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THE X-RAY SPECTRA OF THE CRAB NEBULA AND NP 0532

GILBERT FRITZ, JOHN F. MEEKINS, TALBOT A. CHUBB, AND H. FRIEDMAN
E. O. Hulbert Center for Space Research, Naval Research Laboratory, Washington, D.C.

AND

RICHARD C. HENRY
E. O. Hulbert Center for Space Research and Johns Hopkins University,
Baltimore, Maryland

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ABSTRACT

The X-ray pulsar in the Crab Nebula, integrated over the energy range 0.5–9 keV, has a primary-pulse profile slightly narrower than that of its optical counterpart. The pulsed fraction of the total X-ray emission varies smoothly from about 2 percent near 1 keV to about 10 percent at 7 keV, corresponding to a pulsar spectral index of -0.2 ± 0.1 for the energy flux. If this fraction is constant at 15 percent above 15 keV, then a break in the slope of the pulsar spectrum must occur near 10 keV.

The apparent interstellar absorption of soft X-rays from the Crab Nebula implies 0.55 ± 0.10 hydrogen atoms cm^{-3} between us and the Crab. This is twice the density indicated by 21-cm absorption measurements, but the difference may be due to X-ray absorption by interstellar grains.

I. INTRODUCTION

An X-ray spectrum of the Crab Nebula between 0.5 and 10 keV has been obtained. An earlier time-series analysis of a portion of the total counts recorded had discovered the pulsar phenomenon in X-rays (Fritz *et al.* 1969). We present here the result of a completed analysis of all the pulsar data. We also present certain key results of an analysis of the X-ray spectrum of the total X-rays from the Crab; a more detailed analysis will be published at a later date.

II. THE PULSAR

Since our initial observation, the X-ray pulsar in the Crab has been observed by several other groups. For most of these measurements, however, the time resolution was limited by the telemetry systems, and therefore only upper limits could be placed on the width of the primary pulse. Although our system had an intrinsic time resolution of about 0.02 ms, the first analysis we presented (Fritz *et al.* 1969) did not employ either all of the counts or the full time resolution of the system.

For the present analysis, a computer tape was prepared for which successive words represented time intervals of 0.05 ms. Each word consisted of the number of counts that occurred in that time interval. Times were measured from the 200-kHz frequency of a clock which had been stored on one channel of the data tape recorded during the rocket flight. The stability of this clock was checked by comparing it over short intervals with a highly accurate 1000-Hz clock.

During the 40 seconds the Crab was observed, about 9×10^4 counts were obtained. Figure 1 shows a light curve of the X-rays, and for comparison the optical light curve of Warner, Nather, and MacFarlane (1969). The characteristic shapes of the optical pulses have been described in some detail by Warner *et al.* (1969). The primary X-ray pulse shows the same slow rise and rapid fall as its optical counterpart, but the behavior of the secondary X-ray pulse (slow rise and rapid fall) is just opposite to that of the secondary optical pulse. As we stated previously (Fritz *et al.* 1969), the primary and secondary X-ray pulses contain an approximately equal number of counts, in contrast to the area ratio of about 1.7 reported by Warner *et al.* (1969) in the optical region. The

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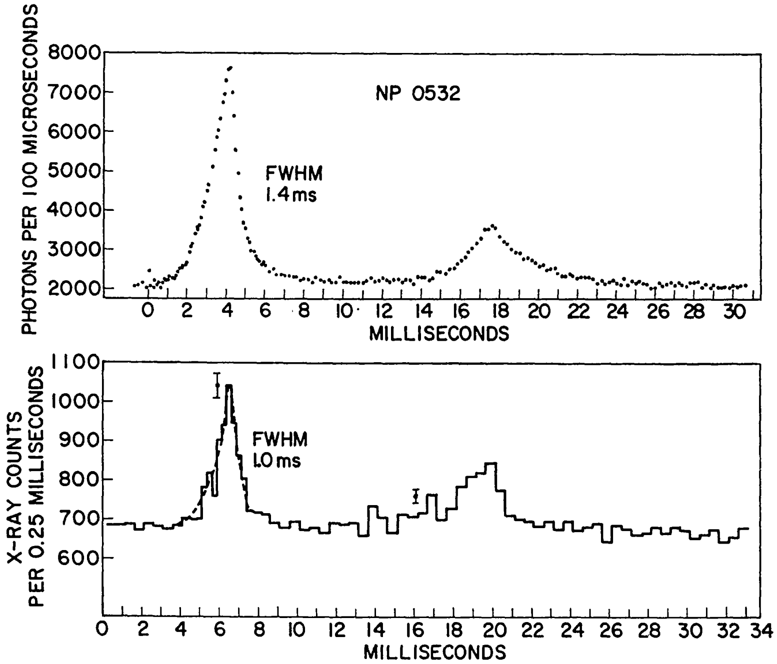

