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# SEARCHES FOR GAMMA RAY EMISSION FROM RADIO PULSARS

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## SUMMARY

Searches have been made for pulsed high energy ($E > 35$ MeV) $\gamma$ radiation from 43 pulsars using the SAS-2 data base and radio parameters which became available after the previous search of Ögelman et al. (1976). No positive results were found, and the upper limits are consistent with the concept that $\gamma$-ray production efficiency increases with increasing apparent age. Two limits from the Ögelman et al. (1976) search, however suggest that efficiency cannot be a simple function of apparent age beyond $10^6$ years.

## I. INTRODUCTION

Studies of the high-energy radiation from the Crab and Vela pulsars (e.g., Kniffen et al., 1974; Thompson et al., 1977; Kanbach et al., 1980; Wills, et al., 1982) have shown that the energy radiated in the form of $\gamma$ rays exceeds that of radio waves by several orders of magnitude. This feature has led to considerable effort to understand $\gamma$ rays as a probe of the high energy phenomena associated with pulsars. In particular, various authors have develped models for $\gamma$-ray emission which might be expected from pulsars in general (e.g., Hardee, 1977; Buccheri et al., 1978; Salvati and Massaro, 1978; Ayasli and Ögelman, 1980; Harding, 1981). Observationally, several searches of $\gamma$-ray data (Ögelman et al., 1976; Kanbach et al., 1977; Knight et al., 1982; Graser and Schönfelder, 1983; Buccheri et al. 1983) have produced upper limits but no confirmed $\gamma$-ray emission from other pulsars.

The present work reports further upper limits to $\gamma$ radiation from radio pulsars, using data from the SAS-2 high energy $\gamma$-ray telescope (Fichtel et al., 1975). This search is based principally on pulsar parameters derived from radio observations since the work of Ögelman et al (1976).

## II. DATA ANALAYSIS

Pulsars to be examined were selected, with two exceptions, from the list of Manchester and Taylor (1981), based on the following criteria:

a. The pulsar must have an apparent age T ($T=P/2\dot{P}$, where P and $\dot{P}$ are the period and period derivative) less than $10^6$ years, or the pulsar must be relatively nearby in space. According to current models, pulsars with small apparent age are most likely candidates to be $\gamma$-ray emitters.

b. The pulsar must fall within the region of sky viewed by the SAS-2 instrument, as shown by Fichtel, Simpson, and Thompson, 1978.

c. The uncertainties in the period and period derivative must be small enough to allow an extrapolation to the time of the SAS-2 observations in 1972-1973 (which were typically one week duration), assuming no "glitches" or other timing variations. Proper motions can be neglected for the present analysis.

d. Those pulsars already studied by Ögelman et al (1976) were excluded unless improved radio data were available.

Forty-two pulsars were selected for study in this way. The recently-discovered X-ray and radio pulsar in the supernova remnant MSH 15-52 (Seward and Harnden, 1982; Manchester, Tuohy, and D'Amico, 1982) was included as a special case due to its similarity to the Crab pulsar. Another special case was the 1.5 ms pulsar reported by Backer et al. (1982), for which a total $\gamma$-ray upper limit was calculated.

For each of the pulsars, $\gamma$ rays with measured energies above 35 MeV in the SAS-2 data base were selected if their measured arrival directions were within an error circle about the known pulsar position. The radius of the circle ranged from 4° to 6°, depending on $\gamma$-ray energy. The arrival time of each $\gamma$ ray was corrected to a corresponding arrival time at the solar system barycenter, and these arrival times were then folded using the known radio period and period derivative. The resulting phase plots were examined in bins of 0.05 period. Taking into account the number of bins (20) and the number of pulsars examined in this analysis and the Ögelman et al. (1976) search, (more than 100), none of the peaks which appeared in the phase plots were considered statistically significant.

