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X-RAY OBSERVATIONS
OF THE VELA PULSAR:
STATISTICS AND SPECTRUM

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X-ray Observations of the Vela Pulsar: Statistics and Spectrum

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Abstract

The Vela pulsar (3U0833-45) was observed in the range 2-60 keV by the GSFC proportional counter experiment onboard OSO-8 with temporal resolution sufficient to make possible a sensitive search for pulsed X-rays at the radio pulsar period. A statistical analysis yielded 8 per cent as the 3σ upper limit on the pulsed fraction. The energy spectrum is fit well by a structureless power law with number index 2.21±0.2 and absorption by a hydrogen column density of \( N_H = (2.9±2.0) \times 10^{22} \text{ cm}^{-2} \).

I. Introduction

The Vela pulsar (PSR 0833-45) has been identified as a high energy photon source over a wide range of x-ray energies (Kellogg et al., 1973, Culhane et al., 1974, Harnden and Gorenstein, 1973, Harnden et al., 1972) and gamma ray energies (Albats et al., 1974, Thompson et al., 1975). The first two of these references cited insufficient temporal resolution to search for pulsed emission at the radio pulsar period (~89 ms). The others reported pulsed emission at or near this period, although Moore et al (1974) and Ricker et al (1973) were unable to detect such pulsations. Between 2-10 keV Rappaport et al (1974) report an upper

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limit to a pulsed component at $1/3$ the intensity of 0833-45. The fact that PSR 0833-45 is the third fastest known pulsar suggests that it, like the Crab pulsar, is a likely candidate for the emission of pulsed x-rays (cf. Pacini, 1971). In this Letter we report an upper limit to X-ray pulsation and the energy spectrum in an observation of the Vela pulsar with a proportional counter onboard OSO-8.

II. Experiment

This observation was performed with a Xenon-filled gas proportional counter mounted on the spinning portion of the satellite, in alignment with the positive spacecraft spin axis. The detector has a 5 degree FWHM circular field of view and net area of $237 \text{ cm}^2$. It has been described previously (Pravdo et al, 1976) in more detail, and is one of the three counters comprising the GSFC Cosmic X-ray Spectroscopy experiment (CXS).

Vela was observed between November 25-27, 1975. For one twenty minute period we were able to utilize essentially the entire spacecraft telemetry in order to obtain 1.25 msec temporal resolution for pulse-height-analyzed events. This "dwell mode" experiment was centered at 18:47, November 25 UT.

III. Statistics

The 5 degree circular field of view of the CXS makes it impossible to separate 0833-45 from other nearby areas of enhanced $>2$ keV emission. Although the Vela supernova remnant as a whole is not a source at this energy, Kellogg et al (1973) suggest two emitting regions, Vela A and B, in addition to the pulsar. Also 0821-42 (Pup A) contributes to the observed flux, but since it was isolated previously in the detector,
its contribution can be subtracted from the total signal. Other weak sources may be in this area (Forman et al. 1976). The observed signal to background (mainly the diffuse X-ray background) ratio is 0.60, with a signal intensity (2-6 keV) of $2.84 \times 10^{-10}$ erg cm$^{-2}$ sec$^{-1}$. The a priori estimate of the fractional contribution to this signal due to 3U0833-45 from its intensity given in the 3U catalogue (Giacconi et al. 1974) is 0.55. From spectral considerations discussed later, we believe this is a lower limit to the source strength.

The data obtained during the dwell mode observation have been folded over a range of periods including that of the radio pulsar. PSR 0833-45 exhibited a discontinuity in its spin down rate near the beginning of October, 1975, and the latest determinations of the period and time rate of charge of period are used (Manchester et al. 1976). If the X-ray pulse width is as large as 4 ms, the data can not be used to discriminate between pulse periods deviating from the radio period by as much as 0.3 $\mu$s. The 1.25 ms resolution allows us to bin the folded data into as many as 70 independent bins. When the folded data are $\chi^2$- tested against a model in which the number of counts in each bin is Poisson-distributed around the average value, no significant deviations from an acceptable value of $\chi^2$ are found.

This result can be interpreted in terms of an upper limit to the pulsed fraction from the source in the following manner. Boldt et al. (1970) have given an expression for the average deviation of $\chi^2$ from its expectation value when the test described above is performed, and when the data contain a pulsed component. This deviation is given by:
where \( f \) is the pulsed fraction, \( \beta \) is the pulse duty cycle, and \( N_T \) is the total number of counts. If the number of temporal bins \( K \gg 40 \), and the data are truly nonpulsed, the expectation value for \( \chi^2 \) is \((K-1)\) with variance \((2K-1)\). The expression for \( \Delta \chi^2 \) in equation (1) should then be added to \((K-1)\) to obtain the expected value of \( \chi^2 \) if the data are pulsed. However, if no significant deviation of \( \chi^2 \) from \((K-1)\) is observed, it is not correct to determine the value of \( f \) which would have produced a 3\( \sigma \) change in \( \chi^2 \), and identify this with the 3\( \sigma \) upper limit to the pulsed fraction. The variance of the relevant distribution (whose expected value is \((K-1) + \Delta \chi^2\)) has been calculated and is

\[
\sigma_f^2 = (2K-1) + 4 \Delta \chi^2 \left(1+\varepsilon\right)
\]

where \( \varepsilon = \frac{f}{1+f} \left(\frac{1-2\beta}{\beta}\right) \). It is clear that since \( \sigma_f^2 \) is larger than the variance for zero pulsed fraction, the statistical significance of any upper limit to the pulsed fraction is reduced. Figure 1 shows pulse fraction upper limits at the 3\( \sigma \) confidence level versus duty cycle for energies between 2-20 keV. The duty cycle interval displayed extends from the radio duty cycle \( 0.04 \) (Downs et al. 1973) to the gamma ray duty cycle \( \sim 0.2 \) (Thompson et al. 1975). Presumably, the x-ray duty cycle falls between these two values.

