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A Search of the SAS-2 Data for Pulsed γ-Ray Emission from Radio Pulsars

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ABSTRACT

Data from the SAS-2 high energy (> 35 MeV) γ-ray experiment have been examined for pulsed emission from each of 75 radio pulsars which were viewed by the instrument and which have sufficiently well defined period and period derivative information from radio observations to allow for γ-ray periodicity searches. When γ-ray arrival times were converted to pulsar phase using the radio reference timing information, two pulsars, PSR1747-46 and PSR 1818-04, showed positive effects, each with a probability less than 10^{-4} of being a random fluctuation in the data for that pulsar. These are in addition to PSR 0531+21 and PSR 0833-45, previously reported. The results of this study suggest that γ-ray astronomy has reached the detection threshold for γ-ray pulsars and that work in the near future should give important new information on the nature of pulsars.

Subject headings: γ-rays, pulsars

*Work started while at NASA/Goddard Space Flight Center as a NAS-NRC Senior Postdoctoral Research Associate

I. INTRODUCTION

The unexpected discovery of radio pulsars by Hewish et al. (1968) represented the beginning of an extensive search for these objects, which has led to the detection of well over a hundred radio pulsars whose periods range from about 0.03 sec. to several seconds. Relatively shortly after this discovery, Gold (1968, 1969) proposed that this radiation probably originated from a neutron star primarily on the basis that no other theoretically known astronomical object could possess such short and accurate periodicities as those observed. This concept is now generally accepted, and the radiation in the radio region is usually attributed to radiation from electrons in the very strong magnetic fields. In spite of extensive searches in the optical and X-ray energy ranges, only one of the known radio pulsars, PSR0531+21, has been detected with certainty. Periodicities in the range of seconds have also been observed for Cen X-3 (Giaconni et al., 1971; Schreier et al., 1972) and Her X-1 (Tananbaum et al., 1972), but the X-radiation from these two sources is generally attributed to accretion onto a compact object of a close binary pair. No radio pulsars have been associated with these X-ray pulsars.

Surprisingly even though γ-ray astronomy has just recently had detectors with enough sensitivity to obtain clear positive results on celestial γ-rays, two γ-ray pulsars ($E \geqslant 10$ MeV) have already been identified and both have radio counterparts. They are PSR0531+21 in the Crab (Browning et al., 1971; Albats et al., 1972; McBreen et al., 1973; and Kniffen et al., 1974) and PSR0833-45 in Vela (Albats et al., 1974; Thompson et al., 1975). There is a marked contrast between these last two pulsars in that, 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 Saa, 1972). Further, 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 at least 1000 for the 1.5-10 keV energy range (Rappaport et al., 1974). PSR 0531+21, being the newer pulsar, might be expected to be more likely to be emitting at all frequencies as observed. These results suggest that, in the case of Vela, there is a dominant high energy component 10^4 years after the supernova. Thus, it is an interesting speculation that pulsars may be a relatively important phenomenon in the γ-ray range. To pursue this possibility, a search has been made through the SAS-2 data for γ-ray emission from pulsars. This investigation and its results are described in the following paragraphs.

II. DATA ANALYSIS

The data from the SAS-2 γ-ray experiment telescope (Fichtel et al., 1975) cover about 60% of the sky and 89% of the galactic plane for γ-rays with energy greater than 35 MeV. In order to compare these results with those of the radio region, the summaries of radio pulsar data of Terzian (1975) and Taylor and Manchester (1975) have been used. These lists contain 147 objects, 13 of which were not included in the SAS-2 exposure. Of the remaining 134, it should be noted that none (with the exception of PSR 0531 +21 and PSR 0833-45) had a significant flux ($> 3\sigma$) purely on the basis of the time-averaged data without considering the pulsar phase distribution. To look for a correlation in phase, the period, P, and the period derivative with respect to time, $\dot{P}$, must be well defined for the time of the SAS-2 exposure (November 19, 1972 to June 8, 1973) so that the phase may be compared with the arrival times of the γ-ray events, which are known to about ± 1 millisecond. After eliminating a total of 59 radio pulsars because P and $\dot{P}$ were not well enough defined, there were 75 pulsars left to be examined. Two of these were the already published pulsars PSR 0531 +21 and PSR 0833-45 (Kniffen et al., 1974; Thompson et al., 1975). For each of the remaining pulsars, the γ-ray events were selected with measured arrival directions within an error circle which is a function of energy and is defined in the previous γ-ray pulsar papers. SAS-2 viewed a given region of the sky for approximately one week; however, in some cases, for example PSR0833-45, the object of interest was in the field of view for more than one week. The arrival time of each γ-ray was converted to a pulsar phase (relative to an arbitrary starting time, since the arrival times of the radio pulses were generally unknown) using programs previously used for the Crab and Vela pulsars. The method used was to correct the arrival time of the photon at the satellite to an arrival time at the solar system barycenter. Using the pulsar barycentric period, the barycentric arrival times were converted into a phase plot. From the work on the Crab and Vela pulsars, it is known that the phase of any γ-ray can be calculated with an error of the order of two milliseconds, provided the radio reference information is known well enough for the observing interval in question. The limited photon statistics and long observing times make a general search of the γ-ray data for unknown and short periodicities impractical. The resulting phase distribution for the observed γ-rays selected as described for each radio pulsar location was then examined in bins of 0.05 period.

The uncertainty in the γ-ray phase calculation can be estimated from the uncertainties in the radio reference information. Unless the pulsar is extremely strong compared to the general γ-ray background (an unlikely occurrence since most of the pulsars lie on the galactic plane where the γ-ray intensity is the greatest), a pulse may be assumed to be unrecognizable if it drifts more than 0.1 period (two bins) during the observation interval. The uncertainty in the period arises from the combined uncertainties of the period determination itself and the uncertainty in the period derivative extrapolated to the epoch of the γ-ray observations. Setting ΔN, the drift or error in the phase distribution, equal to 0.1 gives a maximum time over which the γ-ray data can safely be summed in order to avoid "smearing" a possible pulse. For some radio pulsars, the timing uncertainties were large enough that this computed maximum folding time was shorter than the SAS-2 observation period. For these cases, the SAS-2 data were broken down and summed over smaller time increments.

