X-662-75-102
PREPRINT

NASA TM X-70877

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(NASA-TM-X-70877) SAS-2 HIGH ENERGY GAMMA-RAY OBSERVATIONS OF THE VELA PULSAR (NASA) 14 p HC $3.25 CSCL 03A
N75-23421
Unclas
G3/89 20430

APRIL 1975

GSFC
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SAS-2 High Energy γ-Ray Observations of the Vela Pulsar

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ABSTRACT

The Second Small Astronomy Satellite (SAS-2) high energy (> 35 MeV) γ-ray telescope has detected pulsed γ-ray emission at the radio period from PSR 0833-45, the Vela pulsar, as well as an unpulsed flux from the Vela region. The pulsed emission consists of two peaks, one following the radio peak by about 13 msec, and the other 0.4 period after the first. The luminosity of the pulsed emission above 100 MeV from Vela is about 0.1 that of the pulsar NP0532 in the Crab nebula, whereas the pulsed emission from Vela at optical wavelengths is less than 2×10^{-4} that from the Crab (Kristian, 1970; Lasker, Bracker, and Saa, 1974). The relatively high intensity of the pulsed gamma ray emission and the double peak structure, compared to the single pulse in the radio emission, suggests that the high energy γ-ray pulsar emission may be produced under different conditions from that at lower energies.

Subject Headings: γ-rays, Vela, pulsar

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I. INTRODUCTION

The fastest known pulsar, the Crab, is a strong emitter of X- and γ-rays, both pulsed and unpulsed. The Vela pulsar, PSR 0833-45, is the third fastest pulsar known and is four times closer than the Crab pulsar; therefore, it would seem to be a likely source for pulsed and constant X- and γ-ray emission. The Vela supernova remnant is known to be an extended source of soft X-rays (Seward et al., 1971; Bunner, 1971; Gorenstein et al., 1974), and both the UHURU and Copernicus satellites observe a localized X-ray source within the Vela remnant, centered on PSR 0833-45, but with a total intensity as observed at the earth of only about 1% that of the Crab in the energy interval, 1 to 10 keV (Kellogg et al., 1973; Culhane et al., 1974). In neither of these experiments was the timing resolution sufficient to distinguish the pulsar's 89 ms period. Harnden and Gorenstein (1973) have reported detection of pulsed 0.5 - 1.5 keV X-rays at the radio period with a statistical significance equivalent to about 3σ. Moore et al (1974), however, for a comparable energy range set a 2σ upper limit substantially below the Harnden and Gorenstein result for pulsed X-rays. Rappaport et al. (1974) set a 3σ upper limit for pulsed X-rays at the radio period in the 1.5-10 keV range which corresponds to about 1/3 of the flux seen by UHURU. At higher energies, Harnden et al. (1972) found a pulsed 23-80 keV flux at the 3σ level with a period 155 nsec shorter than the radio pulsar. Ricker et al. (1973) report an upper limit for pulsed 17-42 keV X-rays at about the same level as the positive result of Harnden et al. At γ-ray energies, Albats et al. (1974) reported a single pulse with a statistical significance of about 3.5σ for 10-30 MeV γ-rays from PSR 0833-45 at the radio period with the pulse following the 2388 MHZ radio peak by about 4 msec. Preliminary results from one interval when SAS-2 viewed Vela showed that the Vela region is a very strong source of photons with energies above 100 MeV (Thompson et al., 1974), but that only an upper limit could be set for > 35 MeV γ-rays pulsed at the radio period in phase with the radio pulse (Fichtel et al., 1975) although there was a suggestion of a pulse following the radio pulse by 11 msec. A possible identification of the Vela pulsar at energies above 3×10^{11} eV has been reported by Grindley et al. (1973).

This Letter presents γ-ray data from two other periods when SAS-2 viewed the Vela region, together with additional data from the viewing period previously reported. The improved statistics have made possible the clear identification of a pulsed component at the radio period for PSR 0833-45, having two peaks, neither of which is in phase with the single radio peak.