For each of the pulsars, an upper limit was calculated for the pulsed $\gamma$-ray flux above 35 MeV, based on the single highest peak in the phase plot. These are 95% confidence upper limits calculated using the statistical analysis techniques of Hearn (1969). For those distributions for which two adjacent peaks were high, the data were binned in 0.1 period increments. From the flux upper limit, a $\gamma$-ray luminosity upper limit was calculated based on the distance estimates of Manchester and Taylor (1981) and assuming an emission solid angle of 1 ster, so that the luminosity L is $L = 1 \cdot F \cdot d^2$ where F is the flux upper limit and d is the distance. The $\gamma$-ray upper limits, together with other pulsar data as summarized by Manchester and Taylor (1981), are shown in Table 1.

## III. INDIVIDUAL PULSARS

A. 1509-58. This is the pulsar in the supernova remnant MSH 15-52 (G320.4-1.2). Although its X-ray and radio timing parameters are not sufficiently well defined to allow an unambiguous search of the SAS-2 data, the similarity of this pulsar to the Crab pulsar made it a unique candidate. The procedure followed was to search a range of periods and period derivatives allowed by the uncertainties, extrapolated to the time of the SAS-2 observations in March 1973. The phase distribution with the highest $\chi^2$ value is shown in Figure 1. Although the double peak structure is similar to those of the Crab and Vela, it should be emphasized that the large number of periods searched (over 300,000) precludes any claim of a positive result. The upper limit in Table I and Fig. 2 was derived from the phase distribution by taking the excess in the two high bins above the background as determined from the other 18 bins. Applying the same statistical analysis to this phase distribution as was used for the other pulsars would produce a limit about 40% higher, but such a limit would be an overestimate in light of the fact that the timing search has already maximized the peaks. Neither the SAS-2 data (Hartman et al., 1979) nor the COS-B data (Mayer-Hasselwander et al. 1982) show significant evidence of a localized γ-ray source at the position of this pulsar.

B. 1747-46. Ögelman et al (1976) and Thompson et al (1976) found evidence for a positive pulsed result, based on the radio timing measurements of McCulloch et al. (1973) made approximately one week before the γ-ray observations. Recent radio observations made over a much longer time span (Newton, Manchester, and Cooke, 1981) indicate a significantly smaller period derivative. Using the revised period derivative produces a γ-ray phase plot with a peak of much lower significance than that found by Ögelman et al. The present upper limit is based on the revised radio data.

C. 1818-04. Ögelman et al. (1976) identified this pulsar as a tentative positive result, based on a single large peak in the γ-ray phase plot. The radio data (Manchester and Peters, 1972; Helfand et al., 1980) show no re-evaluation of P or $\dot{P}$ at a level which would affect the γ-ray data. The result in Table 1 is shown as an upper limit principally because of the lack of confirmation in the COS-B data (Kanbach et al., 1977).

D. 1822-09. Mandrou, Vedrenne, and Masnou (1980) found evidence for pulsed radiation in the energy band 454-1126 keV.

E. 1913+16. This pulsar has the shortest period of the three known binary radio pulsars. The analysis of the SAS-2 data used the equations and orbital parameters given by Taylor et al. (1976).

F. 4C 21.53. The 1.5 msec pulsar discovered by Backer et al. (1982) in this radio source is too fast to be resolved by the SAS-2 timing measurements. An upper limit (95% confidence) to a γ-ray source above 100 MeV at the location of this pulsar is $2 \times 10^{-6}$ photons $cm^{-2}s^{-1}$. In light of the very small period derivative for this fast pulsar, little if any γ radiation would be expected.

## IV. DISCUSSION

The upper limits of Table I rest on several assumptions which should be re-emphasized:

a. The extrapolation of the radio parameters to the time of the SAS-2 observations assumes that there were no intervening "glitches", large timing variations, or systematic second derivative of the period.

b. The luminosity calculation assumes a 1 ster emission angle for all pulsars. This assumption is a likely oversimplification.

c. The uncertainties in the distance estimates for some of the pulsars are relatively large, due to the uncertainty in the interstellar electron distribution. Those pulsars in the table which are designated as having large distance uncertainties are ones for which the distance estimates changed by factors of four to fifteen between previous estimates (e.g. Taylor and Manchester, 1975) and the current best estimates (Manchester and Taylor, 1981). If HII regions contribute significantly to their dispersion measures, some of these pulsars may be significantly closer than estimated here.

