de Jager et al., 1986) has been built from the ordered series of absolute phases ϕ_j of the n individual gamma-rays. Due to the asymmetry of the second gamma-ray pulse, the Kernel estimator is expected to provide a better estimate of the position of the maximum emission than the barycenter method. Figure 2 shows the estimator drawn together with the one standard deviation limits obtained for the 1990 observation. As in Agrinier et al. (1990), the zero phase has been set at the maximum of the first main radio pulse at 600 Mhz. Uncertainties which affect the gamma-radio delay include radio uncertainties (i.e. radio extrapolation, dispersion measure) and gamma-ray uncertainties (i.e. registration of the atomic clock time, geographical position of the balloon, inaccuracy of the FIGARO barycentrisation code and gamma-ray pulse position using the Kernel estimation method). Table 2 displays the values obtained in two energy ranges for the radio-gamma time delay $T_{radio-gamma}$ and for the phase difference between the two pulses. The Dispersion Measure DM was not always available every month in the Crab pulsar Ephemeris: for the 1986 flight, the value of DM used to extrapolate the radio arrival time at infinite frequency has been measured on 1986 May 15, two months before the gamma-ray observation. For the 1990 flight, DM has been measured 6 days after the launch, which represents a much shorter delay between radio and gamma-ray observations.

Table 2

Radio-gamma time delay and phase difference between the first and the second gamma-ray pulses.

Flight	Energy range (MeV)	$T_{radio-gamma}$ (μs)	$\phi(P_2)-\phi(P_1)$
1986	0.17-3.75	600±145	0.397±0.005
	0.17-0.51	516±145	0.398±0.005
1990	0.13-3.74	375±148	0.402±0.005
	0.13-0.47	462±148	0.403±0.005

Both measurements show the same trend: a delay between radio and gamma-ray emissions. In both cases, the radio emission follows very closely the gamma-ray emission.

We notice first that the very accurate average pulse profiles obtained with the High Speed Photometer of Hubble Space Telescope (Percival et al., 1993) provide a separation between the two main pulses significantly higher than 0.4, i.e. 0.4167±0.0004 in the V colour and 0.4139±0.0005 in the UV colour. Our results confirm for the Crab pulsar a decrease of intra-peak phase separation with increasing energy from radio to gamma rays noticed for Crab (0.45 to 0.39) and Vela (1.0 to 0.4) pulsars (Ramanamurthy, 1994).

Gamma-ray pulses of the Crab pulsar observed at high energies (>50 MeV) have been found in phase with radio emission with a time uncertainty of 0.5 ms in Wills et al. (1982) and 0.33 ms in Nolan et al. (1993) after a long observing time of several weeks. HEAO3 observations performed in the 50 keV-10 MeV range during 41 days in 1980 obtained phase agreement within 1 ms (Mahoney et al., 1984). No offset between radio and optical or UV pulses has been found within ±1 ms by Percival et al. (1993). Results from OSSE (Ulmer et al., 1994), do not afford a constraint to our results, due to their large radio uncertainty.

4. Discussion.

Gamma-rays are not affected by interstellar dispersion or scattering, either in the interstellar medium or in the solar corona, so that any difference between radio and gamma phases has to be explained either by a delay induced on radio waves by the ionized interstellar medium, assuming a common site of emission in the pulsar magnetosphere, or alternatively by a different region of emission from the pulsar magnetosphere. The high 1990 value of $T_{radio-gamma}$ is constraining since dispersion measures are continuously available from May to August 1990. It might originate from a very rapid change ($\Delta[DM]=0.043$) of the column density of electrons during the lapse of six days between the gamma-ray observation (1990 July 9) and the radio dispersion measure (1990 July 15). It has been established (Rickett, 1977) that dispersion and scattering of the radio waves emitted by the Crab pulsar originate from two components: the first one is slowly variable (Phillips and Wolszczan, 1991) and is due to the ionized interstellar medium on the line of sight, the second one is changing more rapidly and is attributed to the filaments (whisps) of the Crab nebula, drifting at close distance from the pulsar. If attributed to variability of the dispersion in the Crab nebula, the radio-gamma phase difference obtained from the FIGARO 1990 observation, would be equivalent to an increase of the electron column density by $1.3x10^{17}$ electrons cm^{-2} in 6 days. This is five times larger than what has been observed after a sudden spin-up of the pulsar such as the glitch which occured on 1969 September 28.

