V. X-RAY AND γ-RAY EMISSION

X-RAY AND GAMMA-RAY OBSERVATIONS OF PULSARS

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ABSTRACT

Measurements of pulsars in the energy domain above ∿ 1 keV have provided in the last few years new and interesting results. This paper presents a review of the observational features of PSR 0531+21 and PSR 0833-45 (the Crab and Vela pulsars). Searches for pulsed emission from old radio pulsars in the same energy domain are also reviewed and results assessed. The comparison of the observed features with each other and with the corresponding features observed at lower energies reveals similarities and differences capable to constrain theoretical models with special regard to the geometry of the emission mechanisms.

1. INTRODUCTION

Soon after the discovery of pulsars (Hewish et al. 1968), a strong theoretical and observative effort was undertaken by many groups aiming to describe the mechanisms which are on the basis of the phenomenon. The data collected in the course of 1968 and 1969 were only sufficient to demonstrate that the origin of the pulsating signals could be attributed to rotating neutron stars very likely produced as a result of supernovae explosions. For what concerns the geometry and the physics of the mechanism responsible for the observed pulses, however, an undisputed model has not yet been found in spite of the hectic activity of these last twelve years. In this framework the contribution of high energy observations of pulsars is not quantitatively striking, due mainly to the low signal-to-noise ratio available with the instrumentation used up to now. In the following the whole set of results (including the questionable ones) will be reviewed and the measured features and their statistical significance will be assessed.

2. THE OBSERVATIONAL DATA

2.1 The Crab Nebula Pulsar PSR 0531+21

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Detailed references on the behaviour of PSR 0531+21 at radio wavelengths can be found in Manchester and Taylor (1977). In the X-ray range it has been positively measured several times (see for example Rappaport et al. 1971, Fritz et al. 1969), as well as in the low gamma-ray range (Hillier et al. 1970, Kurfess 1971, Haymes et al. 1968) and at high energy gamma-rays (Parlier et al. 1973, Kniffen et al. 1974, Bennett et al. 1977, Lichti et al. 1980).

The intensity spectrum (Fig. 1) follows a single power law with spectral index ∿ 2.18 valid from ∿ 10 keV to a few GeV. Below 10 keV the spectrum flattens down to $\alpha \leqq 2$. The part of the spectrum above 500 GeV is the flattest power law compatible with the measurements of Bhat et al. (1981) and with the intensity measured by COS-B at 3 GeV. There is evidence of steepening with $\alpha \geqq 2.5$.

Fig. 2 shows the light curve of PSR 0531+21 at several energy intervals from radio to high energy gamma-rays, aligned in phase. Several features are observed:

— The general shape of the light curve and the absolute phase of the two main peaks remain unchanged from the radio band up to a few GeV apart from the fact that the "precursor" appears only at radio frequencies. It comes natural to suggest that the pulse emission geometry, and in particular the emission region, is essentially the

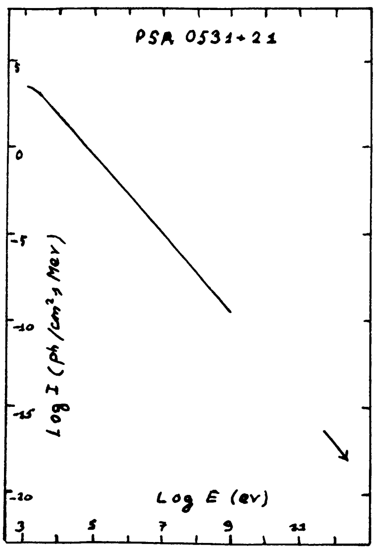

Fig. 1: The intensity spectrum of the Crab pulsar above 1 keV. Data from experiments in the range 10 keV - 3 GeV have been averaged.

