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The radio-gamma time delay of the Crab pulsar

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Abstract. Gamma-ray observations of the pulsar of the Crab nebula, PSR0531+21, have been performed in the low energy range (0.15–4.0 MeV) with FIGARO II, a large area balloon borne NaI(Tl) detector, during two flights performed on 1986 July 11 and 1990 July 9. A Kernel estimator built from the phases of the individual gamma-ray arrival times has allowed an accurate derivation of the radio-gamma time delay from those short duration gamma-ray observations. The gamma-ray pulse is found ahead of the radio pulse by $600 \pm 145\ \mu$s and $375 \pm 148\ \mu$s for the 1986 and 1990 observations respectively. Both radio-gamma delays could be attributed to variability of the interstellar dispersion since dispersion measures are available from radio measurements respectively two months before the 1986 flight and six days after the 1990 flight. An alternative explanation, particularly from the 1990 observation, could be that maximum gamma-ray and radio emissions originate from spatially different regions of the magnetosphere, distant by about 100 km.

Key words: pulsars: Crab pulsar – gamma-ray emission – radio emission – radiation mechanism – interstellar medium

1. Introduction

The FIGARO II telescope has been used to observe the Crab pulsar during two balloon flights, in 1986 and 1990. Preliminary investigations of the light curve obtained in the energy range 0.2–6 MeV during the 1986 flight confirmed that the second peak is the dominant feature and that the interpeak region is more intense than in other energy ranges. The good timing accuracy of FIGARO obtained during the 1986 flight has provided a preliminary estimate (Agrinier et al. 1990) of the delay between the arrival times of the gamma-ray first pulse and of the radio first main pulse using the Massachusetts Institute of Technology (MIT) ephemeris PEP311 (Ash et al. 1967). The gamma-ray pulse was found in advance of the radio pulse by about 300 μs. The knowledge of the radio-gamma delay is an important issue in order to clarify the geometry of emission (Smith 1986) in the Crab pulsar magnetosphere. The aim of this paper is to present an improved estimate of the radio-gamma delay for the 1986 flight, using the Jet Propulsion Laboratory (JPL) ephemeris, and a new delay from the 1990 observation which provides an interesting result.

2. The FIGARO II telescope

The FIGARO II (an acronym for the French-Italian GAmma-Ray Observatory) telescope has been designed to study pulsating sources with well established time signature in the low energy gamma ray range. The main detector is a square array of nine NaI(Tl) tiles, 5 cm thickness, with a total geometrical area of 3600 cm^2. It is actively shielded against cosmic ray and gamma-ray atmospheric background by a surrounding wall of 12 NaI(Tl) modules, together with four blocks of plastic scintillators below the NaI modules. Downwards charged particles are rejected by a thin (5 mm) plastic scintillator shield covering the top of the detector. The energy ranges are respectively (0.17–6) MeV in 1986 and (0.15–3.75) MeV in 1990. The time and energy channel of each individual accepted trigger were transmitted at a ground station through an asynchronous telemetry channel with a bit rate of 300 kHz bandwidth. Simultaneously, and in the case of the 1990 flight only, data were also registered

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Send offprint requests to: J.L. Masnou on an on-board recorder, with an overall capacity of 2 gigabytes, in order to avoid loss of data. A full description of the telescope and of the calibration procedure is provided by Agnetta et al. (1989).

The telescope was launched from the Milo base (Trapani, Italy, latitude 38°00′ N and longitude 12°35′ E) on 1986 July 11 at $5^{h}00^{m}$ UT (Julian date 2446622.7). A float altitude corresponding to 4 mbar residual pressure was reached 3 hours later. The average counting rate was 1360 counts s^{-1}. During the final part of the ascent and for 2.5 hours at ceiling, the experiment pointed in the direction of the Crab pulsar. The observation started at $7^{h}22^{m}$ and stopped at $10^{h}25^{m}$ providing 9000 s of useful data. A second launch was performed on 1990 July 9 at $4^{h}33^{m}$ UT. The Crab pulsar tracking started at $7^{h}06^{m}$ UT at a zenithal distance of about 36° and a residual pressure of 9 mbar. The ceiling was reached at 4.4 mbar on $7^{h}42^{m}$ UT and the Crab observation ended at $14^{h}30^{m}$. Due to a temporary telemetry failure, the results given below correspond to an exposure of 20 940 s.

