GAMMA RAYS OF 0.3 TO 30 MEV FROM PSR 0531+21

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1. Introduction. Pulsed gamma rays from the Crab Pulsar PSR 0531+21 are reported for energies of 0.3 to 30 MeV. The observations were carried out with the University of California, Riverside (UCR) gamma ray double Compton scatter telescope (1,2) launched on a balloon from Palestine, Texas at 4.5 GV, at 2200 LT, September 29, 1978. Two 8 hr observations of the pulsar were made, the first starting at 0700 UT (0200 LT) September 30 just after reaching float altitude of 4.5 g cm^{-2}. Analysis of the total gamma ray flux from the Crab Nebula plus pulsar, using telescope vertical cell pairs only (3), has previously been published. The results presented here supersede the preliminary ones given at the 18th International Cosmic Ray Conference in Bangalore (4).

2. Method. In the double scatter mode the UCR telescope (1,2,5) measures the energy of each incident gamma ray from 1 to 30 MeV and its incident angle to a ring on the sky. The time of arrival is measured to 0.05 ms. The direction of the source is obtained from overlapping rings on the sky. The count rate of the first scatter above a threshold of 0.3 MeV is recorded every 5.12 ms but gamma ray energies and directions were not measured for individual gamma rays. The Crab Pulsar parameters for our observations on September 30 and October 1, 1978 were determined from six topocentric arrival times of optical pulses obtained from E. Lohsen, Bergeldorf Observatory, Hamburg, West Germany (T. L. Jenkins, private communication, 1982). They were converted to the solar system barycenter with our barycenter analysis programs using the MIT ephemeris (6). The values of the parameters are: observation epoch, 2443781.5; absolute phase, ϕ_o, 0.35442; period, P, 0.03322268626 s; and $\dot{P}$, $0.421954804 \times 10^{-12}$ s s^{-1}. The period P and $\dot{P}$ were later confirmed by the HEAO 1 x-ray values (7) obtained one day earlier on September 29, 1978. These parameters are used throughout the analysis. A χ^2 plot of a phase sweep of P at 2 ns intervals over ±50 ns from the derived value also confirmed our value of P. Absolute time of each data interval of 5.12 ms for single scatters and each event for double scatters were obtained from an on board clock accurate to 10^{-9} s s^{-1} that is started from an atomic clock on the ground accurate to 10^{-11}s s^{-1} and calibration with Loran C.

The phase plot for single scatters is given in Figure 1a and for double scatters in Figure 1b. Data were included for angles from 15° before to 30° after PSR 0531+21 zenith passage for single scatters and from 55° before to 55° after for double scatters. In addition, for double scatters, to eliminate the high atmospheric gamma ray background near the horizon, only gamma ray cone angles <75° to the zenith were accepted. The uncertainty in phase of the single scatter light curve is 0.077 (2.56 ms), half the accumulation bin size. The bin numbers are also included in Figure 1 for reference. The dashed lines give the backgrounds calculated from the counts in bins 17 through 5 in Figure 1a and bins 24 through 9 in Figure 1b.

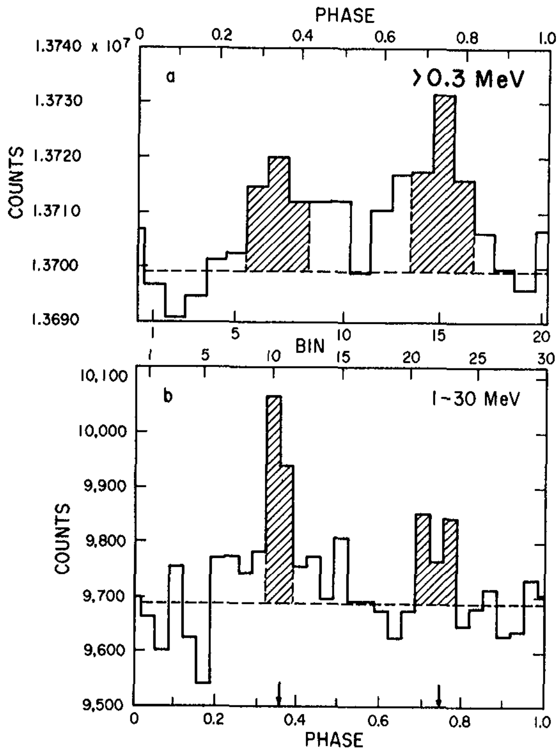

Fig. 1. Phase plots for PSR 0531+21. (a) For single scattered gamma rays with energies > 0.3 MeV. (b) For double scattered gamma rays with energies of 1-30 MeV.