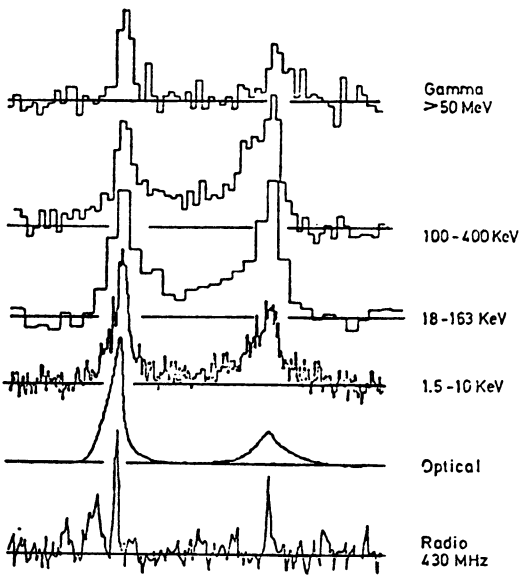

Fig. 2: Light curves of PSR 0531+21. The data in the range 18 - 163 keV have been kindly supplied by E. Kendziorra.

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same at all wavelengths.

— The phase distance between the two main peaks is 0.42 ± 0.05.
— A consistent bridge of pulsed emission is found between the two main peaks in the energy range 10 keV < E < 400 keV.
— The intensity ratio between the interpulse and the main pulse varies with the energy reaching a maximum value at low gamma-rays. This implies a spectral difference between the two peaks, actually measured by Kurfess (1971) in the energy range 100 keV < E < 400 keV.

All these features show that the beaming geometry is a complex one and not certainly compatible with two pencil beams of radiation coming from either poles of a purely dipolar magnetic field.

In the several claimed detections at ultra high gamma-rays the light curve of PSR 0531+21 does not show a stable shape. These results show individually low statistical significance and can well be random fluctuations of the background. On the other side, by considering the frequent appearance of claimed positive results, one could alternatively think of a loss of stability of the emission process at these energies: further effort with more sensitive experiments are worth to prove a possible time variability of the emission.

Lacking a detailed knowledge of the pulsar's beaming geometry a precise calculation of the intrinsic luminosity is not possible. We can however obtain an estimate for the luminosity by assuming that the observed pulsed radiation is concentrated in two conic beams. The corresponding formula is

$$L = \Phi \cdot \bar{E} \cdot 2\pi \cdot (1 - \cos \pi \beta) \frac{d^2}{\beta}$$

where Φ is the "time averaged" pulsed flux, $\bar{E}$ is the average photon energy, $\pi\beta$ is the half angle of each conic beam, and d is the pulsar distance from the sun. In the case of PSR 0531+21 we get for E > 1 keV

$$L \sim 1.5 \cdot 10^{36} \text{ erg/s}$$

of which $\sim$ 70% refers to the interval 1 keV - 1 MeV.

These values, when compared with the energy release of $\sim 3 \cdot 10^{30}$ erg/s in the radio band show that the emission mechanism working around the MeV region is most efficient in converting the braking power of the pulsar into e.m. radiation. It is therefore of primary importance to study the characteristics of the pulsed radiation of PSR 0531+21 at low gamma-rays.

2.2 The Vela Pulsar PSR 0833-45

The first measurement of PSR 0833-45 in the range E > 35 MeV was made by the SAS-II satellite (Thompson et al. 1975). A detailed study of the characteristics of this pulsar in the range 50 MeV - 6 GeV has been performed by the Caravane Collaboration for the COS-B satellite

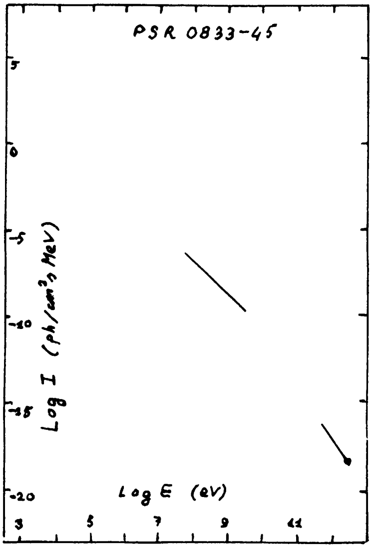

Fig. 3: The intensity spectrum of the Vela pulsar in gamma-rays (Lichti et al. 1980, Bhat et al. 1981)