3. The Crab pulsar light-curve

The geographical position of the balloon was known at any time during the flight through the Loran C System. At the Milo station, a UTC (Universal Coordinated Time) generator, driven by a rubidium clock, provided relative timing within 10 μs. Absolute timing was insured by transportation of an atomic clock from the Time Service of the Istituto Galileo Ferraris (Torino, Italy) followed by regular control using television synchronisation. The on-board recorded events were marked in time using a quartz clock, with an accuracy of 0.1 ms; the drift of the quartz clock was evaluated by comparison of sequences of successive arrival times registered on-board and at the Milo station. A third rubidium clock installed at the second telemetry station of Palma (Majorca Island) and transported from the Centre National d'Etudes Spatiales (CNES) Time Service in Toulouse (France) was also locked on UTC and used to mark the events in time. Comparison between rubidium clocks at Milo and Palma performed both by CNES and ASI (Italian Space Agency) allowed to lock the absolute time within 10 μs.

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). This code uses the equatorial coordinates at the J2000.0 epoch so that the precession matrix of Standish (1982) had to be applied to the coordinates provided (Lyne & Pritchard 1993) in the inertial system B1950.0 based on the FK4 catalog. Since the arrival times were registered at the telemetry station in the coordinated universal time (UTC) scale, they have been first transformed in the Barycentric Dynamical Time (TDB) scale before conversion into the SSB scale. The transformation from Terrestrial Dynamical Time (TDT) to TDB scale has been computed using a routine provided by Fairhead (Fairhead & Bretagnon 1991). The maximum amplitude of this correction is ±1.6 ms. The delays induced on the time of propagation of the gamma-rays by orbital and rotational motions of the Earth and relativistic gravitational distortion have been taken into account using the method of Doroshenko & Kopejkin (1990). 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:

$$\phi(t) = \nu(t - t_0) + \nu' \frac{(t - t_0)^2}{2} + \nu'' \frac{(t - t_0)^3}{6} \qquad (1)$$

where t is the gamma-ray arrival time and t_0 is the reference radio arrival time at infinite frequency corresponding to the pulsar frequency and first derivative ν' and ν'' provided into the Jodrell Bank Crab Pulsar Monthly Ephemeris. Following Lyne & Pritchard (1993), ν'' is computed from the two first radio parameters by the expression:

$$\nu'' = 2\frac{\nu'^2}{\nu} \ . \qquad (2)$$

Table 1. Radio pulsar parameters

Flight date	t_0 (Julian date)	$\nu(s^{-1})$	$\nu'(s^{-2})$
1986 July 11	2446626.5	30.006310227	$-3.7931791\ 10^{-10}$
1990 July 9	2448087.5	29.9585217157	$-3.7793430\ 10^{-10}$

When ν'' is neglected, the corresponding time shift is only 7 μs over 6 days. Table 1 displays the values of the frequency and frequency derivative used for the two flights corresponding respectively to 1986 July 11 and 1990 July 19. The position of the pulsar has been taken as:

$$\mathrm{RA(B1950.0)} = 5^{h}31^{m}31^{s}.406$$

$$\text{and DEC(B1950.0)} = +21°58'54''.391 \ .$$

Figure 1 displays the light-curves obtained in the full energy range during the 1990 flight. The profile shows clearly the outstanding second peak, 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.