In order to assign a level of statistical significance to the observed phase distribution, certain assumptions have to be made since the nature of the γ-ray pulsation is not known. To illustrate this point, whereas the γ-rays from the Crab pulsar follow the phase distribution seen at other wavelengths within the present limited statistics, the phase distribution of the Vela pulsar is quite different from that of the radio pulsar in that the γ-ray distribution shows two distinct peaks of about equal intensity about 0.4 period apart rather than the single pulse at radio frequencies. Furthermore, the radio pulse does not coincide with either γ-ray pulse. Since there is no clear a priori pulse profile, the approach used here was to apply first a straightforward χ^2 test comparing the data in twenty phase bins to that expected for a random distribution with the observed mean.

The results of the χ^2 analysis for the 73 pulsars are given in Table I. The great majority of the surveyed pulsars gave χ^2 values clearly compatible with no signal. Out of 73 pulsars, each with 19 degrees of freedom, even the two highest χ^2 values (46.82 for PSR1747-46 and 37.97 for PSR1818-04) are not very improbable for a sample of this size (9% and 45%). The χ^2 test, however, does not distinguish between random fluctuations throughout the phase plot and a concentration of data in one or two strong peaks. Since a phase distribution for a pulsar would probably contain no more than two peaks, additional information is available beyond the simple χ^2 test. This test, however, provides an initial screening process to select candidates for a detectable pulsed flux.

Figure 1 shows the phase plots from the two pulsars which gave the highest χ^2 values. Each of these pulsars shows a statistically-significant excess at a level sufficiently high to warrant the claim of a tentative positive result. In Figure 1a, the phase plot for

PSR1818-04 contains 264 events, for an average of 13.2 events per bin. The three bins between 0.55 and 0.70 phase contain 67 events. If Gaussian statistics are used, the excess in these bins lies 4.4 standard deviations above the average for all bins. Radio observations from the same time frame as the SAS-2 observations (Reichley, 1975) show that the peak does not coincide with the dispersion-corrected radio pulse. The Poisson probability of finding a peak this large at any random point in the phase diagram is about 4×10^{-5} or 3×10^{-3} for any one of 73 pulsars. Treating this as a positive result and using the 17 bins away from the peak as background yields an excess of 32.2 photons (or 5.5σ above the background) associated with the source. This corresponds to a pulsed γ-ray flux above 35 MeV of $(2.0 \pm 0.5) \times 10^{-6}$ $cm^{-2}s^{-1}$.

In figure 1b, 16 of the 79 events in the phase plot of PSR1747-46 lie in one bin. The Poisson probability of finding this peak in any one of 20 bins is about 8×10^{-5} (equivalent to approximately 4σ), or 6×10^{-3} for any one of 73 pulsars. Treating this as a positive result, the excess represents a pulsed γ-ray flux above 35 MeV of $(2.4 \pm 0.7) \times 10^{-6}$ cm^{-2} s^{-1}. The events used in this analysis lie in a cluster which stands about 2.9 standard deviations above the surrounding region of the sky at the same galactic latitude. Details of the analysis of this source have been discussed by Thompson et al. (1976). For both PSR1818-04 and PSR1747-46, the pulsed flux levels represented by these results are consistent with the time-averaged flux which would be calculated for γ-ray sources at these positions.

Phase plots for the other four pulsars which had χ^2 values above 27 are shown in Figure 2. Although some peaks do appear in these histograms, none of them are statistically significant. These pulsars do, however, represent interesting candidates for future studies of γ-ray pulsars.

For each of the remaining pulsars, a 2σ upper limit to the pulsed γ-ray flux above 35 MeV was calculated based on the highest single peak in the phase plot. These upper limits might be somewhat underestimated in some cases, for example, for a pulsar with both a pulse and an interpulse. From the γ-ray flux upper limit, a γ-ray luminosity upper limit for each pulsar was then calculated based on the distance estimates of Taylor and Manchester (1975) which follow the method developed by Prentice and ter Haar (1969). For the luminosity calculation an emission solid angle of 1 sr was assumed, so that the luminosity L is

$$L = 1 \cdot F\, d^2,$$

where F is the observed flux and d is the distance. The summary of these results is also shown in Table I. It should be borne in mind that the upper limits given here for the luminosities do not truly reflect upper limits in the sense that neither the distance nor the emission solid angle is known accurately for any pulsar.

Some other pulsars, particularly the fastest ones, are also of interest to this study even though the timing information is not sufficiently precise to make a phase calculation. γ-ray flux and luminosity upper limits have been calculated for all additional pulsars with periods shorter than 0.2 seconds which were observed by SAS-2. These results are total values rather than pulsed and are summarized in Table II.

III. DISCUSSION

The encouragement to survey the SAS-2 data for pulsed γ-ray emission from all radio pulsars came from the initial identification of the Crab and Vela pulsars at γ-ray energies. These observations immediately provoked the question: Can γ-rays be found from any other pulsars, which would suggest that γ-ray emission is a general characteristic of radio pulsars, or do γ-rays originate only from a subclass of radio pulsars?

In his original papers, Gold (1968, 1969) suggested that the neutron star might have a surface field strength of from 10^{12} to 10^{13} gauss and that the principal source of energy for the pulsar was the rotational energy of the star. These concepts still seem to be favored. Assuming that the observed pulsar radiation does come from the rotational energy, and assuming the term containing the change in the moment of inertia is negligible compared to the term containing the period change, the rotational energy loss is given by the expression

$$\frac{dE_R}{dt} = I\Omega\dot{\Omega} = \frac{4\pi^2 I}{P^3} \dot{P} \qquad (1)$$

where I is the pulsar moment of inertia, Ω is the angular frequency of the pulsar, and $\dot{\Omega}$ is the time derivative of Ω. Attempts to correlate this expression with observed radio periods, period derivatives, and luminosity have been ambiguous. There could be many reasons for this: (i) many of the distances to pulsars are poorly known, (ii) the moments of inertia are almost certainly not all the same, (iii) the radiated energy even in the radio range is often poorly known because of lack of information over a large part of the spectrum; and (iv) the field strength could vary considerably and the rotational energy could go into other forms of radiation (Lyne et al., 1975). This latter possibility is suggested by the relatively slow decrease in radio luminosity as a function of period for short periods. Hence, it is not yet appropriate to abandon the concept implied by equation (1).

