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HEAO 3 UPPER LIMITS TO PULSED GAMMA-RAY EMISSION FROM PSR 1509−58 AND PSR 0833−45

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ABSTRACT

We report upper limits to the 50 keV–10 MeV gamma-ray pulsations from PSR 1509−58 and PSR 0833−45 (Vela) made with the *HEAO 3* gamma-ray spectrometer. The 2 σ upper limit to the 50–300 keV flux from PSR 1509−58 is 6.9×10^{-6} photons cm^{-2} s^{-1} keV^{-1}. Combined with the best-fit X-ray spectrum, this limit suggests there is a break in the spectrum below $\sim$100 keV. This upper limit is not stringent enough, however, to distinguish between thermal and nonthermal models for the source of the X-ray emission. The 2 σ upper limit to the 3.2–10 MeV flux from PSR 0833−45 is 4.9×10^{-8} photons cm^{-2} s^{-1} keV^{-1}.

Subject headings: gamma rays: bursts — pulsars — stars: individual (PSR 1509−58, PSR 0833−45)

1. INTRODUCTION

We report the analysis of 0.05–10 MeV observations of the pulsars PSR 1509−58 and PSR 0833−45 (Vela) made with the *HEAO 3* gamma-ray spectrometer. PSR 1509−58 has a period of $\sim$150 ms and a braking index of $\sim$2.8 (Manchester, Durdin, & Newton 1985). Since the only other pulsar having a measurable braking index, the Crab pulsar with a braking index of $\sim$2.5, produces a power-law X-ray and gamma-ray spectrum, PSR 1509−58 could also be expected to produce a power-law spectrum. In fact, the observed $\sim$0.2–4.0 keV spectrum of PSR 1509−58 is consistent with a power law (Seward, Harnden, & Elsner 1985; Seward & Harnden 1982), and a simple extrapolation suggests that it should have been detectable by *HEAO 3*. Furthermore, there is an $\sim$1 σ hint that the source was detected above $\sim$100 MeV by *COS B* and *SAS 2* (see Simpson 1980; Swanenburg et al. 1981; Wills et al. 1980; Hermsen 1980). A detectable $\gtrsim$100 MeV gamma-ray flux would suggest that the spectrum is nonthermal and that the X-ray flux might extend to higher energies at levels that would have been detectable by the *HEAO 3* gamma-ray spectrometer.

In contrast to PSR 1509−58, the Vela pulsar is one of the brightest sources observed in the $\sim$1 MeV–1 GeV range (Tümer et al. 1984; Grenier, Hermsen, & Clear 1988). Furthermore, the $\sim$1–300 MeV flux from the Vela pulsar has been found to be variable (Tümer et al. 1984; Grenier et al. 1988; Sacco et al. 1990) with a reported 1–10 MeV high-state flux that might have been detected by *HEAO 3*. The Vela pulsar is also interesting to study because, although it is as easily detected at $\sim$300 MeV as the Crab pulsar (see Simpson 1980; Swanenburg et al. 1981; Wills et al. 1980; and Hermsen 1980), its behavior at other wavelengths is very different (Smith 1986 and references therein). For example, (1) the radio, optical, and gamma-ray emission are all out of phase for the Vela pulsar and in phase for the Crab pulsar; (2) pulsed X-ray emission is observed from the Crab pulsar but is undetected for the Vela pulsar; and (3) the Vela pulsar frequently exhibits macrojumps or glitches (Cordes, Downs, & Krause-Polstorff 1988) which are different in size and frequency from those observed from the Crab pulsar (cf. Manchester 1981).

Specific questions we address here are (1) which model, thermal emission from a hot polar cap (Greenstein & Hartke 1983) or nonthermal emission (e.g., incoherent synchrotron, Pacini 1971), best describes the X-ray emission process from PSR 1509−58; and (2) is the 1–10 MeV flux from the Vela pulsar variable, as suggested by the combined work of Sacco et al. (1990) and Tümer et al. (1984).