Figure 2 summarizes the results of this work, showing the γ-ray luminosity upper limits (converted to a fraction of total pulsar rotational energy loss) as a function of pulsar apparent age T. Also shown are the positive results from the Crab and Vela pulsars from SAS-2, along with results for 0950+08 and 1929+10 from the previous pulsar search (Ögelman et al, 1976). In all cases, the average energy for the γ rays has been taken as 100 MeV, consistent with the energy spectra observed for the Crab and Vela pulsars. The line passes through the Crab and Vela results. The upper limits do not conflict with the trend suggested by the Crab and Vela pulsars for the efficiency of γ-ray production to increase with increasing apparent age. A simple dependence of efficiency on apparent age (such as that proposed by Buccheri, et al., 1978 and Ayasli and Ögelman, 1980) cannot, however, extend to ages beyond $10^6$ years without conflicting with the upper limits for 0950+08 and 1929+10. Unless these two pulsars are uncharacteristic, the efficiency for γ-ray production must either flatten or reach a maximum and then decrease with increasing apparent age. Alternatively, the γ-ray production efficiency may depend on other parameters. The model of Harding (1981) predicts a dependence of $(\text{apparent age})^{1.8} \times (\text{period derivative})^{1.3}$. None of the γ-ray upper limits are in conflict with this model.

As just indicated, upper limits to γ-ray emission from pulsars can place restrictions on models. Future observations will be needed to verify such models. Some of the SAS-2 upper limits are close enought to possible extrapolations from the Crab and Vela pulsars to suggest that the large COS-B data base may reveal additional pulsars. Candidates would be 0740-28, 0919+06, 1055-52, and 1822-09 (all of which lie close to the line in Figure 2), older nearby pulsars such as 0950+08 and 1929+10, and other candidate pulsars listed by Harding (1981). Many pulsars are inaccessible to instruments with the sensitivity and resolution of SAS-2 and COS-B, as can be seen in Figure 2, but might be observable with large instruments such as those on the Gamma Ray Observatory.

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Table 1

SAS-2 Upper Limits to Pulsed $\gamma$-Ray Fluxes Above 35 MeV

| PSR | P(Sec) | $\dot{P}$ ($\times 10^{-15}$ s/s) | Assumed Distance (Kpc) | $2\sigma$ limit of Pulsed Flux ($\times 10^{-6}$ cm$^{-2}$s$^{-1}$) | Log of $\gamma$-Ray Luminosity Limit (photons s$^{-1}$) | Log of Apparent Age (yr) | Notes |
|---|---|---|---|---|---|---|---|
| 0136+57 | .2724 | 10.687 | 2.50 | 2.2 | 38.1 | 5.61 | |
| 0154+61 | 2.3517 | 188.990 | 1.60 | 2.6 | 37.8 | 5.29 | 1 |
| 0656+14 | .3849 | 1.600 | 0.40 | 3.6 | 36.7 | 6.58 | |
| 0727-18 | .5102 | 18.948 | 1.50 | 1.4 | 37.5 | 5.63 | |
| 0740-28 | .1668 | 16.832 | 1.50 | 1.0 | 37.3 | 5.20 | 1 |
| 0743-53 | .2148 | 2.730 | 2.40 | 4.0 | 38.5 | 6.10 | 2 |
| 0919+06 | .4306 | 13.725 | 1.00 | 1.4 | 37.1 | 5.70 | |
| 0922-52 | .7463 | 35.477 | 2.70 | 2.5 | 38.2 | 5.52 | 2 |
| 0940-55 | .6644 | 22.739 | 4.90 | 3.0 | 38.8 | 5.67 | 2 |
| 0941-56 | .8081 | 39.617 | 4.90 | 3.2 | 38.9 | 5.51 | 2 |
| 0959-54 | 1.4366 | 51.665 | 3.30 | 2.9 | 38.5 | 5.64 | |
| 1001-47 | .3071 | 22.074 | 1.60 | 3.7 | 38.0 | 5.34 | 3 |
| 1055-52 | .1971 | 5.834 | 0.92 | 4.3 | 37.6 | 5.73 | |