Using the measured values of P and P^3 and a value for I of 10^{45} g cm^2 (Taylor and Manchester, 1975), an estimate of the values of (dE_R/dt) can be made. These values of the rotational energy loss would then be upper limits for the γ-radiation assuming all energy that is lost comes from the rotational energy. Figure 3 shows the results of this comparison. The γ-ray luminosities and the computed (dE_R/dt) values are all uncertain by an order of magnitude or more due to uncertainties in the values for I, the distance estimates, and the solid angle of emission for γ-rays, but this comparison is still useful. For completeness, the results from the Crab (pulsed flux above 35 MeV = $(6.2 \pm 2.8) \times 10^{-6}$ cm^{-2} s^{-1}, luminosity $(2.2 \pm 1.0) \times 10^{38}$ s^{-1}, Kniffen et al., 1974) and Vela (pulsed flux above 35 MeV = $(1.1 \pm 0.4) \times 10^{-5}$ cm^{-2} s^{-1}, luminosity $(2.3 \pm 0.8) \times 10^{37}$ s^{-1}, Thompson et al., 1975) are also shown. It should be emphasized that the error bars represent only the uncertainties in the γ-ray flux measurements.

Taking a characteristic energy of 100 MeV for γ-rays seen by SAS-2, the ratio of energy loss in the form of γ-rays to energy loss due to rotation can be calculated. Subject to the accuracy of the assumed parameters, the Crab and Vela pulsars appear to convert 10^{-4} and 10^{-3} of their rotational energy loss into γ-rays observed. If the pulsed results from PSR1747-46 and PSR1818-04 are confirmed, the fraction of rotational energy loss appearing in the form of γ-rays would seem to be about 0.3 and > 1.0 respectively, the latter of which would cast doubt on the accuracy of the assumed pulsar parameters. Even taking into account these large uncertainties, the results suggest that PSR1747-46 and PSR1818-04 are losing a larger fraction of their energy as γ-rays than are the Crab and Vela pulsars. It is also worth noting that the upper limits from this study do not rule out the possibility that most or all pulsars may be emitting a small fraction (less than 1%) of their rotational energy in the form of high energy γ-rays.

In some pulsar models (e.g. Ostriker and Gunn, 1969; Ruderman and Sutherland, 1975), the current value of $P/(2\dot{P})$ is representative of the pulsar age. For the Crab pulsar, this apparent age is reasonably consistent with the known age of the pulsar. Although consistency between apparent age and true age may not hold for pulsars with $P/(2\dot{P})$ greater than 10^6 years (Lyne et al., 1975), it seemed worth examining the pulsed γ-ray luminosities and upper limits as a function of this parameter, as shown in Fig. 4.

In Fig. 4, as in Fig. 3, there is no clearly visible simple relationship between the intensities and upper limits to γ-ray luminosities determined from the SAS-2 data and the function to which they are compared; however, there is the hint, especially in Fig. 4, that a threshold for detection is just being approached by the SAS-2 γ-ray instrument. If, for example, the PSR1818-04 result is an improbable statistical fluctuation, then the other three positive results stand nearly alone in Fig. 4. The radio luminosity of pulsars appears to decrease relatively rapidly for pulsars older than about 10^6 years, and various theoretical reasons for this turnoff have been suggested (Gunn and Ostriker, 1970; Ruderman and Sutherland, 1975; Lyne et al., 1975). The data of Fig. 4 suggest that a similar pattern may exist for γ-ray pulsars. The upper limits for many pulsars with apparent ages greater than 10^6 years are at least inconsistent with γ-ray luminosities comparable to the positive results, while no such statement can be made for pulsars with apparent ages less than 10^6 years.

Until further data is available it should also be kept in mind that some or all radio pulsars may exhibit time variability in the γ-ray energy range. An indication has already been found that the Crab pulsar may have a variable γ-ray luminosity at photon energies above 500 MeV (Greisen et al., 1975). Alternately there simply may be no general relationship between different pulsars in the energy range viewed by SAS-2. If this is the case, then PSR1747-46 and PSR1818-04 could be exceptional in having γ-ray emission. Further developments in this field in the near future could be extremely rewarding. Even a γ-ray telescope with modestly greater sensitivity could improve the limits on γ-ray pulsars substantially. As radio measurements continue, better timing information could make possible studies on more of the nearby and fast pulsars than was possible in the SAS-2 exposure. Six of the ten fastest known pulsars were not included in the present search due either to lack of exposure or inadequate period and period derivative information available for the time of observations.

In view of having found two definite and two very likely pulsars with γ-ray luminosities above 35 MeV in the range of 10^{37} to a few times 10^{38} s^{-1}, the question naturally arises as to what fraction of the total galactic γ-ray luminosity they may constitute. Since pulsars are generally thought to be created during supernovae, a reasonable estimate for their generation in the galaxy might be 10^{-2}/year. There is at the moment no generally accepted theory to explain the newly discovered phenomenon of γ-ray pulsars, and therefore, there is certainly no unambiguous prediction of the time dependence of the radiation. However, as a reasonable possibility, assume that pulsars are generated at the rate of 10^{-2}/year, that the concept of each pulsar having a constant luminosity (which will be taken to be 10^{37} s^{-1}) for 10^{6} years is valid, and that no γ-rays are emitted from pulsars older than 10^{6} years. The total γ-ray luminosity above 35 MeV for our galaxy would then be 10^{41} s^{-1}, compared to about 2 x 10^{42} s^{-1} for γ-rays above 35 MeV produced by cosmic rays interacting with matter (e.g. Bignami et al., 1975). Since the assumption that million-year-old pulsars emit γ-rays at about the same rate as 10,000-year-old pulsars seems optimistic, the total contribution to the galactic γ-ray luminosity from pulsars is probably smaller but the uncertainties are large enough that the pulsar contribution may not be negligible.