2. OBSERVATIONS AND RESULTS

The *HEAO 3* spacecraft was launched 1979 September and the gamma-ray spectrometer remained fully operational through 1980 May. The spacecraft was spin-stabilized with a period of $\sim$20 minutes. The field of view of the *HEAO 3* gamma-ray spectrometer was aligned perpendicular to the spin axis of the satellite, and so performed continuous 360° scans of the sky. Generally, the spin axis of the satellite was pointed at the Sun, but during the fall of 1979 and the spring of 1980 the spin axis was pointed toward a Galactic pole so that the experiment was scanning directly in the Galactic plane.

The *HEAO 3* gamma-ray spectrometer consisted of four cooled high-purity germanium detectors with an energy range of 50 keV to 10 MeV (Mahoney et al. 1980). An active collimator defined a field of view of 30° FWHM near 100 keV, increasing to $\sim$40° near 1 MeV. The main detector events were processed using a 8192 channel analog-to-digital convertor and time tagged to 78.125 μs. The absolute universal time is believed to be accurate to $\sim$100 μs.

The data were initially selected to optimize the signal-to-noise ratio for our analysis and to eliminate bad or questionable data. Further data selections were also used to separately constrain the position of the pulsars in the detectors' field of view. For PSR 1509−58, which has been observed at 4 keV, we judged that a detection would most likely occur near 50 keV and so only data collected when the pulsar was within 20° of the center of the field of view were used. For the Vela pulsar, which has been most consistently detected above 10 MeV, we judged that the 1 to 10 MeV region was most likely to yield a detection. Thus, owing to the increased field of view at higher energies, data collected when the pulsar was within 30° of the

TABLE 1

PULSAR EPHEMERIDES[a]

Pulsar	t_0 (Julian Day)	ν_0 (s^{-1})	$\dot{\nu}_0$ ($\times 10^{-11}$ s^{-2})	$\ddot{\nu}_0$ ($\times 10^{-21}$ s^{-3})
PSR 1509−58.........	2,445,144.7437	6.656424796	−6.82427	1.997[b]
PSR 0833−45.........	2,444,135.2177	11.204496279	−1.56406	0.052

[a] The parameters for PSR 1509−58 are from Manchester et al. (1985) and the parameters for PSR 0833−45 are from Downs & Reichley (1983).

[b] Estimated by searching our data for pulsations; see text for details. The value from Manchester et al. (1985) is $(1.982 \pm 0.009) \times 10^{-21}$ s^{-3}, where the quoted error represents two standard deviations.

center of the field of view were used. These selection criteria resulted in effective observation dates for PSR 1509−58 of 1980 January 12 through April 6, and for the Vela pulsar from 1979 September 24 through 1980 May 31. The latter represents the entire duration of the instrument operation.

After being selected using the above criteria, the data were epoch-folded modulo the pulsar phase at the solar system barycenter. The pulsar phase was calculated using the equation

$$\phi = \phi_0 + \nu_0(t - t_0) + \dot{\nu}_0 \frac{(t - t_0)^2}{2} + \ddot{\nu}_0 \frac{(t - t_0)^3}{6}, \quad (1)$$

where ϕ_0, ν_0, $\dot{\nu}_0$, and $\ddot{\nu}_0$ are the pulsar phase, frequency, first time derivative of the frequency, and second time derivative of the frequency, respectively, at the reference epoch t_0, and t is the (barycenter-corrected) photon arrival time. The values of ν_0, $\dot{\nu}_0$, and $\ddot{\nu}_0$ were obtained from the radio ephemerides of the pulsars (Downs & Reichley 1983; Manchester et al. 1985). The ephemerides used to produce the upper limits to the pulsed gamma-ray emission from these pulsars are given in Table 1.

