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SAS-2 HIGH-ENERGY GAMMA-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, following the single radio peak by about 13 ms and 48 ms.

The luminosity of the pulsed emission above 100 MeV from Vela is about 0.1 that of the pulsar NP 0532 in the Crab nebula, whereas the pulsed emission from Vela at optical wavelengths is less than 2×10^{-4} that from the Crab. The relatively high intensity of the pulsed γ-ray emission, and the double peak structure, compared with the single pulse in the radio emission, suggest that the high-energy γ-ray pulsar emission may be produced under different conditions from those at lower energies.

Subject headings: Gamma-rays — pulsars

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 4 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, Harnden, and Tucker 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 percent 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 3 σ. Moore, Agrawal, and Garmire (1974), however, for a comparable energy range, set a 2 σ upper limit substantially below the Harnden and Gorenstein result for pulsed X-rays. Rappaport *et al.* (1974) set a 3 σ upper limit for pulsed X-rays at the radio period in the 1.5–10 keV range, which corresponds to about one-third of the flux seen by *Uhuru*. At higher energies, Harnden *et al.* (1972) found a pulsed 23–80 keV flux at the 3 σ level with a period 155 ns 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 3.5 σ 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 ms. Preliminary results from one interval when SAS-2 viewed Vela showed that the region is a very strong source of photons with energies above 100 MeV (Thompson *et al.* 1974). However, 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) on the basis of 59 photons seen from the Vela region, although there was a suggestion of a pulse following the radio pulse by 11 ms. A possible identification of the Vela pulsar at energies above 3×10^{11} eV has been reported by Grindlay *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 threefold improvement in statistics has 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

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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 35–50 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 ms 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 the 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 ms after the radio peak. The second peak follows the radio pulse by 48 ± 2 ms.

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 ns in period or 1 percent 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 0.71 (+0.14, −0.12). 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 35–200 MeV energy range.

The full widths of the pulses, 14 ms, are large com-

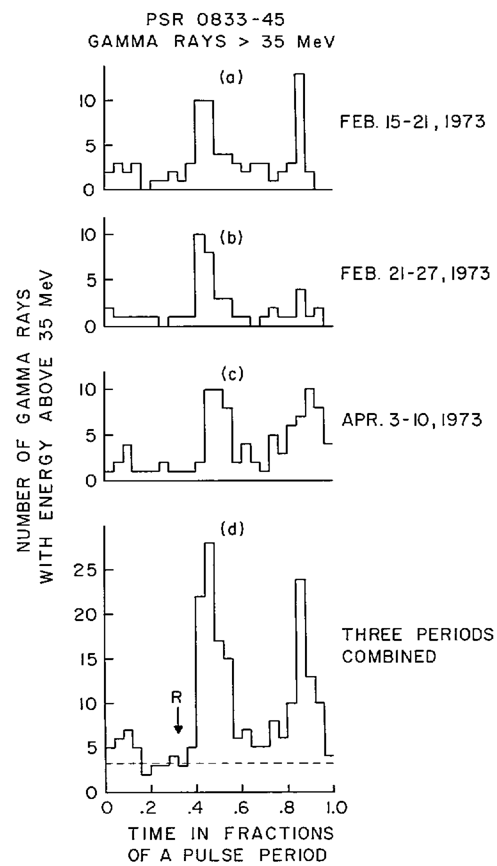

FIG. 1.—Distribution of γ-ray arrival times in fractions of a radio pulse period for γ-rays above 35 MeV from the direction of PSR 0833−45. (a) Data acquired 1973 February 14–21; (b) data acquired 1973 February 21–28; (c) data acquired 1973 April 3–10; (d) data from all three periods combined. Arrow *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.

pared to the full width of about 5 ms 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 γ-ray energy flux reported here with the 2–10 keV data of *Uhuru* (Kellogg et al. 1973), the exponent would be approximately -0.7. Comparison with pulsed fluxes in the X-ray and γ-ray regions are difficult because of the limited number of reported observations and apparent inconsistencies of the results. The marginally significant pulsed flux observed for 0.5–1.5 keV X-rays contrasts with a substantially lower 2 σ upper limit by Moore *et al.* (1974). The 20–80 keV pulsed flux observed by Harnden *et al.* (1972) appears to have a different pulse period from the radio period and must be reconciled with the upper limits reported by Ricker *et al.* (1973). The 10–30 MeV observations of Albats *et al.* (1974) show only one pulse at the 3.5 σ level.

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 with 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 that from 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; Chiu, Lynds, and Maran 1970; Lasker, Bracker, and Saá 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 percent (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 suggests that the high energy γ-radiation is being produced under different conditions from those 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}–10^{12} gauss, then 100 MeV γ-rays can be produced by 10^2–10^3 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.

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