IV. SUMMARY

Including the results reported here, there now appear to be four statistically significant γ-ray pulsars, and there is the suggestion that many more may be detected as more sensitive telescopes are flown. Thus, as γ-ray astronomy begins the exploratory phase, the γ-radiation associated with the pulsars may ultimately be determined to be a very important unexpected high energy phenomenon. Further, the different nature of the Crab and Vela radiation mentioned earlier and the γ-radiation from the "old" pulsars PSR1818-04 and PSR1747-46 suggest that more than one mechanism may be involved. With future more sophisticated and sensitive instrumentation, not only will the history of pulsar emission be better estimated, but also the details of the γ-ray pulse profiles from these objects. There should then be a better hope of determining the exact physical mechanism responsible for this very large pulsed emission of high energy γ-rays, and hence an important clue in the understanding of pulsar dynamics.

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TABLE I

SAS-2 Upper Limits to Pulsed γ-Ray Fluxes Above 35 MeV

PSR	P(Sec)	$\dot{P}$ ($\times 10^{-15}$ s/s)	Distance (pc)	χ^2 (19 deg. of freedom)	2σ limit of pulsed flux ($\times 10^{-6}$ cm^{-2}s^{-1})	γ-ray luminosity limit (photons s^{-1})
0105+65	1.284	12.4	1000	18.94	1.8	1.6×10^{37}
0138+59	1.223	0.2	3000	23.45	1.6	1.3×10^{38}
0153+61	2.352	189	2000	18.59	1.8	6.5×10^{37}
0450-18	0.549	5.78	2400	*	0.6	3.1×10^{37}
0525+21	3.745	40.06	1900	24.31	1.2	3.9×10^{37}
0540+23	0.246	15.43	2800	23.33	1.0	7.1×10^{37}
0611+22	0.335	59.73	3500	19.54	1.2	1.3×10^{38}
0628-28	1.244	2.51	1400	14.33	1.1	1.9×10^{37}
0740-28	0.167	16.7	2600	21.40	2.1	1.3×10^{38}
0818-13	1.238	.11	1600	20.09	1.0	2.3×10^{37}
0834+06	1.274	6.80	480	19.89	1.3	2.7×10^{36}
0943+10	1.098	3.53	630	17.12	1.0	3.6×10^{36}
0950+08	0.253	0.23	100	26.53	1.1	9.9×10^{34}
1112+50	1.656	2.6	310	*	1.7	1.5×10^{36}
1133+16	1.188	3.73	180	20.94	0.8	2.3×10^{35}
1237+25	1.382	0.96	370	19.45	0.7	8.6×10^{35}

* Number of γ rays insufficient to make χ^2 test meaningful.

TABLE I (Page 2)

1508+55	0.740	5.04	920	*	1.4	1.1×10^{36}
1541+09	0.748	0.41	2500	15.33	1.0	5.6×10^{37}
1604-00	0.422	0.31	400	18.94	0.9	1.3×10^{36}
1642-03	0.388	1.78	160	16.16	0.9	2.1×10^{35}
1700-32	1.212	0.7	470	17.69	1.8	3.6×10^{36}
1706-16	0.653	6.37	160	23.28	1.1	3.5×10^{35}
1717-29	0.620	0.8	1600	16.79	2.2	5.1×10^{37}
1718-32	0.477	0.7	4400	15.20	2.4	4.2×10^{38}
1727-47	0.830	180	5900	18.80	1.7	5.3×10^{38}
1730-22	0.872	0.0	1600	10.57	1.5	3.5×10^{37}
1742-30	0.367	10.7	2900	20.33	2.5	1.9×10^{38}
1747-46	0.742	70	740	46.82	$2.4 \pm 0.7^{+}$	1.2×10^{37}
1749-28	0.563	8.15	1700	18.00	2.4	6.2×10^{37}
1813-26	0.593	-0.3	3500	23.77	1.4	1.5×10^{38}
1818-04	0.598	6.32	3200	37.97	$2.0 \pm 0.5^{+}$	1.8×10^{38}
1819-22	1.874	0.6	5700	25.79	2.3	6.7×10^{38}
1822-09	0.769	52.2	650	15.72	2.7	1.0×10^{37}
1826-17	0.307	5.59	8800	17.43	1.8	1.3×10^{39}
1831-03	0.687	41.5	9400	16.43	3.0	2.4×10^{39}

+ Positive result assumed

TABLE I (page 3)

1831-04	0.290	0.1	2300	25.26	3.8	1.8×10^{38}
1845-04	0.598	51.9	4900	28.76	3.6	7.8×10^{38}
1845-01	0.659	5.2	5400	19.69	3.1	8.1×10^{38}
1846-06	1.451	45.7	5700	25.54	3.6	1.1×10^{39}
1857-26	0.612	0.16	1400	25.92	0.9	1.6×10^{37}
1859+03	0.655	7.50	15000	13.69	1.2	2.4×10^{39}
1900-06	0.432	3.4	9000	14.82	3.6	2.6×10^{39}
1900+01	0.729	4.12	8800	12.37	2.9	2.0×10^{39}
1907+00	1.017	5.4	4300	22.37	3.1	5.2×10^{38}
1907+02	0.495	2.76	7500	8.20	3.6	1.8×10^{39}
1907+10	0.284	2.69	5000	21.34	4.9	1.1×10^{39}
1910+20	2.233	9.5	3200	23.33	3.9	3.6×10^{38}
1911-04	0.826	4.06	3700	13.52	2.1	2.6×10^{38}
1915+13	0.195	7.20	3200	20.67	2.1	1.9×10^{38}
1917+00	1.272	7.67	3400	14.29	1.0	1.0×10^{38}
1919+19	0.821	0.8	5300	24.49	1.3	3.3×10^{38}
1919+21	1.337	1.35	420	17.31	1.3	2.1×10^{36}
1920+21	1.078	8.2	9200	22.30	2.7	2.1×10^{39}
1929+10	0.227	1.16	110	16.74	1.6	1.7×10^{35}