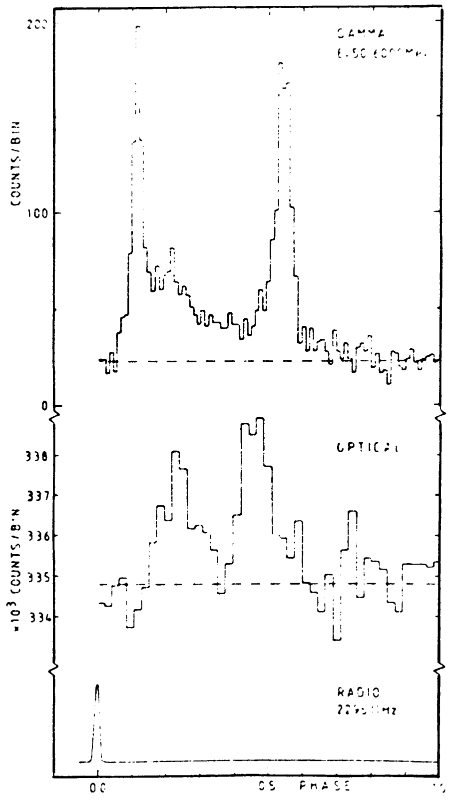

Fig. 4: Light curves of PSR 0833-45

(Bennett et al. 1977, Buccheri et al. 1978a, Lichti et al. 1980, Kanbach et al. 1980). In the range below 35 MeV and above 500 GeV we are confronted with several conflicting results which could be due to time variability of the emission and/or random fluctuations of the background.

Fig. 3 shows the intensity spectrum of PSR 0833-45; in the interval 50 MeV - 6 GeV the experimental points are well fitted by a power law having α = 1.89 with a possible break at 300 MeV (Kanbach et al. 1980). Above 6 GeV the spectral index must increase up to α = 3 in order to fit the observations at E > 500 GeV (Bhat et al. 1981). The recent measurements of the Einstein Observatory are expected to clarify the situation at E $\sim$ 1 keV where a consistent flattening should show up.

Fig. 4 shows the light curve of PSR 0833-45 in the gamma-ray range compared in phase with those observed in the optical and in the radio band. As comment to the figure we stress the following points:

— In contrast to the case of PSR 0531+21, the shape of the light curve of the Vela pulsar varies considerably with the observing frequency. The beaming geometry must therefore change with frequency as well as the location of emission. It would be interesting to see whether or not this difference of behaviour between the Crab and the Vela pulsar can be explained by pulsar evolution theories.

— The gamma-ray light curve shows consistent pulsed emission in the region between the two peaks, as for the Crab but at lower energies. The intensity ratio between the interpulse and the main pulse increases with energy showing a spectral difference between the two peaks, the interpulse being harder than the main pulse. Again, a similar behaviour is observed for the Crab at lower energies.

As for the Crab the observed features don't fit a simple pencil beam geometry. Recent suggestions from Manchester and Lyne (1977) tend to explain the Vela pulsar by proposing a radiation beam in the form of a hollow cone differently located with respect to the neutron star surface at different frequencies. Alternative suggestions from Massaro et al. (1979) tend to explain both Crab and Vela by proposing a radiation beam coming from the surfaces of two skew hollow cones at either poles of the magnetosphere.

As for the Crab the intrinsic luminosity in the radio and optical band is negligible with respect to the luminosity at high energies. Using the conic beam geometry we obtain

$$L \sim 4 \cdot 10^{34} \text{ erg/s}$$

in the range 50 MeV - 10 GeV. The fraction η_γ of the braking power $\dot{E}$ converted into gamma-ray power in this energy range is $\eta_\gamma = 6 \cdot 10^{-3}$ to be compared with $\eta_\gamma = 4 \cdot 10^{-4}$ for the Crab in the same energy interval.

2.3 Pulsed High Energy Emission from Old Radio Pulsars

Searches for pulsed emission from old pulsars in the range above $\sim$ 1 keV have been quite inconclusive. At ultra high gamma-ray energies the results consist of several upper limits and one indication of pulsed emission from PSR 0950+08, not confirmed by other experiments in the same energy range. Searches at X-ray energies have not given valuable results.