4. Estimation of the delay between radio and gamma-ray main pulses

4.1. Estimation of the phases of the gamma-ray peaks using a non-parametric method

In order to obtain a non-parametric evaluation of the gamma first peak absolute phase and of the phase difference between the two peaks, a Kernel estimator (de Jager et al. 1986) has been built from the ordered absolute phases ϕ_j of the n individual gamma-rays. The estimator at any phase ϕ is defined by:

$$f_n(\phi) = \frac{1}{nh_n} \sum_{j=1}^{n} K \left[\frac{\phi - \phi_j}{h_n} \right] \qquad (3)$$

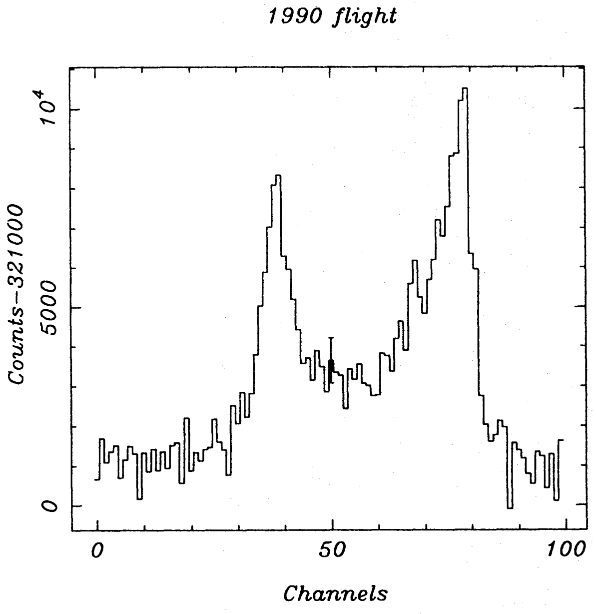

Fig. 1. Light-curve of the Crab pulsar in 100 channels for the 1990 flight (0.15–3.74 MeV). The choice of the zero phase is arbitrary

where K is a weighing function and h_n an optimized smoothing parameter. For the sake of convenience, a gaussian function has been chosen for $K(y)$:

$$K(y) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{y^2}{2}\right]. \tag{4}$$

In this case, the estimator $f_n(\phi)$ is the convolution product between the sample of gamma-ray phases and a gaussian of variance h_n^2. h_n has been determined by minimizing the Mean Integrated Squared Error following de Jager et al. (1986) and $f_n(\phi)$ has been expanded (Lemoine 1991) into the first 100 Fourier harmonics. Due to the asymmetry of the second gamma-ray peak, the Kernel estimator is expected to provide a better estimate of the position of the maximum of this peak than the barycenter method. It has been checked however that use of the barycenter method did not change significantly the value found for the radio-gamma delay. Figures 2a and 2b show the Kernel estimator drawn with the one standard deviation limits in the full energy range for the 1986 and 1990 flights with values of h_n equal to 0.026 and 0.0196 respectively. As in Agrinier et al. (1990), the zero phase has been taken at the maximum of the first main radio pulse at 600 Mhz.

4.2. Timing uncertainties

Uncertainties which affect the gamma-radio delay are listed below.

4.2.1. Radio uncertainties

– The extrapolation of the ephemeris radio parameters at the date of the gamma-ray observation induces an uncertainty which is function of the time elapsed, always below one month. The error due to the uncertainties on the pulsar radio ephemeris (Lyne & Pritchard 1993) is smaller than 50 μs in 1986 and 1990.

– The error on the dispersion measure (DM) is 0.005 (Lyne & Pritchard 1993), equivalent to a 56 μs uncertainty.

4.2.2. Gamma-ray uncertainties

– Inaccuracy of registration of the atomic clock time on the analogic tape of the telemetry station: 10 μs

– Uncertainty on the geographical position of the balloon during the flight: 30 μs in 1986 and 40 μs in 1990. For the 1990 flight, two trajectories were possible in order to link gamma-ray arrival times registered independently at Milo and Palma and both have been considered to evaluate the corresponding uncertainty.

– The precision of the FIGARO barycentrisation code adapted from JPL DE200 has been estimated by comparison of the computed arrival times at the Solar System barycentre and infinite frequency with the times provided after reduction by Lyne & Pritchard (1993). The absolute differences found are always smaller than 10 μs.