Estimating a flux from observed counts requires an assumption about the spectral index. Over the range of reasonable spectral indices, 1 to 3, the conversion to flux from observed counts is found to vary by less than 10% (Mahoney, Ling, & Jacobson 1984). Since the upper limits are clearly insensitive to the exact choice of spectral index, for simplicity we have chosen to use a value of 2.0 for both PSR 1509−58 and the Vela pulsar.

2.1. *PSR 1509−58*

Although there were some contemporaneous X-ray observations of PSR 1509−58 (Weisskopf et al. 1983), the resulting X-ray ephemeris was not accurate enough to determine the pulsar phase over the 60 day interval during which our data were accumulated. We therefore used the more accurate radio ephemeris of Manchester et al. (1985) measured between 1982 and 1984. Since the radio ephemeris is consistent with the X-ray ephemeris, and there is no evidence of glitches or other irregularities in the pulsar phase in the radio data, we believe that the radio ephemeris provided the greatest accuracy in the determination of the pulsar phase over the interval during which our data were accumulated.

Since PSR 1509−58 has a significant $\ddot{\nu}$, this term was included in the determination of the pulsar phase (eq. [1]). The accuracy to which $\ddot{\nu}$ was determined, however, was marginal for our purposes. To properly estimate the pulsar phase, we searched for pulsations over a ± 30 σ range of $\ddot{\nu}_0$ values from 1.855×10^{-21} to 2.104×10^{-21} s^{-3} in 50 equally spaced steps. The search was performed using data in the energy range 50–300 keV to be as close as possible in energy to the previously reported X-ray flux. No statistically significant pulsations were found in these data as determined by either a simple χ^2 test for a constant flux versus pulse phase or by fitting the data with a cosine function to approximate the X-ray pulse profile. The largest excess was found for $\ddot{\nu}_0 = 1.997 \times 10^{-21}$ s^{-3}, within ~ 3 σ of the value reported by Manchester et al. (1985). Using this value of $\ddot{\nu}_0$, we epoch-folded the data once more using the individual 8192 detector energy channels.

The resulting epoch-folded spectra, covering the energy range 0.05–10 MeV, were then accumulated into five broad energy bands to increase the statistics and to produce a compact set of upper limits on the pulsed emission. To determine the limits to the pulsed emission, the epoch-folded data were fitted using a cosine function to approximate the observed X-ray pulse profile. The fit was performed for all energy bands simultaneously and with the requirement that the phase be the same in all energy bins. The actual phase was a free parameter in the fit. The 2 σ upper limits based on these fits, calculated by adding the fitted 1 σ error to the fitted amplitude, are given in Table 2 and are plotted in Figure 1. Since these upper limits are somewhat subjective, we have also calculated the upper limits using equation (2) (discussed below) with a value of $\beta = 0.5$. The pulsar phase is not known, however, and so the latter upper limits are also somewhat subjective, though on the average they are close to those derived using the fitted intensities, as can be seen in Table 2.

For completeness, we also searched for pulsations over the 1–10 MeV range using both the ephemeris from the radio observations (Manchester et al. 1985) and the ephemeris from the X-ray observations (Weisskopf et al. 1983). No statistically significant emission was detected using either of these ephemerides.

2.2. *Vela Pulsar*

Nearly continuous radio observations were performed over the interval during which the *HEAO 3* observations of the Vela

TABLE 2

LIMITS TO PULSED GAMMA-RAY EMISSION FROM PSR 1509−58

ENERGY RANGE (MeV)	2 σ UPPER LIMITS (10^{-6} photons cm^{-2} s^{-1} keV^{-1}) Cosine Fit[a]	Eq. (2)[b]
0.05–0.3....................	6.9	2.0
0.3–0.5....................	1.9	1.8
0.5–1.0....................	1.6	1.4
1.0–5.0....................	1.7	0.4
5.0–10.0....................	0.3	0.7

[a] Based on fitting the data with a cosine function to approximate the observed X-ray pulse profile; see text for details.

