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X-ray Spectra of the Crab Pulsar and Nebula

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ABSTRACT

We have measured the spectrum of the Crab pulsar from 2-50 keV as a function of pulse phase and find a progressive hardening and subsequent softening of the spectrum across the pulse. The fraction of the pulsed flux which exhibits spectral variability is ~ 0.14 and is concentrated solely in the region between the two peaks. We suggest a model in which the pulsed X-ray emission from the Crab pulsar consists of two components: one which has no spectral dependence with pulse phase and which is physically related to the double-peaked gamma ray pulse and, perhaps, the radio and optical pulses; and another component which exhibits spectral variability with pulse phase , is confined to and comprises the interpeak emission, and which is only seen at X-ray energies. These results and spectral studies of the binary X-ray pulsar Hercules X-1 suggest a phenomonological similarity. If the spectrally varying component in the Crab pulsar arises from a hot, magnetised plasma near the neutron star surface then higher energy spectral observations of this particular phase region might reveal spectral features which can be used to determine the surface field strength. On another topic, we present the spectrum of the Crab Nebula and upper limits to several emission lines therein.

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I. Introduction

The discovery of pulsars (Hewish et al. 1968) and the identification of the Crab pulsar (Staelin and Reifenstein 1968) were experimental evidence for the existence of neutron stars (Baade and Zwicky 1934). The pulses are formed by periodic changes in the angle between the line of sight and beamed radiation sources, which are coupled with the rotating neutron star (Gold 1968). Both the general idea of magnetic flux conservation during stellar collapse and an interpretation of the energy source as magnetic dipole radiation (e.g. Rose 1974) suggest that the surface mangetic fields are superstrong $B \gtrsim 10^{12}$ gauss. This interpretation is supported by observations of pulsar spin downs (e.g. Davies, Hunt, and Smith 1969), a natural consequence of such radiation with a rotational energy source. There are more than one hundred known radio pulsars (e.g. Groth 1975a), but the Crab is the only known isolated X-ray pulsar.

X-ray pulsars in binary systems are a second class of objects identified with neutron stars (e.g. Tannanbaum and Tucker 1974). One major difference between the two classes is that binary pulsars, with mass accretion as the energy source, are spinning up. Radio pulses are not expected to be observable in accreting binaries because of the large optical depth of ambient material to free-free absorption at radio frequencies (Illarionov and Syunyaev 1975). Additional evidence for strong magnetic fields in binary X-ray pulsars comes from analysis of the period variations (e.g. Lamb 1977).

For the binary pulsar, Hercules X-1, detailed studies of the X-ray spectrum also suggest the presence of a superstrong surface magnetic field. Detection of a narrow cyclotron resonance line near ~ 60 keV

(Trumper et al. 1978) could be a direct determination of the magnetic field strength. Other observations (Pravdo, Bussard, and White 1979, Gruber et al. 1980) have confirmed the existence of an additional emission component at this energy, but it is not certain that a narrow line is present. Spectral variations with pulse phase from 2-60 keV in Hercules X-1 (Pravdo et al. 1978, Gruber et al. 1980) and other binary pulsars (e.g. Rose et al. 1979) may be due to energy-dependent anisotropic Compton scattering in a strong magnetic field (Pravdo and Bussard 1980).

The X-ray spectrum of the Crab pulsar has also shown variations with pulse phase (Toor and Seward 1977). In this paper we present a detailed analysis of the Crab pulsar and nebular spectra.

II. Observations and Analysis

The Crab was observed with OSO-8 on March 17-18, 1978. A gross observing time of ~ 1 day was equally divided between a xenon proportional counter (A detector; 2-50 keV) and an argon proportional counter (B detector 1.5-20 keV) with 5° and 3° circular fields of view and 263 cm^2 and 37 cm^2 effective areas respectively. Serlemitsos et al. (1976a) provide a full experiment description. During this observation the satellite was commanded into the "dwell mode", an extraordinary operating mode in which all spacecraft telemetry (including seven experiments) was temporarily assigned to one detector. This enabled us to obtain 1.25 msec resolution for pulse-height-analyzed (PHA) counts in 64 channels.