TABLE I (page 4)

1933+16	0.359	6.00	6000	21.76	1.7	5.5×10^{38}
1944+17	0.441	0.024	550	19.14	1.6	4.4×10^{36}
1946+35	0.717	7.05	5400	26.46	2.1	5.5×10^{38}
1952+29	0.427	0.003	670	14.23	1.6	6.5×10^{36}
2002+31	2.111	74.58	7800	19.44	2.0	1.1×10^{39}
2016+28	0.558	0.15	480	27.71	1.8	3.7×10^{36}
2020+28	0.343	1.90	2000	26.22	2.0	7.2×10^{37}
2021+51	0.529	3.04	800	4.36	1.7	9.8×10^{36}
2045-16	1.962	10.97	430	16.27	1.5	2.5×10^{36}
2106+44	0.415	0.1	780	12.36	1.7	9.3×10^{36}
2111+46	1.015	0.72	4000	18.44	1.5	2.2×10^{38}
2148+63	0.380	0.16	840	28.24	1.7	1.1×10^{37}
2154+40	1.525	2.9	3200	24.33	1.6	1.5×10^{38}
2217+47	0.538	2.76	1600	13.11	1.0	2.3×10^{37}
2223+65	0.683	9.5	730	10.43	1.2	5.8×10^{36}
2255+58	0.368	5.75	2100	21.57	1.4	5.6×10^{37}
2305+55	0.475	0.1	1600	15.22	1.0	2.3×10^{37}
2319+60	2.256	7.6	2500	19.25	1.4	7.9×10^{37}
2324+60	0.234	0.36	760	30.29	1.5	7.8×10^{36}

TABLE II

SAS-2 Upper Limits to Time-Averaged γ-Ray Fluxes above 35 MeV from Short-Period Pulsars

PSR	P(Sec)	Distance (pc)	2σ limit of γ-ray flux ($\times 10^{-6}$ cm^{-2}s^{-1})	γ-ray luminosity limit (photons s^{-1})
1055-52	0.197	830	9.1	5.6×10^{37}
1449-64	0.179	2600	9.0	5.5×10^{38}
1557-50	0.193	10000	6.2	5.6×10^{39}
1913+16	0.059	6200	9.0	3.1×10^{39}
1930+22	0.144	8100	7.8	4.6×10^{39}

FIGURE CAPTIONS

Figure 1 -- Distribution of γ-ray arrival times in fractions of a radio pulse period for γ-rays above 35 MeV from the directions of (a) PSR1818-04 and (b) PSR1747-46. In (a), the arrow marked R is the expected position of the pulse based on radio observations (Reichley, 1975).

Figure 2 -- Distribution of γ-ray arrival times in fractions of a radio pulse period for γ-rays above 35 MeV from the directions of four pulsars: PSR1845-04, PSR2016+28, PSR2148+63, and PSR-2324+60.

Figure 3 -- Observed γ-ray luminosities and upper limits to luminosity as a function of pulsar rotational energy loss rates. The rotational energy loss rates are from Taylor and Manchester (1975), where the moment of inertia of each pulsar is taken to be 10^{45} g cm^2. Open circles are the Crab (Kniffen et al., 1974) and Vela (Thompson et al., 1975) observations from SAS-2. The open boxes are for PSR1747-46 and PSR1818-04, under the assumption that these are positive results. The γ-ray luminosities are calculated using the distance estimates of Taylor and Manchester (1975) and taking the solid angle of emission for each pulsar to be 1 sr. The error bars shown reflect only the uncertainties in the γ-ray flux measurements. If the assumptions discussed in the text are all valid, then the line $\frac{dE_R}{dt} = L_\gamma$ represents the condition for which all the pulsar rotational energy appears in the form of γ-rays.

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Figure 4 -- Observed γ-ray luminosities and upper limits to luminosity above 35 MeV as a function of pulsar apparent age (apparent age = $P/2\dot{P}$). The γ-ray luminosities are calculated using the distance estimates of Taylor and Manchester (1975) and taking the solid angle of emission for each pulsar to be 1 sr. The error bars shown reflect only the uncertainties in the γ-ray flux measurements.