[b] These upper limits were calculated using eq. (2) of the text with a value of $\beta = 0.5$. The use of this equation is not strictly valid for these data, however; see text for details.

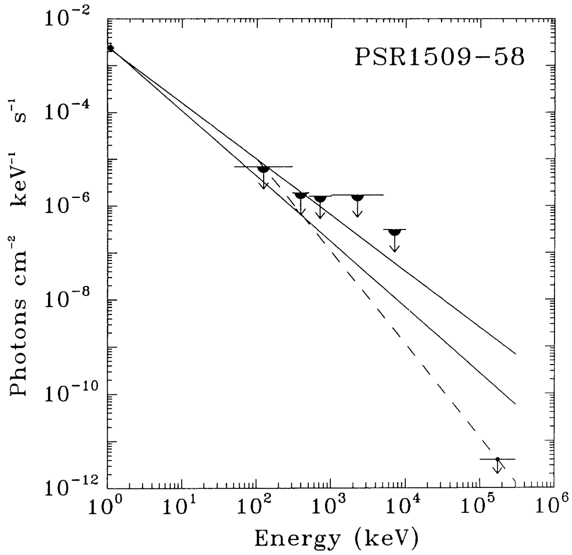

FIG. 1.—X-ray and gamma-ray measurements of PSR 1509−58. The 2 σ upper limits from the current work are represented by the filled half circles. The diamond in the upper left is the measured pulsed X-ray flux (Seward et al. 1985). The 2 σ upper limit in the lower right is based on the quoted sensitivity of *COS B* (Hermsen 1980; Simpson 1980; Swanenburg et al. 1981). The solid lines represent the power laws for the best-fit pulsed X-ray flux and the steepest model (2 σ) consistent with the X-ray upper limits. The dashed line was generated by taking the 100 keV point from the best-fit X-ray model and connecting it to the sensitivity/upper limit point at 300 MeV.

pulsar were performed. This was important since the Vela pulsar exhibits significant timing glitches. No timing glitches were observed during our observations, or for over 400 days prior to the beginning of our observations (see Grenier et al. 1988). We used the ephemeris data of Downs & Reichley (1983) to determine the pulsar phase as a function of time. We then epoch-folded the *HEAO 3* data using the derived phase.

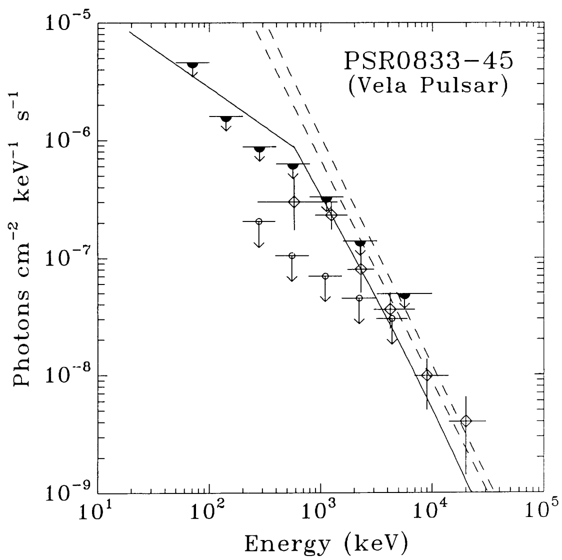

FIG. 2.—Gamma-ray measurements of PSR 0833−45. The 2 σ upper limits from the current work are represented by the filled half circles. The limits from Sacco et al. (1990) are represented by the open circles. The open diamonds are from Tümer et al. (1984). The dashed lines are the extrapolated spectra from the data of Lichti et al. (1980) with spectra indices of 1.9 and 2.0, coupled with the best-fit intensity and the 1 σ sensitivity normalization, respectively. The theoretical spectrum (*solid curve*) is based on the model of Cheng et al. (1986), with $\omega_{min} = 576$ keV.