The barycentric pulsar period was determined to be 33.2138715 ± 0.0000010 msec (estimated 1σ error), assuming a period derivative of $\dot{P} = 4.2 \times 10^{-13}$ sec sec^{-1} (Gullahorn et al. 1977). Figure 1 shows the folded light curve of the A detector data for the best estimate of the period. This light curve is similar to those obtained by other X-ray observers. The width of the primary pulse, FWHM = 2.7 msec, is intermediate between the smaller width measured at lower mean energy (Kestenbaum et al. 1977) and the larger width at higher mean energy (Zimmermann 1974).

The folded PHA data were divided into several phase intervals. Data from the longer interval between the pulses were taken to represent the phase-independent Crab nebula spectrum which was used as background for the pulsar spectral analysis. This procedure assumes that the pulsar component in the nebular phase region is negligible; Wolff et al. (1975) measure an upper limit of ~ 2% for the pulsar contribution. There were no apparent variations of the low energy photoelectric absorption (e.g. Fireman 1974) with pulse phase and it was held fixed at $N_H = 2 \times 10^{21}$ H-atoms cm^{-2} (Hill et al. 1974). Spectral parameters and confidence ranges, including upper limits to line emission, were determined using the statistical procedure described by Avni (1976). The method of spectral analysis was described by Serlemitsos et al. (1976b).

III. Pulsar Spectra and Superstrong Magnetic Fields

a) Results

In Figure 1 the slope of the Crab spectrum is plotted *versus* pulse phase. There is good agreement between these results and those of Toor and Seward (1977). These new results show an evolution of the spectrum from a slope near the nebular value, to a minimum slope of ~1.4 at our defined phase zero, and finally back toward the nebular value. Figure 1 also shows the data from Her X-1 in the same representation (Pravdo et al. 1978). The spectral hardening occurs near the interpeak intensity minimum in the Crab and near the intensity maximum in Her X-1. Only ~0.14 of the pulsed Crab emission exhibits spectral variability. As discussed below, the remainder of the pulsed emission (i.e., away from the interpeak) may be separate component which extends to the γ-ray regime with a single, continuous power law. If we consider only the spectrally varying component, then phase zero in the Crab is also near the maximum of that emission.

Figure 2 shows the phase-averaged pulsar spectrum. Although this spectrum contains constituent spectra with varying slope, it is well described by a single power law with number index, $\alpha = 1.73 \pm 0.06$. and normalization 0.35 ± 0.04 photons cm^{-2} sec^{-1} keV^{-1}.

b) The Crab Broadband Spectrum and Pulse

The γ-ray spectrum of the Crab pulsar can be described as a single power law continuum, $\alpha = 2.1$, extending from ~ 100 keV to $>10^6$ keV with no apparent pulse phase variability (Bennett et al. 1977 and references therein). An extrapolation of the γ-ray spectrum is superposed on Figure 2. The intensity of the phase-averaged X-ray spectrum is in reasonable agreement with the γ-ray extrapolation (Figure 2), although the spectral index, $\alpha = 1.7$, is significantly different. However, if the X-ray interpeak emission is subtracted from the total X-ray emission, then while the total intensity of the residual emission is still ~0.86 of its former value, the averaged spectral slope is now $\alpha \sim 2.0$, as can be seen from Figure 1. Thus, the phase-averaged intensity and slope of this residual component appear to be a single continuum from the X-rays to the γ-rays.

The high energy γ-ray pulse ($E > 50$ MeV) has two peaks which are roughly aligned with the X-ray peaks, but does not exhibit interpeak emission (Bennett _et al_. 1977). At 30 keV $< E <$ 200 keV, the pulse still contains interpeak emission but at no higher level than that seen in our energy range (Zimmermann 1974). This indicates that the interpeak spectra must turn over at $E <$ 200 keV. Otherwise, because of their flatter spectra, the interpeak emission would be relatively larger near 200 keV and dominant near 50 MeV.

The optical and X-ray pulses also show a great similarity in shape (Kestenbaum _et al_. 1976). However, as with the high energy gamma ray pulse, there is a much smaller percentage of interpeak optical emission (see also Groth 1975b), than there is of X-ray emission. The high frequency radio pulse apparently exhibits no interpeak emission (e.g., Manchester and Taylor 1977).

c) Pulse Phase Spectral Variability and Superstrong Magnetic Fields

We suggest the possibility that the interpeak component of the X-ray emission arises near the surface of the Crab pulsar. The interpeak X-ray spectrum in the Crab pulsar is now seen to vary in a similar manner and in the same energy range as that of some binary X-ray pulsars. This could be due to the effects of energy-dependent anisotropic Compton scattering in a superstrong magnetic field (Canuto, Lodenquai, and Ruderman 1971) as has been suggested for binary X-ray pulsars (Pravdo and Bussard 1980). Since X-rays from a neutron star surface are likely to have a significant linear polarization (e.g., Chanan, Novick, and Silver 1979), it is also suggestive that the interpeak region in Her X-1 (Silver et al. 1979) and the leading edge of the secondary pulse in the Crab (Silver et al. 1978) show the best evidence for linear polarization. Observations of the interpeak spectra above 40 keV could reveal spectral features and lead to a more direct determination of the surface field strength.