II. OBSERVATIONS AND RESULTS

A description of the SAS-2 high energy γ-ray experiment, together with a discussion of calibration and data analysis procedures, is given by Derdeyn et al. (1972) and by Fichtel et al. (1975). During three of the satellite observing periods, the Vela region was in the field of view of the experiment; 1973 February 15-20, 1973 February 21-27, and 1973 April 3-10. Only a portion of the first of these was included in the preliminary SAS-2 results (Thompson et al., 1974). In each of these three periods, a significant excess stands out in the direction of the Vela supernova remnant. The center of the excess lies inside the outline of the supernova remnant, and within uncertainties is consistent with the direction of PSR 0833-45 or of the peak of the radio emission from the supernova remnant (Milne, 1968).

For purposes of comparison with the pulsar, events were chosen which had measured arrival directions with a circle of 5° radius at energies above 100 MeV and circles with larger radii for events with lower energies, up to 8° for 35 to 50 MeV γ-rays. This choice of angles reflects the angular accuracy of the detector (Fichtel et al., 1975) and approximate minimization of the uncertainty in the signal in the given background. The arrival time for each of the 223 events selected in this way was converted to a pulsar phase using a program previously applied to the Crab nebula data together with the radio period and period derivative (Kniffen et al., 1974; Reichley, 1975). As a further test on the program, and in order to compare with the radio phase, three or more actual arrival times for the 2388 MHz radio pulse at Goldstone were obtained for each of the following days: 1973 February 15, March 2, March 16, April 1, and April 15 (Reichley, 1975). These times were corrected by 50.3 msec for dispersion and included in the same pulsar phase program. The calculated PSR 0833-45 phases for these radio data all lay within 0.03 periods of each other. This residual phase uncertainty is consistent with the approximations used in the program. An independent set of radio data from NRAO on

1973 May 25 and 29 (Backer, 1975) gave calculated phases which were consistent with the Goldstone radio data.

Figure 1 (a), (b), and (c) shows the SAS-2 data from Vela plotted in fractions of a pulsar period for each of the three observations of the source. Figure 1(a) includes the additional data from the first period not reported in the previous letter. The bin size, 0.04 period, is equivalent to the total estimated uncertainty in the calculated phase, based on ± 0.015 period from the pulsar phase program and ± 0.011 period from the SAS-2 timing accuracy. Figure 1(d) gives the combined results from all three observations, together with the calculated position of the pulse derived from the radio measurements, shown by arrow, R. The data show two significant peaks in the phase plot. Comparison with the plots from the three individual observations shows that the two peaks are present in all three, but with lesser statistical significance. The Poisson probability that fluctuations in the data could cause two peaks this size at any random phases is on the order of 10^{-12}. The center of the larger of the two peaks falls 13 ± 2 msec after the radio peak. The second peak follows the first by approximately 0.4 period.

Since the data were accumulated over 54 days, the pulsar phase calculation is extremely sensitive to the assumed pulsar parameters.

Shifts from the nominal radio parameters of less than 1 nsec in period or 1% in period derivative cause the pulses to lose most of their statistical significance, indicating clearly that the pulsed γ-rays seen by SAS-2 are associated with PSR 0833-45.

The dashed line in Figure 1 shows the γ-ray flux level expected from galactic and diffuse radiation if no excess were present, and if the γ-radiation is at the level deduced from that on either side of the Vela region along the galactic plane at the same galactic latitude. The excess above this level includes both the pulsed component and a component from the Vela region which is unpulsed. If the two pulses are assumed to be contained in the phase intervals 0.40 to 0.56 and 0.80 to 0.96, the fraction of the excess radiation from the Vela region above 35 MeV which is pulsed is $.71^{+.14}_{-.12}$. While the pulsed γ-rays presumably have to originate at the pulsar, the "unpulsed" radiation may come partially or totally from the region of the supernova remnant or the Vela region in general; the angular resolution of the SAS-2 γ-ray telescope does not permit a distinction between these several possibilities. Within statistical and experimental uncertainties, the observed pulsed fraction does not vary over the 35 MeV to 200 MeV energy range.

The full widths of the pulses, 14 m sec., are large compared to the full width of about 5 m sec for the single 8.4 GHz radio pulse (Downs, Reichley, and Morris, 1973), even when the small broadening effect of timing errors is considered.