– Uncertainty on the best gamma-ray pulse position using the Kernel estimation method: from runs performed using three increasing values of the smoothing parameter h_n from the minimum and also on 4 independent subsets of each flight, this error has been estimated at about 120 μs for both flights. Conservatively, the barycenter method provides a peak position which is consistent with the Kernel position within 120 μs.

Table 2. Radio-gamma time delay and phase difference between the first and the second gamma-ray peaks

Flight	Energy range (MeV)	$T_{\text{radio-gamma}}$ (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	0.15–3.74	375 ± 148	0.402 ± 0.005
	0.15–0.47	462 ± 148	0.403 ± 0.005

5. Results

Table 2 displays the values obtained in two energy ranges for the radio-gamma time delay $T_{\text{radio-gamma}}$ and for the phase difference between the two peaks. Errors quoted in Table 2 have been obtained by adding in quadrature all uncertainties listed above. Both measurements are in the same direction. The dispersion measure DM is not available every month in the Crab pulsar ephemeris and, 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 observation, DM has been measured 6 days after the flight. The new delay $T_{\text{radio-gamma}}$ given for the 1986 flight is higher than the value given in Agrinier et al. (1990). The corresponding increase is due partly to the change of ephemeris from MIT to JPL and partly to the use of the Kernel method applied to better selected data. Results from OSSE