The double-peaked emission, perhaps including the radio and optical emission, and which extends from X-ray to γ-ray energies with a single spectral index could arise from a separate emission region (e.g., the velocity-of-light radius - Pacini 1971) and be only indirectly related to the interpeak X-ray surface emission since the superstrong magnetic field creates a preferred direction in both regions.

IV. Crab Nebula Spectrum

The nebula spectrum is obtained from the phase region indicated in Figure 1. There were no apparent spectral changes with phase over this region. Figure 3 shows the count and photon spectra upon which is superposed the hard X-ray result of Strickman, Johnson, and Kurfess (1979). There is close agreement in the overlapping energy range. Our spectral fit indicates a normalization of 6.87 ± 0.15 photons cm^{-2} sec^{-1} keV^{-1} with $\alpha = 2.10 \pm 0.01$, while that measured by Strickman et al. (1979) is somewhat flatter at $\alpha = 1.99$ (+0.06, - 0.07).

We found no evidence for features in the nebula spectrum. Table 1 lists equivalent width and line photon upper limits (3σ) for several iron lines: a 6.4 keV fluorescence line, a 6.7 keV thermal emission line, and a broad (FWHM ~ 2 keV) 6.7 keV charge exchange line. Similar limits are obtained for nearby line energies (e.g. redshifted lines). The lack of a fluorescence line reflects the absence of significant column density of cool material. This is however less restrictive than the limits placed by measurements of photoelectric absorption.

The limit to narrow 6.7 keV line emission restricts the intensity of a thin thermal bremsstrahlung component in the temperature range 1 keV < kT < 20 keV (e.g. Raymond and Smith 1977). For example, if kT = 5 keV with normal elemental abundances, then the bremsstrahlung intensity is $\lesssim 5 \times 10^{-10}$ erg cm^{-2} sec^{-1} between 4-50 keV, or less than ~ 2% of the total nebula luminosity. Note that the higher helium abundance seen in the Crab (e.g. Woltjer 1958, Davidson 1978) could increase this limit by ~ 50% since the expected iron line equivalent width is correspondingly smaller in such a gas. This upper limit is a factor of ~ 16 less than the intensity derived for a possible soft X-ray (kT ~ 0.5 keV) thermal component in the Crab (Toor, Palmieri, and Seward 1976). Thermal emission from the Crab would, therefore, be significantly different from that of remnants without pulsars but with similar ages. In both Cas A and Tycho, for example, the luminosity in a soft component, kT < 1 keV, is comparable to that in a hotter component, kT > 5 keV (e.g., Davison, Culhane, and Mitchell 1976).

Finally, the absence of a charge exchange line in the nebula places upper limits to γ-ray line emission due to energetic particles in many models (Bussard, Ramaty, and Omidvar 1978). For example, our value, $< 9.1 \times 10^{-3}$ photons cm^{-2} sec^{-1}, implies an upper limit of $< 10^{-5}$ photons cm^{-2} sec^{-1} in the narrow 4.4 MeV carbon line.

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TABLE 1

Iron Line Upper Limits (3σ)* in the Crab Nebula

	Equivalent Width (eV)	Line Photons (10^{-3} photons cm^{-2} sec^{-1})
6.4 keV line (narrow)	92	7.0
6.7 keV line (narrow)	70	6.1
6.7 keV line (broad)	104	9.1

*An acceptable fit was obtained after an empirical introduction of 2% systematic errors in each channel. This did not affect the best-fit values but did allow us to use the statistical procedure of Avni (1976) to obtain the upper limits.

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FIGURE CAPTIONS

Figure 1 - Pulse light curves and the variations of the spectral number index versus phase for the Crab pulsar and Hercules X-1.