As was the case for PSR 1509−58, we detected no statistically significant pulsations. In the case of the Vela pulsar, however, the pulse shape and phase are known (see Tümer et al. 1984; Grenier et al. 1988). With this information, the upper limits were determined using the equation

$$\sigma = \frac{f^{1/2} C_t^{1/2}}{A T \Delta E}, \quad (2)$$

where

$$f = \frac{\beta}{1-\beta}$$

and β represents the pulsar duty cycle, which we took to be 0.12 from Sacco et al. (1990) and Tümer et al. (1984), C_t represents the total number of counts observed in all phase bins, A is the net effective area, T is the source exposure time, and ΔE is the energy range over which the data were accumulated. Equation (2) can be derived exactly assuming a square-wave pulse profile, that the pulse phase is known, and neglecting β^2 terms. The upper limits for the Vela pulsar using equation (2) are given in Table 3 and are plotted in Figure 2. These upper limits are ~10% higher than would be estimated if equation (3) of Sacco et al. (1990) were used. The form of the latter formula is similar to equation (2) above with C_t replaced by C_{np}, the total number of counts in the nonpulsed phase bins. Note that, based on the Tümer et al. (1984) work, the value of β may be as low as ~0.06. This would decrease our upper limits, and those of Sacco et al. (1990), by a factor of ~1.4.

3. DISCUSSION

As noted in Taylor & Stinebring (1986) and Michel (1982), there is no simple picture that describes how pulsars shine. The problem is complex and it is likely that several processes and regions are involved in producing the observed emission from a single pulsar (cf. Smith 1986; Cheng, Ho, & Ruderman 1986). Since there is no *a priori* reason why we should expect different pulsars to have the same regions radiating in the same proportions, intercomparisons and searches for patterns may not lead to fruitful results. This is the best we can do, however, until we have a better understanding of pulsar emission.

As noted above, PSR 1509−58 is both a radio and X-ray pulsar. The radio observations show that PSR 1509−58 has a measurable breaking index similar to the Crab pulsar, and the X-ray observations are consistent with a power-law spectrum. As shown in Figure 1, if the observed X-ray power law from PSR 1509−58, having a best fit spectral index of 1.2 (Seward et

TABLE 3

LIMITS TO PULSED GAMMA-RAY EMISSION FROM THE VELA PULSAR

Energy Range (MeV)	2 σ Upper Limits[a] (10^{-6} photons cm^{-2} s^{-1} keV^{-1})
0.05–0.1	4.6
0.1–0.2	1.6
0.2–0.4	0.88
0.4–0.8	0.63
0.8–1.6	0.33
1.6–3.2	0.14
3.2–10.0	0.049

[a] The upper limits were calculated using eq. (2) of the text with a value of $\beta = 0.12$.

al. 1985), were extrapolated to higher energies the expected gamma-ray flux would be inconsistent with both our upper limits and the upper limit to the ~300 MeV flux reported from *SAS 2* and *COS B* (see Simpson 1980; Swanenburg et al. 1981; Wills et al. 1980; and Hermsen 1980). Unless the emission is variable, a break in the spectrum is required. Our data (Table 2 and Fig. 1), combined with the best-fit X-ray spectrum, indicate that the break occurs below ~100 keV, and that the size of the break could be in the range of ~0.5–1.0. If, indeed, the PSR 1509−58 spectrum does have a break of between 0.5 and 1.0 near 50 keV, then its spectrum would be similar to that of the Crab pulsar (Knight 1983). One interpretation of the data, then, would be that the emission from PSR 1509−58 is simply a scaled-down version of the Crab pulsar (Pacini & Salvati 1987). There are, however, significant differences in the X-ray pulse profiles for these two pulsars. The X-ray pulse profile of PSR 1509−58 consists of a single broad pulse with a duty cycle of ~50%, while the X-ray pulse profile of the Crab pulsar consists of two narrow pulses separated by ~0.4 of the pulse period and having a combined duty cycle of ~15% (Seward et al. 1985; Smith 1986).