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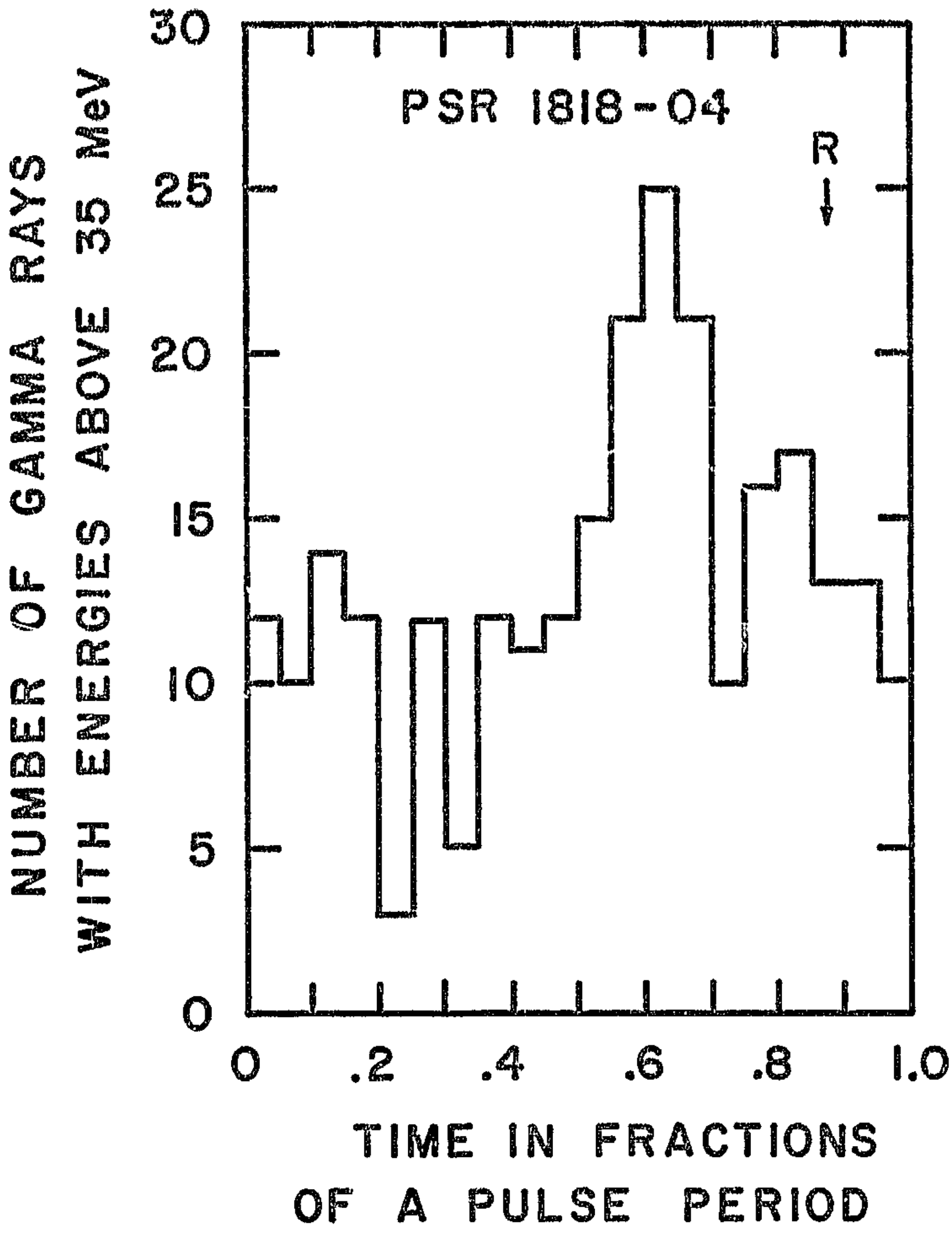
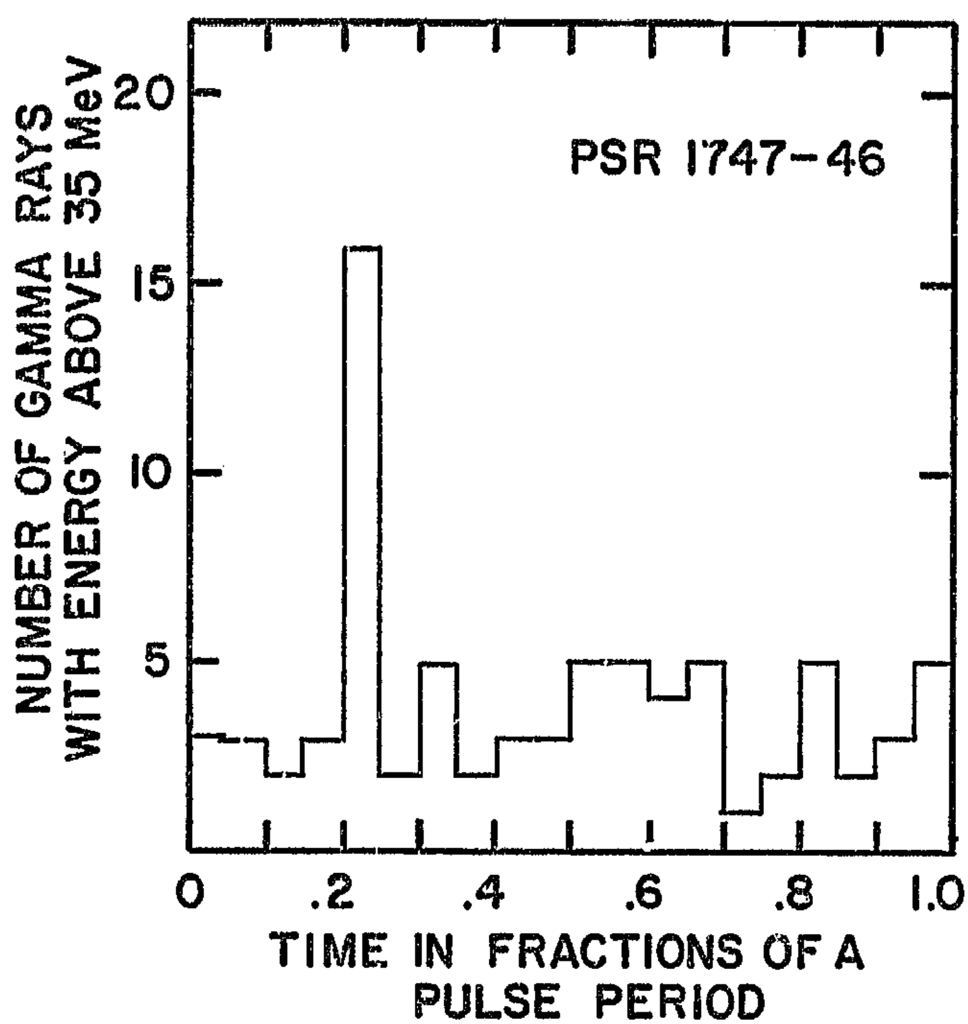