Figure 2 - The phase-averaged Crab pulsar spectrum obtained with OSO-8. The extrapolation of the γ-ray spectrum (Bennet, et al., 1977) is superposed.

Figure 3 - The pulse-height (left) and incident spectrum of the Crab nebula. Superposed on the pulse-height spectrum is the best-fit model (see text) and superposed on the incident spectrum is the hard X-ray result of Strickman et al. 1979.

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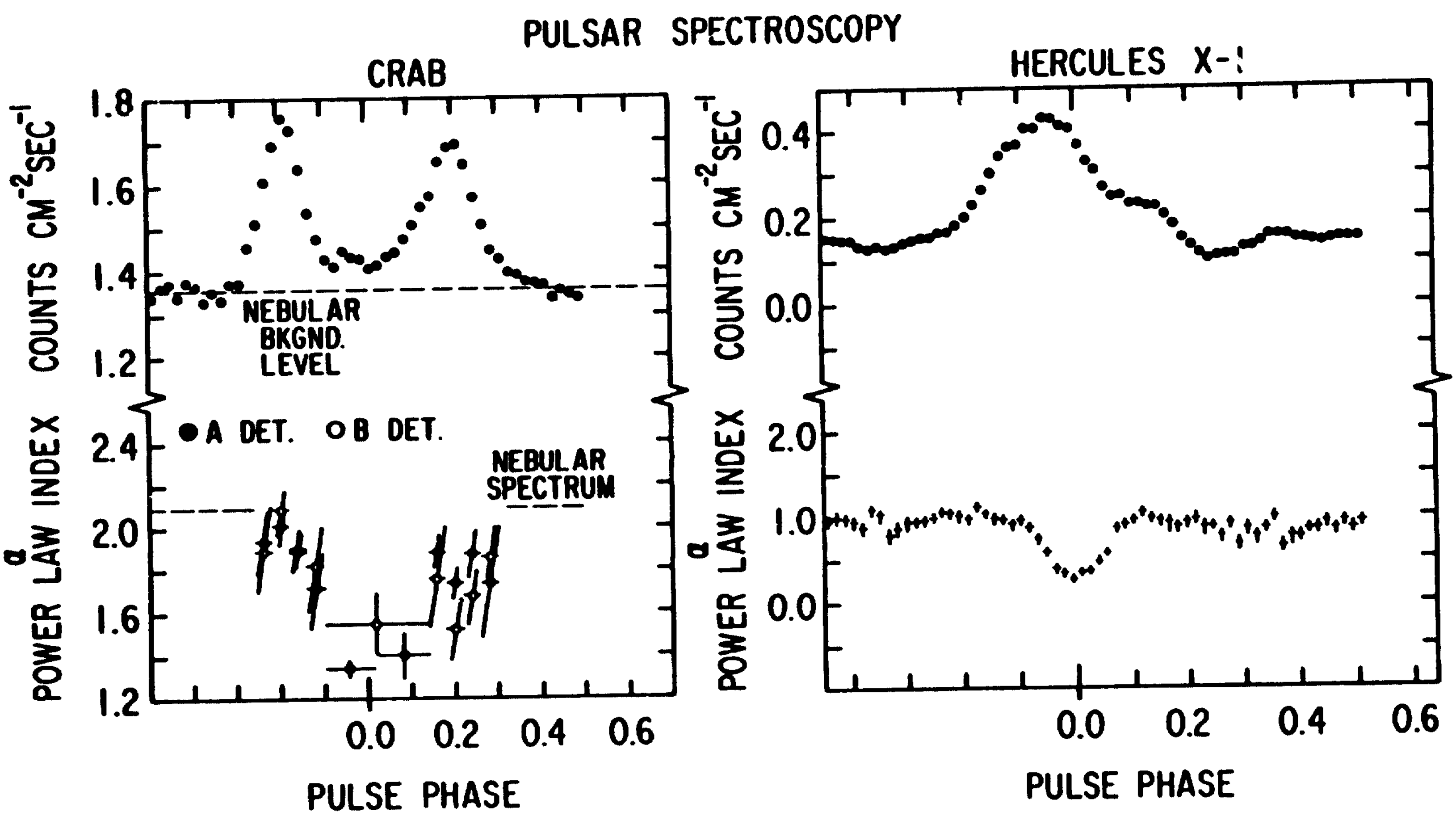