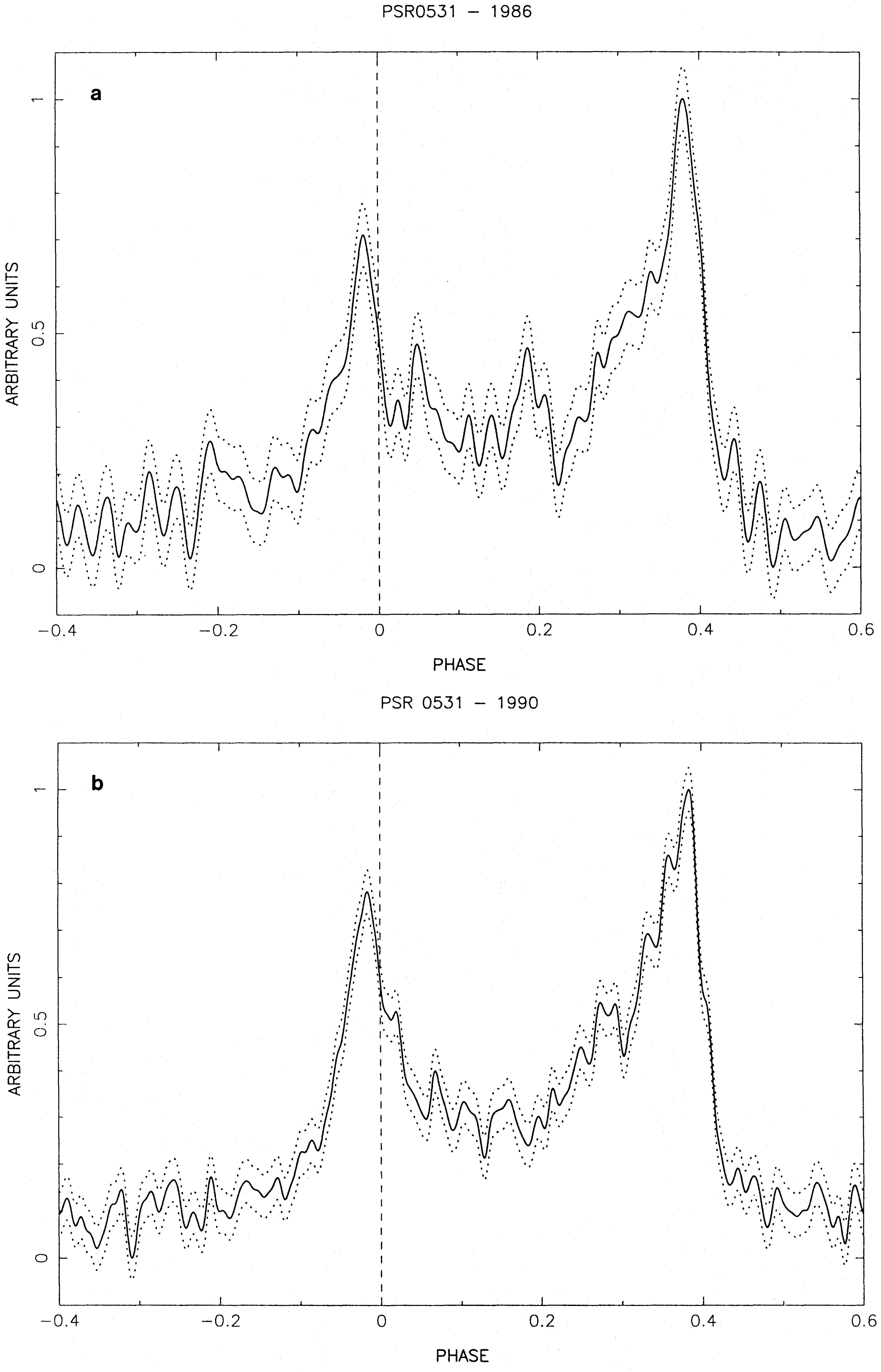

Fig. 2a and b. Kernel estimator curve (full line) with the one standard deviation limits (dashed lines). The zero phase is defined at the maximum of the main radio pulse (Lyne 1988): **a** 1986 flight (0.17–3.75 MeV), **b** 1990 flight (0.15–3.74 MeV)