An alternative explanation assumes that high-energy photons are produced in the PSR 1509−58 system, but that absorption by a strong magnetic field prevents their escape. The inferred magnetic field strength of PSR 1509−58 is $\sim 10^{13}$ gauss (Pacini & Salvati 1987), which is strong enough to absorb photons $\gtrsim 1$ MeV (Daugherty & Harding 1983). These high-energy photons could also be absorbed by the polar cap, resulting in a hot polar cap which could produce significant quantities of X-rays (Greenstein & Hartke 1983). As noted by Helfand (1983), however, the model of Greenstein & Hartke requires a large (and therefore unlikely) temperature difference between the magnetic pole and equatorial regions of the neutron star. In the event that the hot polar cap model is correct, our data suggest that measurements in the 4–100 keV range should reveal the characteristic steep fall of a thermal spectrum. In conclusion, while the spectrum of PSR 1509−58 probably steepens somewhere below ~100 keV, whether the X-ray emission has a thermal or nonthermal origin remains an open question.

The Vela pulsar was observed by *COS B* to be in a high state during observations made in 1976, 1977, and 1981 (Grenier et al. 1988), consistent with the assumption that it was in a high state when observed at lower gamma-ray energies by Tümer et al. (1984) during a balloon flight in 1981 November. A large glitch was observed in 1981 October. The next previously detected glitch was in 1978 July. Whether or not the Vela pulsar was in a high state at 300 MeV during our 1979–1980 observations is not known, but Grenier et al. (1988) report a low flux in 1979 November. The pulsar certainly could have been in a low state, which is consistent with our data and with the hypothesis that high states in the ~1–10 MeV energy range only follow glitches. Sacco et al. (1990) failed to detect the pulsar at low levels, however, and our upper limits are not sensitive enough to have detected emission at the level reported by Tümer et al. (1984). Therefore, confirmation of the Tümer et al. (1984) result is required before one can safely conclude that the Vela pulsar is variable in the 1–10 MeV energy range.

We concur with the conclusions of Grenier et al. (1988) and Smith (1986) that the Vela pulsar probably has several emission regions. Assuming the validity of the Sacco et al. (1990) and Tümer et al. (1984) results, we suggest that the region responsible for the bulk of the 1–300 MeV gamma-ray emission is unstable, causing the observed variability. Furthermore, if the pulsed gamma-ray spectrum is extrapolated to X-ray energies, it is found to be a factor of ~4 above the observed upper limits to the pulsed X-ray flux (Lichti et al. 1980). This dearth of pulsed X-ray emission from the Velar pulsar could be related to the instability of the region that is responsible for the ~1–300 MeV emission. In contrast, the Crab pulsar X-ray and gamma-ray flux seem quite stable (Mahoney et al. 1984; Knight et al. 1982), and the (presumably) nonthermal pulsed X-ray emission from the Crab pulsar could be related to the stability of its 1–300 MeV emitting region. This hypothesis suggests that monitoring the Vela pulsar in the X-ray region may yet lead to a detection, and that it is important to have simultaneous monitoring of the 1–300 MeV flux. NASA's *Gamma Ray Observatory* will provide the latter capability.

4. SUMMARY AND CONCLUSIONS

We have presented upper limits to pulsed gamma-ray emission from the pulsars PSR 1509−58 and PSR 0833−45. In the former case our limits, combined with previous X-ray detections, suggest that there is a break in the spectrum below ~100 keV. We cannot, however, distinguish between the thermal and nonthermal hypotheses for the origin of the X-ray emission. Based on the current data, both are still equally likely. The upper limits to the pulsed emission from the Vela pulsar are not sensitive enough to have detected emission at the level reported by Tümer et al. (1984). Taking the results of Sacco et al. (1990) and Tümer et al. (1984) at face value, we suggest that the instability of the region on the Vela pulsar responsible for the 1–300 MeV emission may be related to the lack of detectable pulsed X-ray emission from this source.

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