FIG. 1.—A light curve of the X-ray pulsar NP 0532 (*bar histogram*) compared with the optical-light curve for the same object (Warner *et al.* 1969). The X-ray bandwidth is 0.5–10 keV. For the X-ray curve, points are plotted every 0.5 ms except in the primary pulse, where they are shown every 0.25 ms to clarify the structure. The apparent period used for the X-ray light curve was 33.0987 ms.

slight enhancement of one interpulse region in the optical curve (near 100 ms in Fig. 1), compared with the other (near 28 ms), is also true for the X-ray data. However, in the X-ray range this enhancement may be part of an extended leading edge of the secondary pulse, possibly showing some structure itself.

If we disregard any possible features of the primary pulse, then the width for X-rays is close to 1.0 ms, significantly less than the 1.426 ms reported by Warner *et al.* (1969) for visible-light measurements. A drift of about fifty parts per million occurred in our 200-kHz timing signal toward the end of the Crab observation, and this could add an instrumental pulse width as much as a large fraction of a millisecond. However, light curves made both with this drift corrected and during the time when the drift was negligible showed the full width of the primary pulse at half-maximum to be never less than 1.0 ms. This number thus represents not an upper limit, but a measured value, with an uncertainty that we estimate to be 20 percent. Our data (Fig. 1) show some possibility of a precursor to the primary pulse, at a very low level of statistical confidence; but this uncertain feature has little effect on the primary pulse width. A radio observation by Richards (1970) showed a splitting of the primary pulse into two distinct parts; judging by the time of arrival of the secondary-pulse peak, the positions of the primary X-ray pulse and its possible precursor would correspond closely to the two split peaks of the radio pulse.

The X-ray light curve in Figure 1 included essentially all the counts from our two detectors (0.5–9 keV). Additional light curves were made in the spectral ranges 0.5–1, 1–2, 2–3, 3–4, 4–6, and 6–9 keV. Some energy ambiguity exists in these data because the energy bins were simply selected according to detector pulse heights, and the detector resolution width was great enough to cause some counts with the wrong photon energy to be included in a given pulse height bin. However, this effect is small compared with the statistical uncertainties in the data. The resulting light curves for the various energy intervals showed no significant differences in structure.

A portion of the light curve after the secondary pulse (corresponding to 0–3 and 22–33 msec in Fig. 1) was used to determine the apparent unpulsed level for each spectral interval, since a χ^2 test on this region showed no indication of pulsed structure. The fraction pulsed was then defined as the total count minus the expected unpulsed count, divided by the total count. In agreement with our previous approximate result (Fritz *et al.* 1969) of 0.05 for the total spectrum, we now obtain 0.053 ± 0.004. The data for the individual spectral intervals are shown in Figure 2 (*heavy lines*), along with the results of other groups. Fishman *et al.* (1967) obtained a nearly constant fraction in the range 45–200 keV. This is in agreement with data by Floyd, Glass, and Schnopper (1969) in the range 25–100 keV. Ducros *et al.* (1970) obtained four spectral points in the region 2.5–30 keV, showing a definite decrease in the pulsed fraction from about 0.16 at the high end to 0.08 below 5 keV. Broad-band observations by Bradt *et al.* (1969) and by Boldt *et al.* (1969) also suggested a decrease in the pulsar fraction toward lower energies.