The flux observed from the Vela source does not change noticeably from one observing period to another. The estimated total flux from the Vela source above 35 MeV is $(15.1 \pm 2.4) \times 10^{-6}$ photons $cm^{-2}s^{-1}$ and above 100 MeV is $(6.3 \pm 1.1) \times 10^{-6}$ photons cm^{-2} s^{-1}. Averaged from 35 to 100 MeV, the energy flux is $(7.7 \pm 2.6) \times 10^{-6}$ MeV $cm^{-2}s^{-1}MeV^{-1}$. For each of these three numbers, the error includes the various uncertainties in the flux and energy calculation as well as the statistical error, which is typically equal to or slightly less than that due to all the others combined.

The energy spectrum of the excess radiation from the Vela region does not differ significantly from the energy spectrum of the surrounding region of the galactic plane within the rather coarse estimates of the energy spectrum possible with the SAS-2 instrument, as noted previously (Thompson et al., 1974). If a single power law spectrum were used to connect the differential gamma ray energy flux reported here with the 2 to 10 keV data of UHURU (Kellogg et al., 1973), the exponent would be approximately -0.7.

III. DISCUSSION

The appearance of two pulses in the phase diagram for the γ-ray emission from PSR 0833-45 in addition to the constant component suggests a comparison to the Crab nebula (Kniffen et al., 1974; McBreen et al., 1973). Both sources exhibit a large fraction of their high energy (> 35 MeV) γ-radiation in pulsed form, and in both cases the pulsed radiation has the same frequency as the radio pulsar and has two peaks separated by 0.4 period. At lower photon energies, however, the emission from the Crab and Vela are markedly different. Whereas the pulsed luminosity ratio, L(Crab)/L(Vela), above 100 MeV is only about 8, the pulsed optical luminosity ratio is at least 5000 (Kristian, 1970; Lasker, Bracker, and Saa, 1972). In the X-ray energy range, the luminosity ratio is at least 80 (Fritz et al., 1971; Harnden and Gorenstein, 1973) at about 1 keV, and may be 1000 or higher for the 1.5-10 keV energy range (Rappaport et al., 1974).

In the case of Vela, the upper limit to a second pulse away from the main pulse of PSR 0833-45 in the radio region is 0.1% (Backer, Boriakoff, and Manchester, 1973). This result, together with the relatively low flux of the emission in the optical and X-ray region and the observation that neither pulse in the high energy γ-ray region reported here is in phase with other PSR 0833-45 data, strongly suggest that the high energy γ-radiation is being produced under different conditions from that producing the lower energy photons. Further, the relatively wide γ-ray pulses suggest that the emission region of the γ-rays is larger either in area or angle than the region of the radio emission. A change of pulse mechanism, from coherent curvature radiation in the optical to incoherent synchrotron radiation in the X-ray energy range, has recently been suggested for the Crab (Sturrock, Petrosian, and Turk, 1975). These authors also note that the Vela counterpart of the Crab optical radiation might appear in the infrared. If the pulsed γ-radiation is assumed to originate from synchrotron radiation of electrons in the extremely strong magnetic field near the surface of the neutron star, then the observed γ-ray flux could be produced without assuming unreasonably high electron energies for the

Vela pulsar region. If, for example, the magnetic field is on the order of 10^{10} to 10^{12} gauss, then 100 MeV γ-rays can be produced by 10^2 to 10^3 MeV electrons.

The unpulsed radiation from the Vela source has already been discussed in terms of interactions of cosmic-ray particles surrounding the supernova remnant with the local matter (Thompson et al., 1974; Fichtel et al., 1975). The presence of the Vela pulsed γ-ray flux implies that at least some particles are still being accelerated to cosmic-ray energies by PSR 0833-45 and gives weight to the postulate that some of the galactic cosmic rays may be accelerated in the pulsar phase rather than in the supernova explosion itself.

We wish to thank Dr. P. Reichley of JPL and Dr. D. Backer for their assistance in comparing the SAS-2 results with radio observations.

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FIGURE CAPTION

Fig. 1 Distribution of γ-ray arrival times in fractions of a radio pulse period for γ-rays above 35 MeV from the direction of PSR 0833-45. (a) Data acquired 1973 February 14-21. (b) Data acquired 1973 February 21-28. (c) Data acquired 1973 April 3-10. (d) Data from all three periods combined. Arrow R marks the position of the 2388 MHZ radio pulse (Reichley, 1975). The dashed line shows the γ-ray level expected from galactic and diffuse radiation if no localized source were present.