PULSAR SPECTROSCOPY
CRAB
COUNTS CM^{-2}SEC^{-1}
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PULSE PHASE
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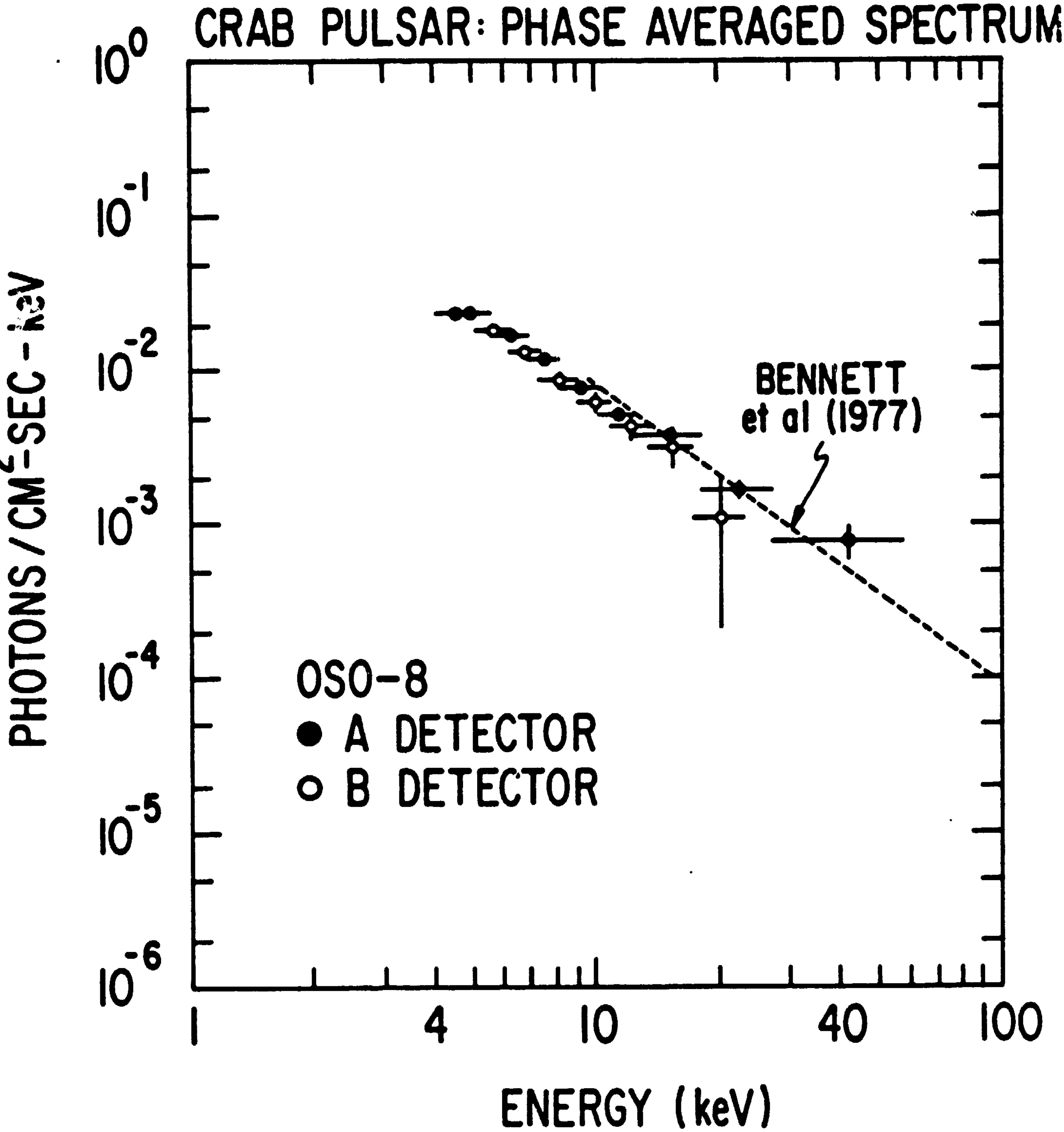
α POWER LAW INDEX
PULSE PHASE



CRAB PULSAR: PHASE AVERAGED SPECTRUM
PHOTONS / CM^2-SEC - keV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
4
10
40
100
ENERGY (keV)
BENNETT et al (1977)
OSO-8
A DETECTOR
B DETECTOR

CRAB NEBULA SPECTRUM OSO-8