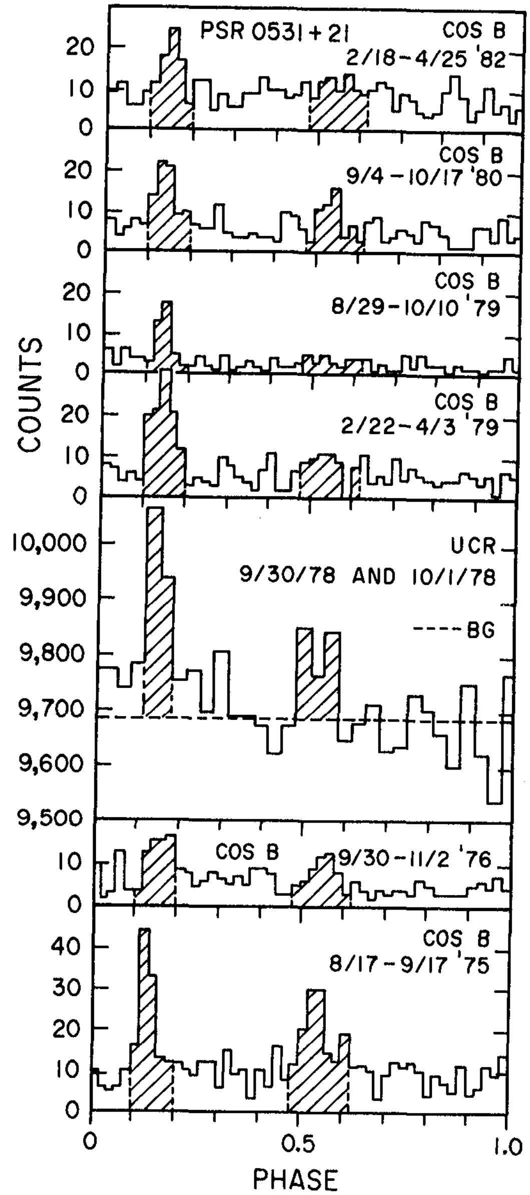

Fig. 2 Phase plots for PSR 0531+21 at various times from 1975 to 1982.

3. Results. For energies of 1-30 MeV the 1st and 2nd pulses of PSR 05321+21 are seen where expected with statistical significances of 4.2 and 2.1 σ. Absolute positions and separation of the 2 maxima, 12.9±0.3 ms (0.39±0.02 in phase) are in agreement with the arrows that give the absolute phase maxima of the 1st and 2nd radio pulses and with those for energies above 50 MeV found by COS B (8) and SAS 2 (9), at energies of 1-20 MeV (10) and at optical and x-ray energies. The width of the 1st pulse is 2.2±0.5 ms FWHM, 0.07 in phase, slightly wider than the COS B (8) width of 1.6±0.4 ms FHWM. However, the width of the 2nd pulse is 3.3±0.5 ms FWHM, 0.10 in phase, wider than the COS B width of 2.0±0.5 ms FWHM, summed over all observation times.

Wills et al. (8) used the COS B observations from August 1975 to October 1980 to study the variation of the high energy gamma ray phase plots from PSR 0531+21 with time. Özel and Mayer-Hasselwander (13) added the COS B phase plot for 1982. We have added ours at energies of 1-30 MeV to give the summary of gamma ray phase plots in Figure 2. Our phase plot is similar to the others nearby, in nearly all respects.

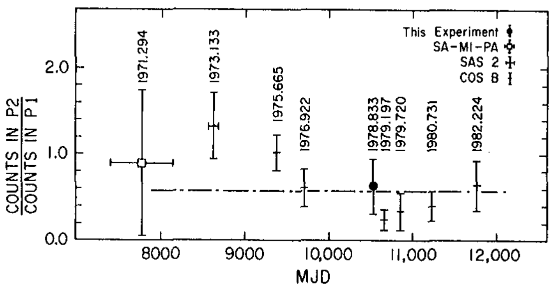

Fig. 3 Ratios of counts in the 1st to the 2nd pulse in PSR 0531+21 at various times from 1971 to 1982.