IV. Spectrum

The spectrum shown in Figure 2 is obtained from data taken at arbitrary times in the 3-day exposure. It represents approximately
1200 seconds effective time on source. The method of spectral analysis has been described in an earlier work (Pravdo et al. 1976). Above 20 keV the source signal falls into the background, but no cutoff is observed. The spectrum is fit well by a power law of number index $2.21 \pm 0.2$ with interstellar absorption (Brown and Gould, 1970) by a hydrogen column density of $N_H = (2.9 \pm 2.0) \times 10^{22}$ cm$^{-2}$. This structureless power-law spectrum is similar to that observed for the Crab Nebula (i.e. comparable spectral index at those energies). There is an indication of spectral hardening for energies above 10 keV, although these high energy points are statistically consistent with the single power law.

An analytical approximation to a thermal spectrum with gaunt factor gives a less acceptable fit (5% probability that this model would yield the data). The best fit thermal temperature is 11 keV with negligible absorption.

V. Discussion

In general, the distribution of $\chi^2$ values obtained when data are tested against the true model is nearly Gaussian if the number of degrees of freedom (the number of temporal bins in this case) is $> 40$. However, there is no reason to believe a priori that the same is true about the distribution of $\chi^2$ values described in Section III. Here, data which are assumed to have a finite pulsed fraction are tested against a model with zero pulsed fraction. Computer simulated experiments were performed to study this "pseudo" $\chi^2$ distribution more fully. The distribution was found to be approximately Gaussian, with measured mean value and variance very close to those calculated in Section III. This is not surprising since $\chi^2$ is still measuring Poisson deviations from a mean. In particular, when the simulated data contained a pulsed
fraction equal to the $3\sigma$ upper limits displayed in Figure 1, less than 1% of the trials resulted in a $\chi^2$ value equal to or less than the value of $\chi^2$ observed in the Vela data. Therefore these $3\sigma$ upper limits can be interpreted in the usual manner. These simulations also showed that the lower "$3\sigma$" upper limits obtained if the variance of the normal $\chi^2$ distribution is used, are incorrect.

This observation lowers to 8% the upper limit to pulsed 2-10 keV x-ray emission with the radio duty cycle. If the X-ray duty cycle is as large as the gamma ray, the upper limit is somewhat larger. The solid lines in Figure 1 demonstrate this for two energy ranges.

The spectrum shown in Figure 2 is remarkably similar in form to, although of a higher intensity than, that obtained by Kellogg et al (1973) with a detector having a much smaller field of view. The absorption measured here is larger than that characteristic of the Vela region in soft x-rays (Seward et al 1971, Gorenstein et al 1974) but consistent with the determination of Culhane et al (1974). This spectral similarity could indicate that essentially all the observed signal originates at 3U0833-45 but at a level which may be as high as twice the 3U value. The possibilities of source intensity variability and absorption intrinsic to the source have been discussed in the preceding reference. The dashed lines in Figure 1 shows the resultant pulsed fraction if the total CXS flux is from the pulsar.

Regardless of the fraction of the signal coming from the pulsar, the pulsed flux upper limit is the same. From 2-10 keV for the two extremes of duty cycle, this pulsed flux upper limit is $2.0 \times 10^{-11}$ erg
cm$^{-2}$ s$^{-1}$ ($\theta = 0.04$) and $4.8 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ ($\theta = 0.2$). From 10-20 keV these limits are $2.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and $6.3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

This result is inconsistent with some models of pulsed emission from pulsars (see Rappaport et al. 1974 for discussion) but is still a factor of 2-10 above the predicted pulsed flux in Thompson (1975). In this model for pulsed gamma ray emission the accelerated charges responsible for the radio pulse give rise to gamma rays when forced to leave magnetic field lines which are unable to corotate with the neutron star at the speed of light radius. The pulsed component has a flatter spectrum than the total pulsar spectrum. This last statement is supported by the spectrum measured here, as the extrapolation to gamma ray energies of the flattest spectrum consistent with our data falls a factor of 3 below the intensity reported in Thompson et al. (1975).

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REFERENCES


FIGURE CAPTIONS

Figure 1. Pulsed fraction upper limits (3σ) for the Vela pulsar versus pulse duty cycle for the energy range 2–10 keV and 10–20 keV. The solid and dashed lines refer respectively to the pulsar intensity at the 3U catalogue level and at the total OSO-8 level.

Figure 2. The incident X-ray Spectrum from the Vela pulsar. See text for discussion of other possible contributions to this flux.
PULSED FRACTION UPPER LIMITS

(3σ) VS. DUTY CYCLE

PULSED FRACTION

2-10 keV

10-20 keV

PULSE DUTY CYCLE