| PSR | P(Sec) | $\dot{P}$ ($\times 10^{-15}$ s/s) | Assumed Distance (Kpc) | 2σ limit of Pulsed Flux ($\times 10^{-6}$ cm$^{-2}$s$^{-1}$) | Log of γ-Ray Luminosity Limit (photons s$^{-1}$) | Log of Apparent Age (yr) | Notes |
|---|---|---|---|---|---|---|---|
| 1133-55 | .3647 | 8.228 | 2.90 | 6.2 | 38.7 | 5.85 | |
| 1323-62 | .5299 | 18.890 | 7.90 | 16.0 | 40.0 | 5.65 | 3 |
| 1356-60 | .1275 | 6.339 | 8.80 | 5.3 | 39.6 | 5.50 | |
| 1358-63 | .8428 | 16.905 | 2.90 | 6.7 | 38.7 | 5.90 | |
| 1509-58 | .1502 | 1520. | 4.20 | 9.1 | 39.2 | 3.19 | 4 |
| 1552-31 | .5181 | 0.050 | 2.60 | 2.2 | 38.2 | 8.22 | 2 |
| 1552-23 | .5326 | 0.700 | 1.80 | 3.0 | 38.0 | 7.08 | 2 |
| 1555-55 | .95. | 20.479 | 6.30 | 3.2 | 39.1 | 5.87 | |
| 1557-50 | .1926 | 5.063 | 7.80 | 5.0 | 39.5 | 5.78 | 3 |
| 1558-50 | .8642 | 69.572 | 2.50 | 4.3 | 38.4 | 5.29 | |
| 1600-27 | .7783 | 2.920 | 1.60 | 1.5 | 37.6 | 6.63 | |
| 1641-45 | .4551 | 20.137 | 5.30 | 2.4 | 38.8 | 5.55 | 6 |
| 1648-17 | .9734 | 3.042 | 1.10 | 0.9 | 37.0 | 6.79 | 2 |
| 1702-18 | .2990 | 4.140 | 0.74 | 3.0 | 37.2 | 6.06 | 2 |
| 1707-53 | .8992 | 15.494 | 3.60 | 2.3 | 38.5 | 5.96 | |
| 1719-37 | .2362 | 10.816 | 2.50 | 1.3 | 37.9 | 5.54 | |
| 1727-47 | .8297 | 163.672 | 4.10 | 2.2 | 38.6 | 4.90 | 1 |

| PSR | P(Sec) | $\dot{P}$ ($\times 10^{-15}$ s/s) | Assumed Distance (Kpc) | $2\sigma$ limit of Pulsed Flux ($\times 10^{-6}$ cm$^{-2}$s$^{-1}$) | Log of $\gamma$-Ray Luminosity Limit (photons s$^{-1}$) | Log of Apparent Age (yr) | Notes |
|---|---|---|---|---|---|---|---|
| 1729-41 | .6280 | 12.838 | 6.10 | 1.7 | 38.8 | 5.89 | |
| 1747-46 | .7424 | 1.295 | 0.66 | 2.3 | 37.0 | 6.96 | 1,3 |
| 1818-04 | .5981 | 6.338 | 1.50 | 3.5 | 37.9 | 6.17 | 1 |
| 1821-[illegible] | .1893 | 5.238 | 6.80 | 2.1 | 39.0 | 5.76 | |
| 1822-09 | .7690 | 52.320 | 0.56 | 2.1 | 36.8 | 5.37 | 1 |
| 1834-10 | .5627 | 11.775 | 8.90 | 1.5 | 39.1 | 5.88 | |
| 1900+05 | .7466 | 12.896 | 4.20 | 11.0 | 39.3 | 5.96 | |
| 1913+16 | .0590 | 0.009 | 5.20 | 2.2 | 38.9 | 8.03 | 5,3 |
| 1916+14 | 1.1809 | 211.40 | 0.76 | 3.2 | 37.3 | 4.95 | 3 |
| 1924+16 | .5798 | 18.004 | 4.30 | 1.8 | 38.5 | 5.71 | |
| 1927+13 | .7600 | 3.661 | 6.40 | 3.8 | 39.2 | 6.52 | 3 |
| 1930+22 | .1444 | 57.780 | 7.00 | 3.9 | 39.3 | 4.60 | |
| 2351+61 | .9448 | 16.226 | 2.50 | 1.5 | 38.0 | 5.96 | |