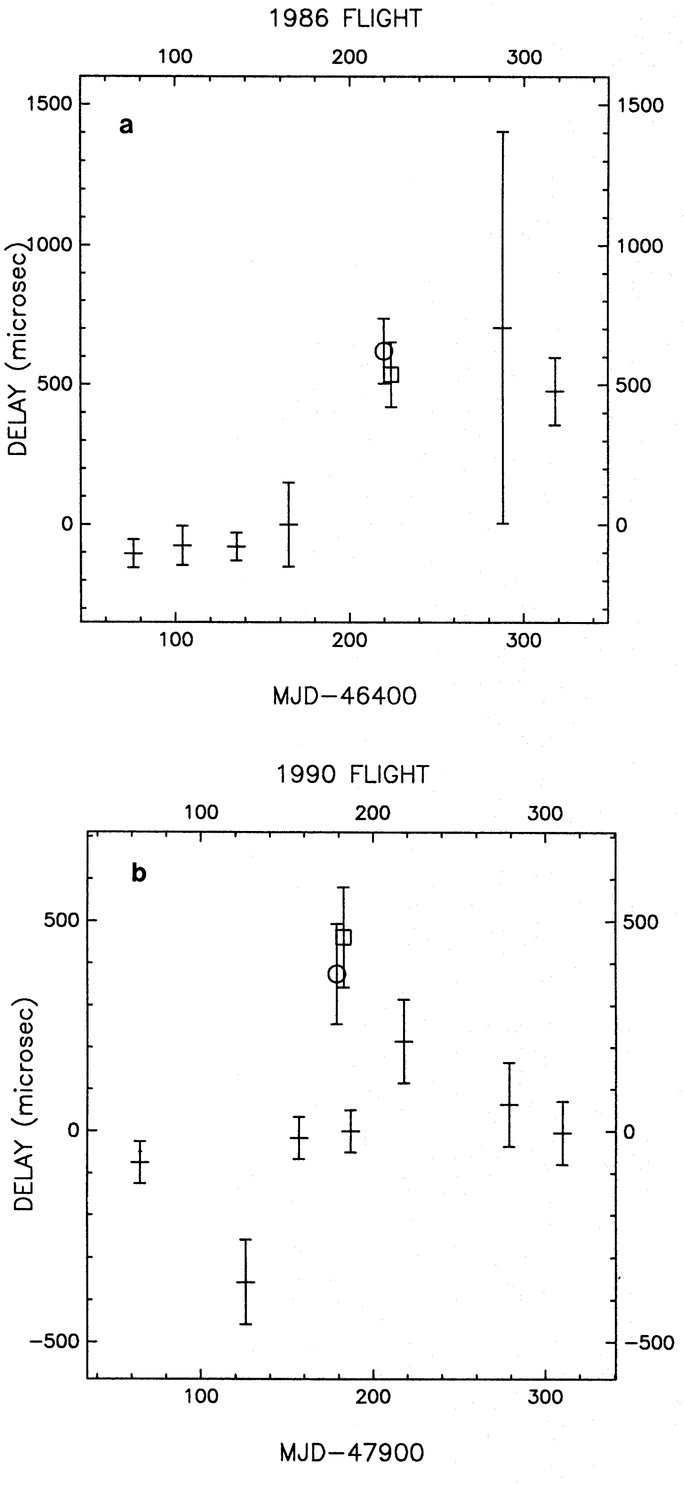

Fig. 3a and b. Relative delay $\Delta T - \Delta T_0$ from dispersion and scattering (crosses) as a function of epoch modified Julian Day) compared with the gamma-radio delay: **a** 1986 flight (open circle: 0.17–3.75 MeV; open square: 0.17–0.51 MeV), **b** 1990 flight (open circle: 0.15–3.74 MeV; open square: 0.15–0.47 MeV)

(Ulmer et al. 1994), with a large radio uncertainty of 300 μs, do not constrain results obtained with FIGARO.

The two gamma-ray peaks observed with FIGARO are separated by a phase difference, 0.397 ± 0.005 (1986 observation) and 0.402 ± 0.005 (12.06 ± 0.15 μs, 1990 observation) in agreement with the separation between the radio main pulse and interpulse 0.40402 ± 0.00001, measured at Jodrell Bank (Lyne 1992). Our results agree also with separations obtained at higher gamma-ray energies (> 50 MeV) with COSB (0.39 ± 0.01; Wills et al. 1982; Clear et al. 1987) and with EGRET on CGRO (0.40 ± 0.02; Nolan et al. 1993), as well as in the 0.3–30 MeV range (0.39 ± 0.02; White et al. 1985), and in the X-ray 0.1–4.5 keV range with HEAO-2 (0.403 ± 0.003; Harnden & Seward 1984). The fact that the phase difference between the peaks is constant at radio and gamma-ray wavelengths is a severe constraint for the models. We notice however that the very accurate average pulse profiles recently obtained with the High Speed Photometer of HST (Percival et al. 1993) show a slightly higher separation of the two peaks, 0.4167 ± 0.0004 and 0.4139 ± 0.0005 in the visible and UV respectively.

Gamma-ray peaks 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. HEA03 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). The better absolute timing together with the short duration (a few hours) of the FIGARO balloon observations allow a significant improvement for this phase comparison.

In order to understand the origin of the observed radio-gamma time difference, we have computed in function of epoch the delays due to dispersion Δt_{DM} and scattering ($\Delta t_{\mathrm{SCATT}} = 20\,\mu$s). The dispersion delay Δt_{DM} has been computed from the values of DM provided by Lyne & Pritchard (1993) using formula (5) where ν_{r} is the radio frequency at the source deduced from the observing frequency 610 Mhz by Doppler shift correction:

$$\Delta t_{\mathrm{DM}} = k \frac{\mathrm{DM}}{\nu_{\mathrm{r}}^2} \tag{5}$$

with $k = 4.14879\ 10^3\ \mathrm{cm}^3\ \mathrm{pc}^{-1}\ \mathrm{Mhz}$.