The decrease in pulsar flux, relative to the nebular emission at the lower X-ray energies, is clearly indicated by our present data. Assuming that the X-ray flux of the pulsar is a combination of power-law spectra, we have drawn dotted lines in Figure 2 to suggest a break in the spectrum near 10 keV. The situation is shown more clearly in Figure 3, where the energy spectrum of the nebula (*upper curves*) is shown together with the pulsar spectrum (*lower curves*). The difference between the energy spectral index α of -1.3 above 10 keV (Peterson and Jacobson 1970) and the value -1.0 that we obtain for the nebula below 10 keV (see Fig. 4 and discussion below) is within the range of probable error of the two sets of measurements in the region of overlap, but the spectrum undoubtedly must flatten toward lower energies. The spectral slope of the X-ray pulsar is about the same as that of the nebula above 10 keV (constant fraction pulsed), but changes to a value of about -0.2 below that energy. Within the un-

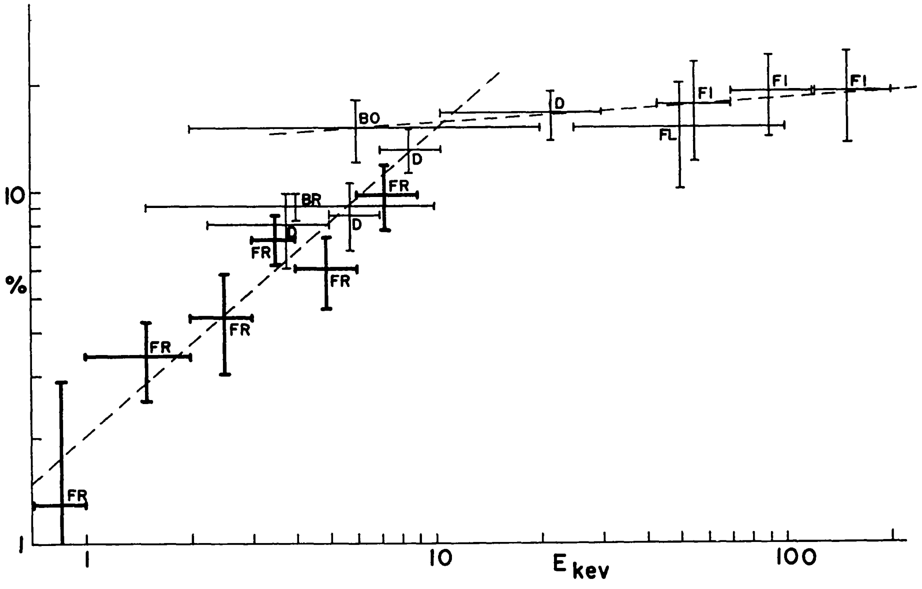

FIG. 2.—Spectrum of the X-ray pulsar in the Crab, expressed as the pulsed fraction of the total X-ray emission from the Crab. Heavy lines marked *FR* indicate the present observations. Other measurements are identified by the letters *FI*, Fishman *et al.* (1969); *FL*, Floyd *et al.* (1969); *BO*, Boldt *et al.* (1969); *BR*, Bradt *et al.* (1969); *D*, Ducros *et al.* (1970). Errors bars show the energy range and statistical uncertainty (generally ±1 σ) of each data point.

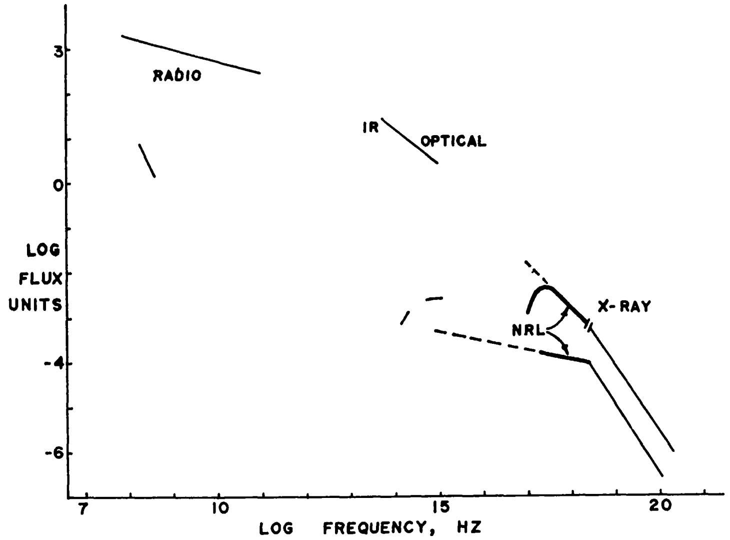

FIG. 3.—Electromagnetic spectrum of the Crab Nebula and pulsar, adapted from Woltjer (1970). *Upper curves*, nebula; *lower curves*, pulsar. The observed absorption of nebular X-rays at low energies is shown together with the unabsorbed source spectrum (*dotted line*). Extrapolation of the observed spectrum of the X-ray pulsar (*dotted line*) roughly connects the X-ray and optical pulsars.