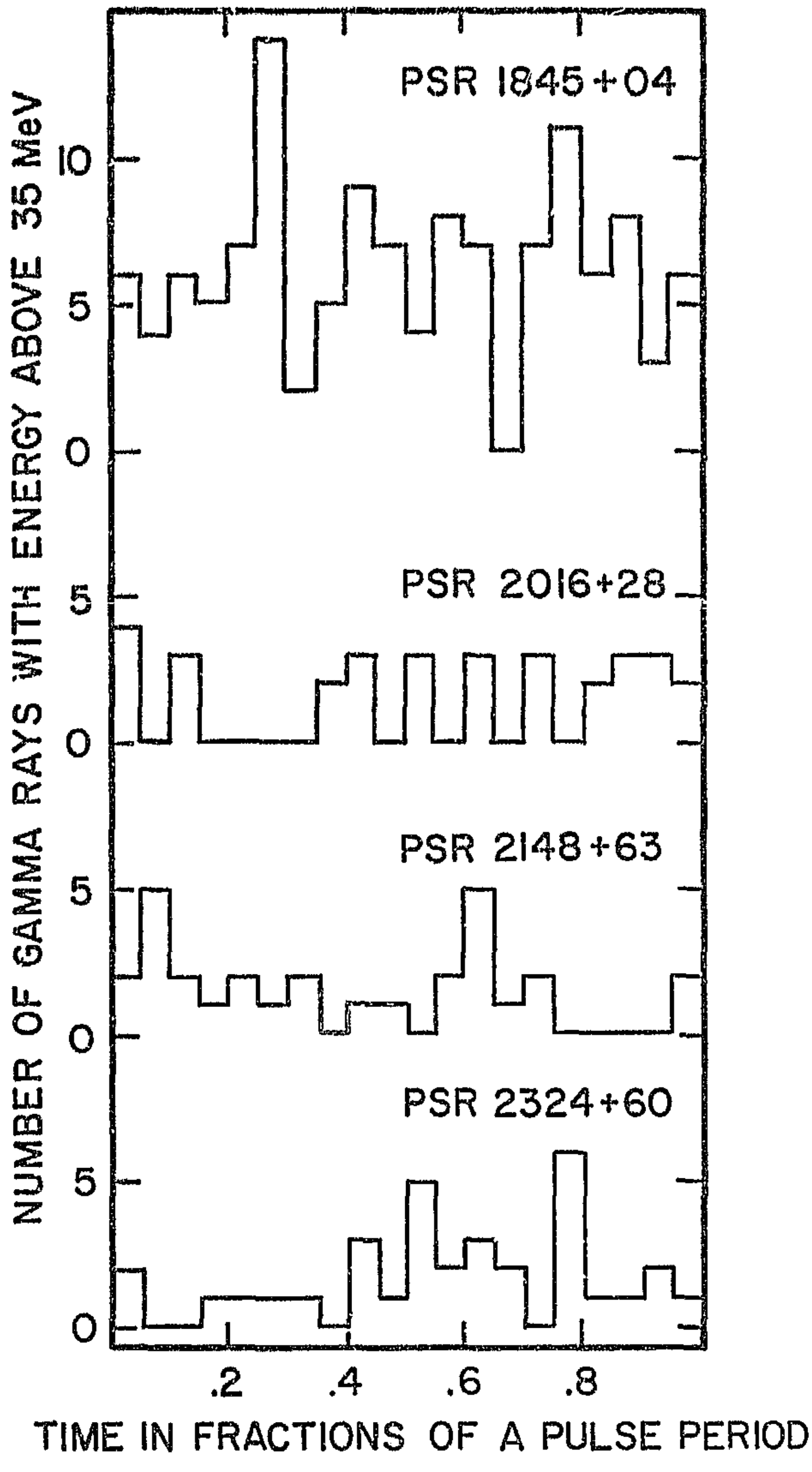
PSR 1818-04
R
NUMBER OF GAMMA RAYS WITH ENERGIES ABOVE 35 MeV
TIME IN FRACTIONS OF A PULSE PERIOD
0
5
10
15
20
25
30
0
.2
.4
.6
.8
1.0

Fig. 1 (a)



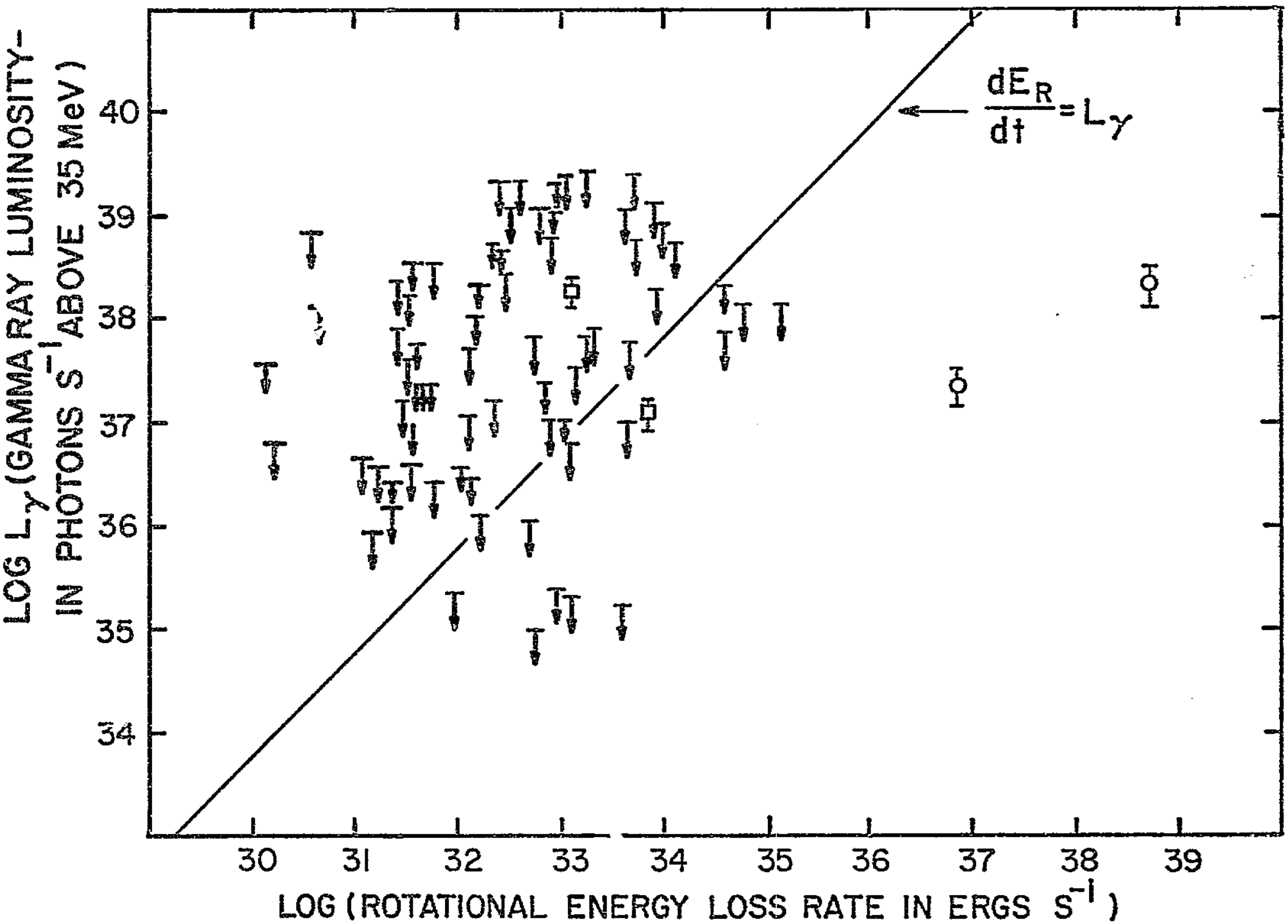
NUMBER OF GAMMA RAYS
WITH ENERGY ABOVE 35 MeV
20
15
10
5
PSR 1747-46
0
.2
.4
.6
.8
1.0
TIME IN FRACTIONS OF A
PULSE PERIOD