Taking $\Delta T = \Delta t_{\mathrm{DM}} + \Delta t_{\mathrm{SCATT}}$ and defining ΔT_0 as the value of ΔT at a close date (1986 May 15 and 1990 July 15 respectively) when DM is available from Lyne & Pritchard (1993), the relative delay $\Delta T - \Delta T_0$ is represented as a function of epoch in Fig. 3a and 3b together with the difference $T_{\text{radio-gamma}}$ found with FIGARO. It can be seen that the values of $T_{\text{radio-gamma}}$ do not change with the energy range and are higher than the relative delays expected at previous epochs from dispersion and scattering. In the case of the 1990 flight, for which DM has been measured 6 days after the gamma-ray observation, the enhancement is significant at the 2.5–3 sigma level. The effect goes in the same direction for the 1986 observation which uses however a dispersion measure known two months in advance. The large uncertainty of 700 μs shown in Fig. 3a on 1986 September 15 comes from the inaccuracy induced on the monthly predicted radio arrival time by a glitch which occurred on 1986 August 22, after the gamma-ray observation. Figures 4a and 4b allow a comparison of the variations of measured DM as a function of epoch (Lyne & Pritchard 1993; Lyne et al. 1988) with DM deduced from the gamma-ray observation applying formula (5) at the frequency $\nu_r = 610$ Mhz with $\Delta t_{\mathrm{DM}} = T_{\text{radio-gamma}}$

6. 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.

The gamma-ray first peak occurs in advance of the main radio pulse at infinite frequency by a difference which, for the 1986 flight, seems higher than the expected variability of the dispersion due to the interstellar medium during the two months between the date of the nearest available DM (1986 May 15) and the date of the gamma-ray observation (1986 July 11). However, the long interval of time during which DM has not been measured does not allow (Agrinier et al. 1990) for a more precise conclusion.

The high 1990 value of $T_{\text{radio-gamma}}$ is more constraining since dispersion measures are continuously available from May to August 1990. It might originate from a very rapid change (Δ[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). However, it is now 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 & 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.

The influence of the solar corona is important only when the line of sight is at a few solar radii of the Sun. The change of DM due to this crossing occurs in June during a few days each year and is not represented in Fig. 4a and 4b. The maximum expected arrival time shift due to this effect is 500 μs at 610 Mhz (Lyne et al. 1988).

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 1.3×10^{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 occurred on 1969 September 28. For the same reasons, it appears difficult to explain the variation observed in July 1990 as a delayed effect of the large glitch which occurred one year before on 1989 August 29 (Lyne et al. 1992). We propose then to attribute