NOTES:
1 Also appears on list of Ögelman et al. (1976). Updated parameters
2 Distance uncertainty relatively large
3 Based on 10 bin phase plot
4 Upper limit based on search of periods around the nominal value
5 Binary pulsar
6 Uses parameters prior to the 1977 glitch (Manchester et al., 1978)

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## FIGURE CAPTIONS

Figure 1 - Most likely candidate phase plot for $\gamma$ rays from the direction of pulsar 1509-58. Although similar to phase plots for the Crab and Vela pulsars, this result is not statistically significant due to the large number of period and period derivative combinations searched.

Figure 2 - Gamma ray efficiences for radio pulsars (energy radiated as $\gamma$ rays/total rotational energy loss), under assumptions discussed in the text. Several pulsars of interest are identified.

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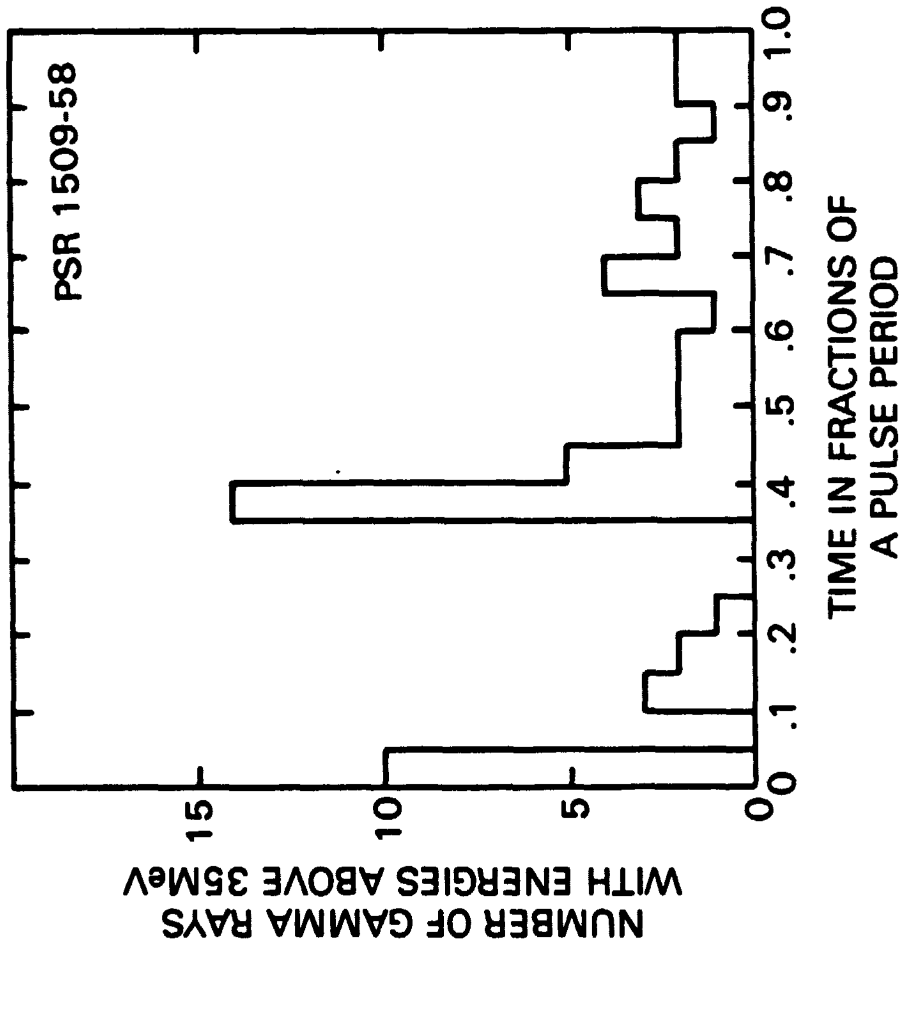

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