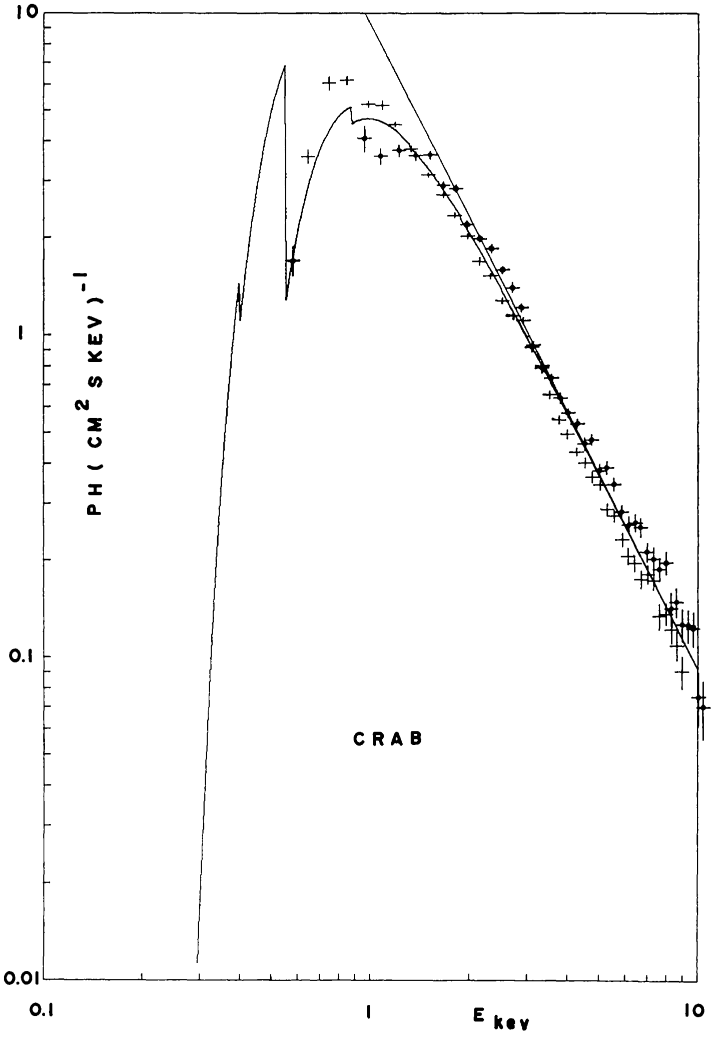

FIG. 4.—X-ray spectrum of the Crab Nebula. *Crosses*, data points obtained with a Mylar-windowed counter; *crosses-with-dots*, data points from a Teflon-windowed counter. Vertical error bars indicate ±1 σ. The lowest-energy point shown is a particularly well-determined measurement. The straight line is a power-law spectrum of photon index −2.0. The other solid curve is the same spectrum attenuated by a normal cosmic abundance of interstellar matter relative to 0.55 H atoms cm^{-3} (if the Crab is at 2 kpc). The transmission edge at 0.54 keV is due to oxygen.

certainties of our data this slope, extrapolated to the optical region, falls slightly below the optical flux which has been corrected for interstellar extinction. We did not obtain sufficient counts to measure interstellar absorption of the pulsar X-rays at the lowest energies.