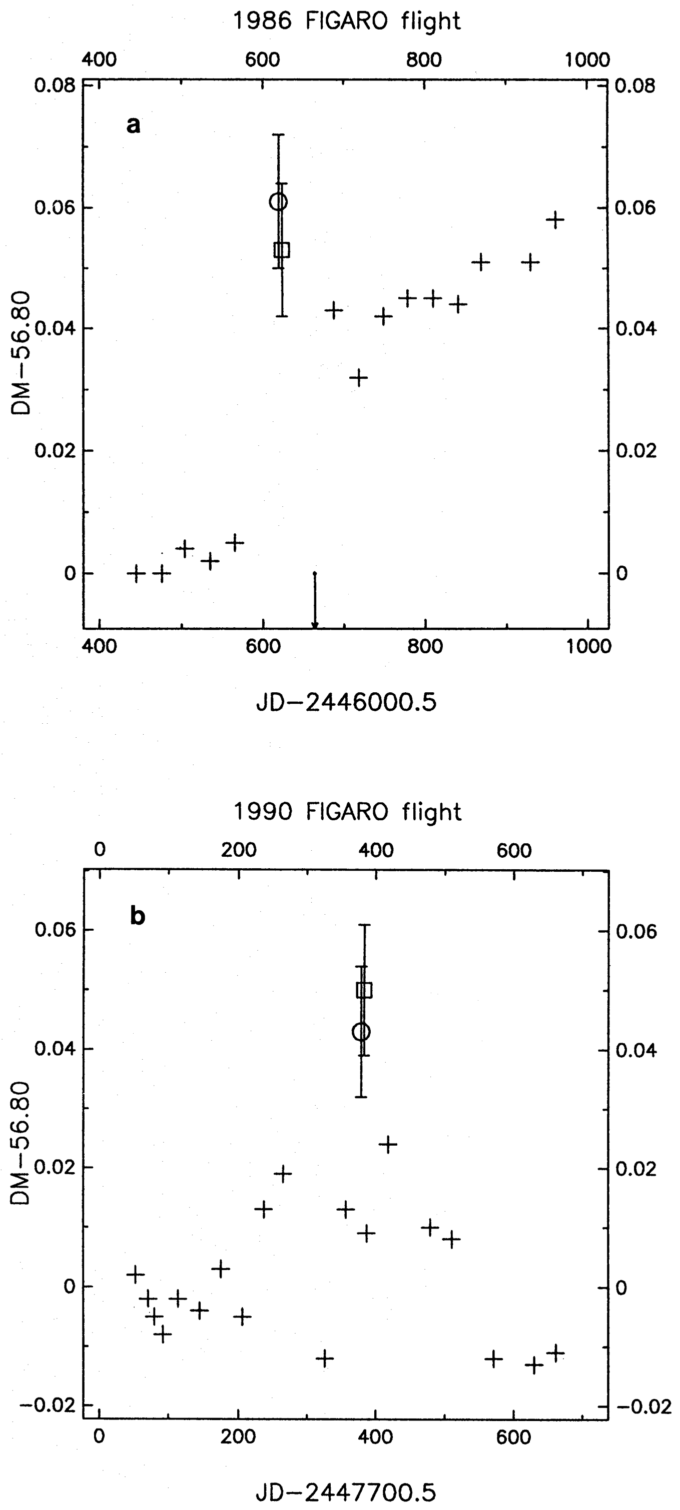

Fig. 4a and b. Radio dispersion measures (DM) as functions of epoch in Julian Day. The typical error on DM values is 0.005. The arrow at MJD = 46664.42 marks the glitch of 1986 August 22. Values of DM computed from the radio-gamma time delay are represented as follows: **a** 1986 flight (open circle: 0.17–3.75 MeV; open square: 0.17–0.51 MeV) , **b** 1990 flight (open circle: 0.15–3.74 MeV; open square: 0.15–0.47 MeV) the 1990 radio-gamma delay to distinct radio and gamma-ray maximum emissions in the pulsar magnetosphere rather than to an unexpected large increase within six days of the dispersion inside the Crab nebula.

The 1969 glitch has been discussed by Scargle & Pacini (1971) and Scargle & Harlan (1970) in connection with the corresponding expected increase of ionisation in the Crab nebula after release (Roberts & Sturrock 1972) of a large mass of cool gas in the pulsar magnetosphere. The time scale of the increase of the interstellar dispersion is of the order of 50 days (Rankin & Counselman III, 1973). A glitch of the Crab pulsar occurred in fact on 1986 August 22 (Epoch 46664.42 ± 5 MJD) with a recovery time of about 30 days (Lyne & Pritchard 1987; Lyne et al. 1988). This glitch occurred 45 days after the FIGARO observation and cannot be the cause of the DM increase (see Fig. 3a) following the low average value from January to May 1986. It might explain the increase of the average dispersion measure observed after September 1986. It is then found that the FIGARO 1986 observation is also compatible with a significant radio-gamma delay which could not be entirely due to changes of dispersive and scattering properties of the Crab nebula.

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. Variable bridge emission between the two narrow pulses is also observed. The precursor, which precedes the main pulse by 1.64 ± 0.1 ms is usually attributed to an emission site close to the neutron star polar cap (Graham Smith 1991) at an altitude which increases with decreasing frequency (Phillips 1992). The narrow radio pulses and high-energy pulses, from optical to gamma-ray, are attributed, in the framework of the standard model (Smith 1986; Morini 1983; Lyne & Graham-Smith 1990), to synchrotron emission (Davila et al. 1980) from the outer magnetospheric gaps, emitted tangentially to open field lines close to the limiting field lines, at a radial distance $0.9r_c$ where r_c is the radius of the light-cylinder.

An appealing interpretation of the radio-gamma phase difference is that the narrow radio pulses are not emitted exactly at the same location in the outer gaps as the high energy broader gamma-ray components. The corresponding distance between the regions of maximum radio and gamma-ray emissions would be of the order of 100 km.

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