At energies of 1-30 MeV we use channels 10-11 and 21-23 to determine our value, 0.64±0.33, for the ratio of the counts in the 2nd to the 1st pulse. In Figure 3 our ratio is added to those from the previous phase plots (8,13), an additional ratio (13) from COS B in 1982 and balloon flights in 1970-71 (14) from the Saclay-Milano-Palermo Group at energies >20 MeV. Our value is consistent with the other ratios near the same epoch and close to the average of all ratios. As our energy interval of 1-30 MeV is lower than the energy for the other 8 points, mostly >50 MeV, a comparison may be invalid. Certainly a transition in the ratio exists between the >50 MeV gamma-rays where the 1st pulse dominates and those in the hard x-ray region which favors the 2nd pulse. Comparison of our ratio from single scatters for energies >0.30 MeV with the double scatters of 1 to 30 MeV below confirm this possibility. The ratio of 1-30 MeV counts in the interpulse, the region between the 1st and 2nd pulses, bins 12-20, to the total pulsed counts, 1st pulse plus 2nd pulse plus interpulse, bins 10 through 23, is 0.17±0.30, not in disagreement with the COS B value of 0.15±0.04 (8).

The phase plot for single scatters given in Figure 1a for energies >0.3 MeV shows characteristics similar to those at lower energies. The separation of the pulses is 13.2±0.4 ms (0.40±0.03 ms in phase) in good agreement with those found in radio, optical, x-rays and gamma rays. Using bins 6-8 and 14-16 for the 1st and 2nd pulses, respectively, the ratio of counts in the 2nd to the 1st pulse is 1.4±0.3. This value is difficult to compare with other observations because of different criteria for the shapes of the pulses. However, our >0.3 MeV ratio is higher than our value at 1-30 MeV and higher than all observations of COS B in 1976 and later. The ratio is in general agreement with the value of 1.06±0.18 at 45-360 keV found on October 6, 1980 (12) but not as high as the ratio of 2.3±0.2 at 100-400 keV found from combining 2 flights in October, 1970 (11).

Phase plots similar to Figure 1b were generated for 4 energy intervals between 1 and 20 MeV. The pulsed signals and backgrounds were taken from the same channels as for Figure 1b. The count rates were converted to fluxes and plotted on Figure 4. These fluxes agree well with the values of Graser and Schönfelder (10) at similar energies and with their fit, $6.17 \times 10^{-4} E^{-2.2}$ photons cm^{-2} s^{-1} MeV^{-1}, from about 5×10^{-2} to 2×10^{3} MeV. Because of the steep spectrum 0.87 of the photons from our single scatters above 0.3 MeV come from the interval 0.3 to 1.5 MeV. The counts above 0.3 MeV have been converted to flux then multiplied by 0.87 to obtain the point from 0.3 to 1.5 MeV plotted on Figure 4. This also agrees with the above fit. The energy distribution from PSR 0531+21 appears to be well established as a continuous power law of $E^{-2.2}$ over almost five decades in energy.

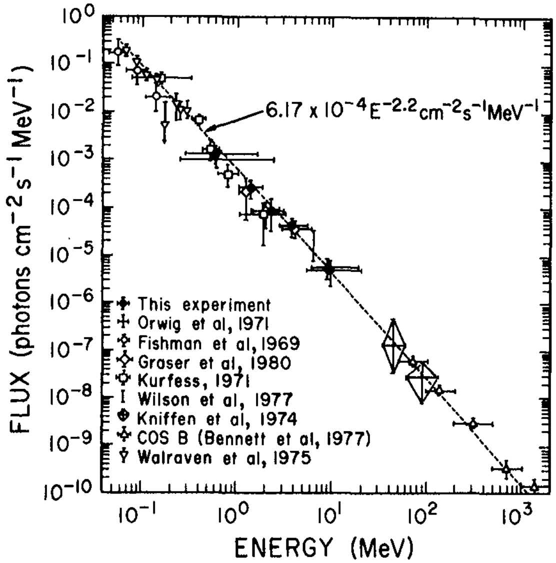

Fig. 4 The energy distribution of gamma rays from PSR 0531+21.

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