Shklovsky (1970) has pointed out that the nebular spectrum of the Crab, between the optical and X-ray regions, is much softer ($\alpha \approx -1.2$) than the pulsar spectrum ($\alpha \approx -0.5$) in the same frequency range. The index -0.5 was obtained by simply joining the average flux observed in the 1.5–10-keV range with the optical flux. By attributing a sufficient loss of pulsed flux to small-angle scattering of X-rays on interstellar dust particles, the spectral index could be reduced from -0.5 to -0.28, the index for nebular radio emission. The essence of Shklovsky's argument is that agreement of the "reduced" index of pulsed X-rays with the nebular radio index identifies a common energy spectrum of relativistic electrons. Close to the neutron star, these electrons generate X-ray pulses in a field $H_\perp \sim 4 \times 10^3$ gauss, and after escaping to the nebula they generate radio waves in a field $H_\perp \sim 2 \times 10^{-4}$ gauss.

Since we derive our pulsar spectrum from the ratio of pulsar flux to nebular flux, the resulting spectral index for the pulsar reflects the value of the index used for the nebula. The Peterson and Jacobson value, $\alpha_{\text{nebula}} = -1.3$ above 10 keV, would, if extended to the lower energies, lead to $\alpha_{\text{pulsar}} = -0.5$ (1–10 keV). We believe, however, that our nebular spectrum (1–10 keV) is defined within the limits $\alpha = -1.0 \pm 0.1$ and that the pulsar's spectral limits are correspondingly $\alpha = -0.2 \pm 0.1$. Shklovsky's requirement that α_{pulsar} from ultraviolet to soft X-rays should approximately equal -0.3 would therefore be satisfied by these observations without invoking any correction for small-angle scattering.

III. THE SPECTRUM OF THE NEBULA

We have performed a pulse-height analysis of all the counts from the Crab, and have fitted the resulting pulse-height distribution following Meekins *et al.* (1969). The final result, after the removal of all instrumental effects, is shown in Figure 4, where data from both the Mylar (*crosses*) and Teflon (*dots-on-crosses*) counters are plotted. The straight line in the figure is the spectrum of the Crab fitted to the data above 2 keV. The strong effects of interstellar absorption appear below 2 keV. Our data permit us to conclude that the density between us and the Crab is equivalent to (0.55 ± 0.10) hydrogen atoms cm^{-3}, and also that the photon spectral index of the Crab over the energy range shown is -2.0 ± 0.1 ($\alpha = -1.0 \pm 0.1$). Our density is in marked disagreement with the 21-cm radio absorption measurement (Clark 1965), which gives 0.26 atoms cm^{-3} if a kinetic temperature of 100° K is assumed. A higher temperature (200° K) which would reconcile the two methods, is probably not allowable. There is no evidence of enough material in the nebula itself to account for the difference. Our Teflon-windowed detector had sufficient sensitivity beyond the oxygen absorption edge to show that an overabundance of oxygen in the interstellar medium is not the explanation.

One possibility is that part of the X-ray absorption is by interstellar grains. Matter in grains should have nearly the same absorption properties for X-rays as matter in atomic form, as long as the optical depth for X-rays is large compared with the grain size; for the common sub-micron models of interstellar grains, this criterion is satisfied. Our absorption calculations took into account the contribution of all elements (the total cross-sections of Brown and Gould 1970 were used), so that additional absorption by interstellar dust would imply a considerable overabundance of one or more elements.

Naranan and Shah (1970), in a paper dealing with the possibility that the pulsar X-rays are scattered by interstellar dust so as to produce the apparent X-ray nebula, showed that dielectric grains (graphite grains coated with ice) of radius $\sim$0.25 μ and density $\sim$1 provide a good fit to the observed optical and near-infrared extinction. The required column density of grains was about 6×10^8 cm^{-2}, which would imply a mass density of 3.6×10^{-5} g cm^{-2}. Such interstellar dust would provide some attenuation for X-rays, amounting to about 20 percent at 1 keV for oxygen (ice) and 10 percent at 1 keV for carbon. This is not sufficient to account for the difference between the 21-cm hydrogen measurements and our observed X-ray absorption, which would require several times more mass in the form of grains. An excess of oxygen in any form is probably excluded by our data because we do not observe the expected effect of the K-edge of oxygen. Similarly, we cannot entirely account for the additional X-ray absorption by postulating grains containing predominantly magnesium, aluminum, silicon, or iron. Absorption by carbon is the most likely alternative, but that would require at least an order of magnitude more carbon in the grains than is compatible with cosmic abundance in the interstellar gas.

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