At low gamma-rays a detection of PSR 1822-09 has been recently announced by Mandrou et al. (1980). The main characteristics of this detection are the following:

- a chance probability less than 1%,
- a light curve structure with two main peaks separated by 0.5 ± 0.1 periods,
- an intrinsic luminosity $L \sim 5\ \dot{E}$.

At high gamma-ray energies systematic searches have been undertaken by the satellites SAS-II and COS-B with different philosophies.

The SAS-II workers applied directly the published radio parameters to a sample of 73 pulsars which were in the field of view of their telescope. Due to the fact that the radio and the gamma-ray observations were not in most cases contemporary, the search was made using unprecise parameters thus implying a consistent degree of randomization. In particular, the indication of pulsed emission from PSR 1747-46 and PSR 1818-04 are questionable on the basis of the uncertainty of the parameters used and of the high value of η_γ found ($\sim$ 50 for PSR 1747-46 and $\sim$ 20 for PSR 1818-04). This implies that also the negative results of the SAS-II search must be judged with caution due to the use of unprecise parameters.

The approach used by the COS-B workers was based on the following assumptions:

a) The only energy reservoir for pulsed radiation is the braking power $\dot{E}$.

b) The fraction of $\dot{E}$ converted into gamma-ray luminosity is an increasing function of the pulsar age. This assumption is based on the facts that η_γ increases from the Crab to Vela and that the ratio of the radio luminosity L_r to the braking power $\dot{E}$ increases as well with the age of the pulsars as shown in Fig. 5. If this assumption is valid, 5 to 10 radio pulsars of the Taylor and Manchester list (1975) would be detectable by COS-B (Buccheri et al. 1978b).

c) The high precision required in the pulsar parameters for long duration gamma-ray experiments is not guaranteed by extrapolation from far epochs. Therefore only pulsar parameters obtained simultaneously in the radio and gamma-ray range are directly usable.

Due to the lack of contemporary data at the time of the analysis, a period scan was performed by looking at values of the pulsar period smaller than those extrapolated from the radio epoch. The possibility of glitches between the radio and the gamma-ray observations was thereby taken into account. The search was made by looking for the phase histogram showing the maximum deviation from uniformity with the simplest structure.

Fig. 6 shows the phase histograms obtained with this analysis in the case of PSR 1822-09 and PSR 0740-28. In order to check the significance of these results the following information must be taken into account:

1. The chance probability of the effects found, calculated from the probability distributions of the used statistical variables (χ^2 and run-test) and taking into account all the trial periods looked for, is $\sim$ 1% if no a priori assumption is made on the structure of the light curves.

2. When we include the similarity of the found phase histograms with

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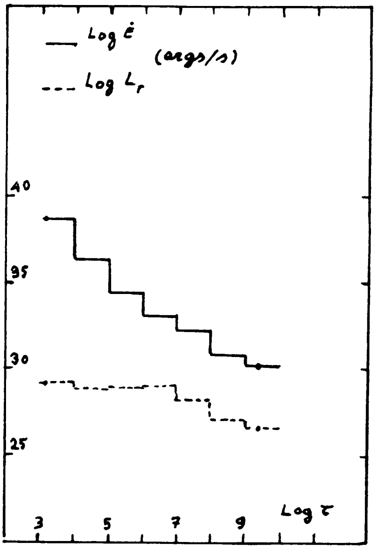

Fig. 5: Average values of radio power and Ė per decade of timing age τ = P/Ṗ. Data are from Taylor and Manchester (1975).

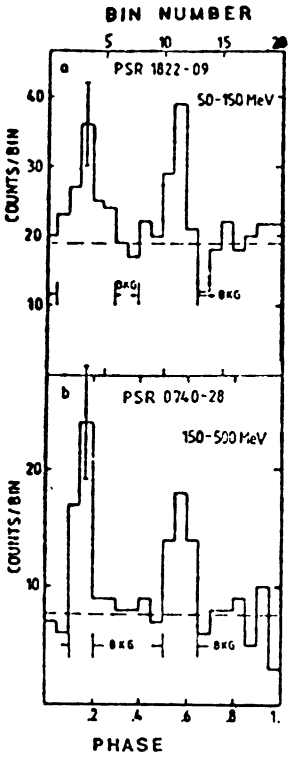

Fig. 6: Gamma-ray phase histograms obtained for PSR 0740-28 and PSR 1822-09

those of the Crab and Vela pulsars, the chance probability drops to ∿ 0.1%.