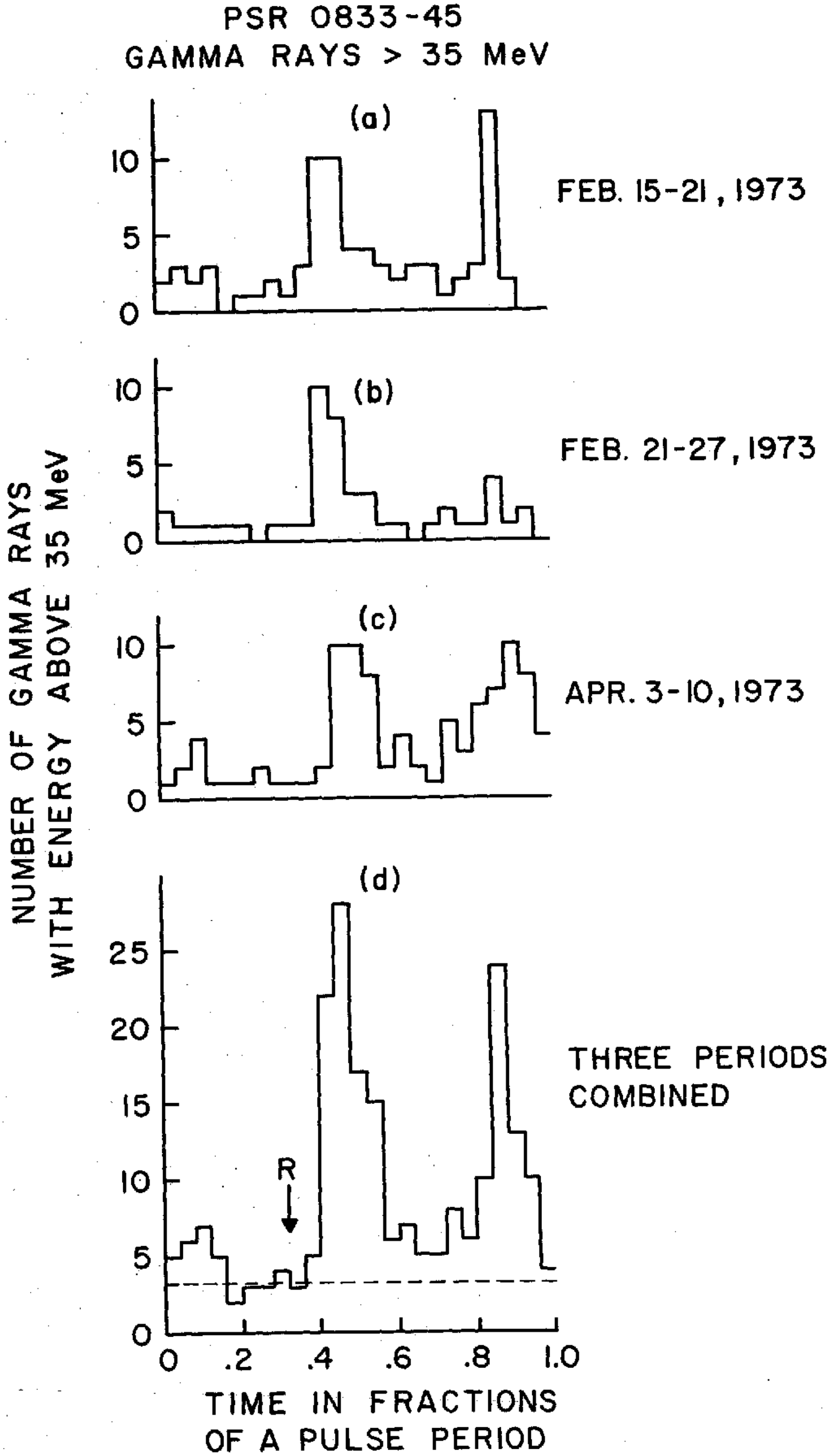
PSR 0833-45
GAMMA RAYS > 35 MeV
(a)
FEB. 15-21, 1973
(b)
FEB. 21-27, 1973
(c)
APR. 3-10, 1973
(d)
THREE PERIODS COMBINED
R
NUMBER OF GAMMA RAYS WITH ENERGY ABOVE 35 MeV
TIME IN FRACTIONS OF A PULSE PERIOD
0
.2
.4
.6
.8
1.0

Fig. 1