The radio emission of the Crab pulsar is characterized at the highest frequencies (Rankin et al., 1970) by two variable narrow components, a pulse and an interpulse, and a broader polarised precursor which precedes the main pulse by 1.64±0.1 ms and is usually attributed to an emission site close to the neutron star polar cap (Graham Smith, 1991, Phillips, 1992). The narrow radio pulses and high-energy pulses, from optical to gamma-ray, have been attributed (Morini, 1983, Lyne and Graham-Smith, 1990) to synchrotron emission (Davila et al., 1980) from outer magnetospheric gaps. They are emitted tangentially to open field lines, close to the limiting field lines, and at a radial distance $0.9\,r_c$ where r_c is the radius of the light-cylinder. An appealing interpretation of our results is that the locations of maximum radio and gamma-ray emissions are distant by roughly 100 km. Such a difference is consistent with expectations from Dermer and Sturner (1994) and Ozernoi and Usov (1977).

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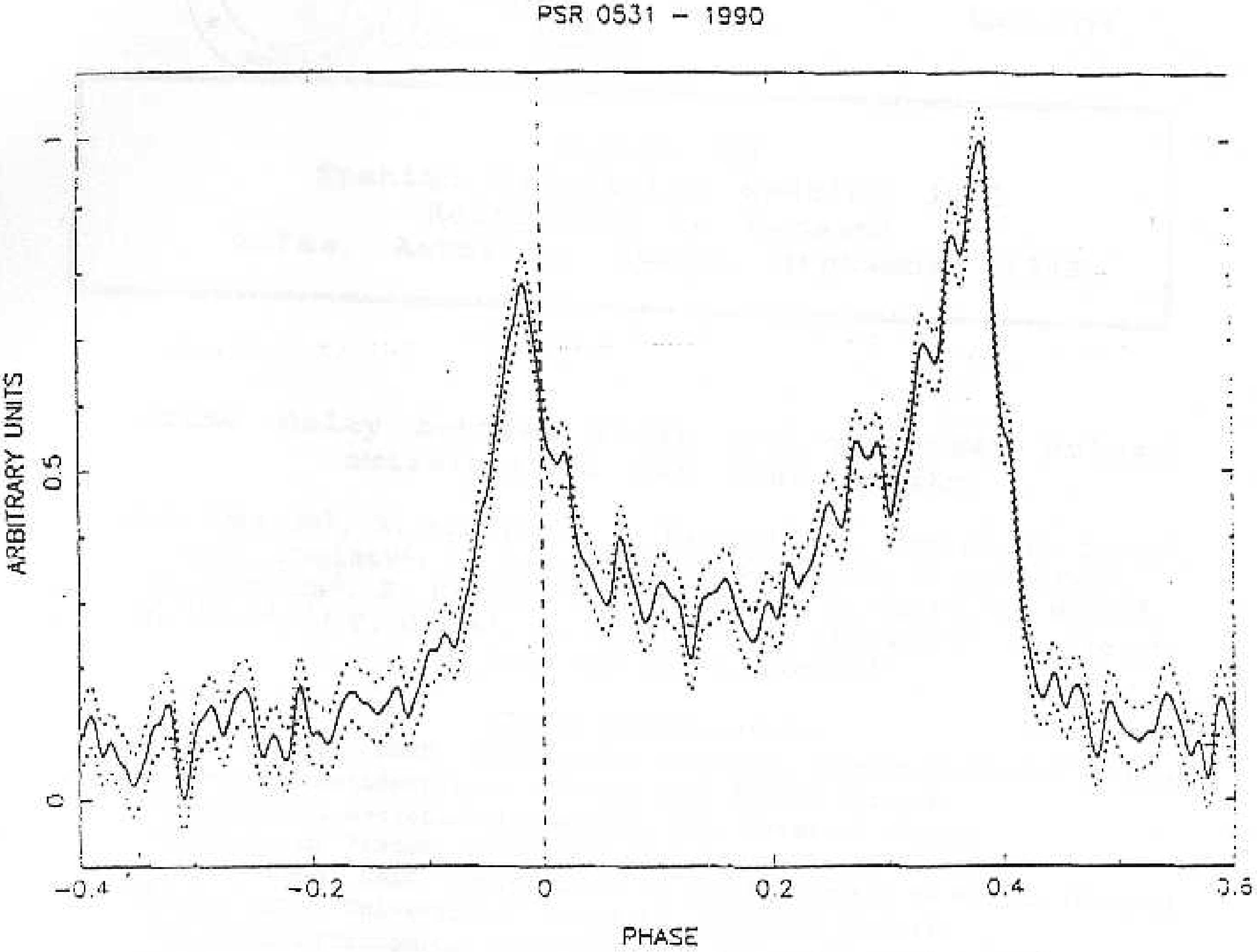

Fig.2. Kernel estimator curve (full line) with the one standard deviation limits (dashed lines) for the 1990 flight (0.13-3.74 MeV). The zero phase is set at the maximum of the main radio pulse (Lyne et al., 1988).