3. The confidence level was confirmed numerically by simulation of ∿ 2000 searches using the same criteria as in the real case.

4. At the location of each of the two pulsars we find an excess of counts consistent with that derived from the timing analysis and with the COS-B point-spread-function.

5. The values of η_γ derived from the measured fluxes are 0.2 for PSR 0740-28 and 2.0 for PSR 1822-09. Both values are compatible with $\eta_\gamma \leqq 1$ if one takes into account the possible errors in the momentum of inertia I and in the pulsar distance.

6. More recent radio pulsar parameters for PSR 0740-28, supplied by R.N. Manchester and contemporary to the COS-B observation, show that the gamma-ray period is ∿ 163 ns shorter than the radio period. The situation may be similar for PSR 1822-09.

It is rather difficult to draw a final conclusion about the reality of the detection of PSR 1822-09 and PSR 0740-28; more sensitive future observations will perhaps clarify the situation which appears quite intriguing also on the basis of the claimed detection of PSR 1822-09 at low gamma-rays and on the unusual properties of this pulsar observed in the radio band (Fowler et al. 1981).

3. CONCLUSIONS

The second COS-B catalogue of discrete sources of gamma-ray emission (Swanenburg et al. 1980) lists 25 objects with typical luminosities in the range (0.4 - 5) x 10^{36} erg/s for an estimated distance between 2 and 7 kpc. Since two of them have been identified with the two youngest pulsars PSR 0531+21 and PSR 0833-45 it is natural to look at young pulsars as a class of astronomical objects showing detectable localized emission in the gamma-ray range. On the other side the number of known young pulsars has not yet increased, perhaps due to the limited sensitivity for fast periodicities in the present radio surveys.

In view of these facts, collaborative programs of search for young radio pulsars inside the error boxes of the COS-B gamma-ray sources have been undertaken by the Caravane Collaboration with the Radiophysics Division of CSIRO and with the Arecibo Observatory.

We believe that the discovery of some more young pulsars would actually add important information about the behaviour of these objects. In particular we expect to answer the questions related to:

— the similarity of the light curves in the gamma-ray range showing the time stability of the emission mechanisms at these energies,

— the loss of stability at lower and higher energies,

— the increase with age of the conversion efficiency up to high percentage values.

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DISCUSSION

FOWLER: Is there any narrowing of the component separation in PSR 1822-09 between your observations and those of Mandrou, Vedrenne and Masnou (1980) at 400 - 1100 keV?

BUCCHERI: The separation between the two main peaks is 0.5 ± 0.1 at low γ-rays and 0.4 ± 0.05 for the COS-B phase histogram. In this respect the two results show compatible structure, even if the duty cycle at low γ-rays is greater. Unfortunately it is not possible to compare the absolute phases of the peaks in the two experiments due to the great differences in the accuracy of the pulsar period ($\sim$ 50 ns for COS-B and 1 μs for low γ-rays).and due to the fact that neither of the two experiments were simultaneous to the radio observations.

HELFAND: It seems unlikely to me that, as you suggest, many of the 25 COS-B point sources are pulsars: There are $\sim 10^3$ pulsars of Vela's age or younger in the Galaxy; for a beaming factor of 5 we get 200 visible sources. Putting Vela beyond 1 - 2 kpc reduces its γ-ray flux below that of the COS-B point sources. Thus, one expects $\lesssim$ 1 detectable γ-ray emitting pulsars, not 25.

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BUCCHERI: You may be right, but probably you are on the pessimistic side. First, the reduction by a factor of 5 due to beaming looks to me arbitrarily in the light of the uncertain beaming geometry in γ-rays. Actually, for hollow cone models this factor can be reduced to ∿ 2. Second, the luminosity in γ-rays seems to decrease with age. A pulsar younger than Vela could therefore be seen also at greater distances from the sun. The major difficulty in detecting young pulsars lies, in my opinion, on the low sensitivity of the radio surveys for fast periodicities and, in principle, on possible differences in the beaming structure between radio and γ-rays.