Fig. 1 (b)



PSR 1845+04
PSR 2016+28
PSR 2148+63
PSR 2324+60
NUMBER OF GAMMA RAYS WITH ENERGY ABOVE 35 MeV
10
5
0
5
0
5
0
5
0
.2
.4
.6
.8
TIME IN FRACTIONS OF A PULSE PERIOD

Fig. 2



LOG L_γ (GAMMA RAY LUMINOSITY-
IN PHOTONS S^{-1} ABOVE 35 MeV)
40
39
38
37
36
35
34
$\frac{dE_R}{dt} = L_\gamma$
30
31
32
33
34
35
36
37
38
39
LOG (ROTATIONAL ENERGY LOSS RATE IN ERGS S^{-1})

Fig. 3

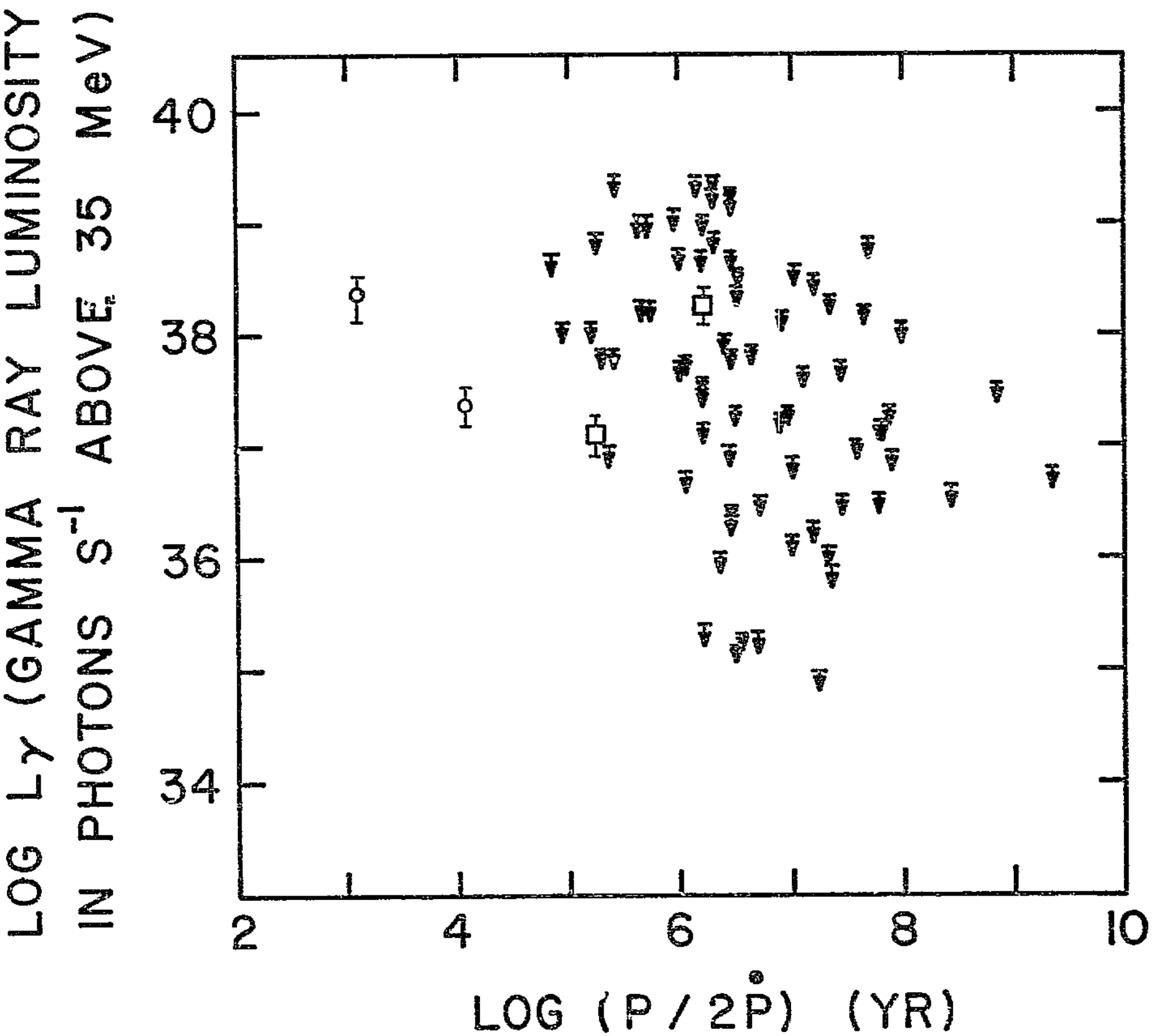

LOG Lγ (GAMMA RAY LUMINOSITY
IN PHOTONS S⁻¹ ABOVE 35 MeV)
40
38
36
34
2
4
6
8
10
LOG (P / 2Ṗ) (YR)

Fig. 4