X-RAY STUDY OF THE CRAB NEBULA AND THE CRAB AND VELA PULSARS

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INTRODUCTION

The Crab Nebula has been intensely studied by X-ray astronomers ever since its discovery as the first, optically identified X-ray object (Bowyer et al. 1964); and a large majority of X-ray experiments during the past two decades have observed the Crab, seeking not only the answers to scientific questions but also assurance that the instruments' calibrations were understood. It is therefore no surprise that, following its launch in 1978 November, the Einstein X-ray Observatory too had the Crab Nebula on its list of mandatory targets.

The <u>Einstein</u> telescope, as had other pioneering experiments preceeding it, held the promise of new discoveries concerning this frequently observed object. <u>Einstein</u> for the first time brought X-ray imaging techniques to bear on questions regarding the spatial structure of the nebula and its famous 33 millisecond pulsar. As part of the effort to understand the relationship between the nebula and the pulsar, the only other such pair of objects known at the time of <u>Einstein's</u> launch, the Vela supernova remnant and the Vela pulsar, were also selected for intensive study.

Because the Vela supernova remnant (SNR) is so much closer and older (distance ~ 500 pc, age ~ 10,000 yr) than the Crab SNR (distance ~ 2 kpc, age ~1900 yr.), the Vela SNR has a much larger angular extent than does the Crab: nearly 5 degrees as compared to ~3 arcmin. This made study of the Vela SNR with the 1-degree field-of-view <u>Einstein</u> telescope tedious, requiring nearly 40 separate pointings to cover the entire extent of the X-ray shell. These observations were carried out, but will be discussed elsewhere. This paper centers mainly on the data for the two pulsars, and also includes brief discussions of the nebular structure surrounding each of them.

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OBSERVATIONS

All four *Einstein* focal-plane instruments (see Giacconi *et al.* 1979 for a description of the observatory) were used to observe the Crab and Vela SNR's, but only the High Resolution Imager (HRI) and Imaging Proportional Counter (IPC) data are discussed here. Table I gives some details of the observing program. The HRI, with its 4 arc second resolution, was used primarily to study detailed spatial structure, but the IPC with its greater sensitivity to low-surface-brightness features was also useful in studying the outer regions of the Crab's X-ray emission.

The possibility of "burning out" the IPC by exposure to the intense flux of the Crab dictated that the IPC observation of the Crab be postponed until the end of the mission. The IPC did survive this exposure; but the 1000 per second counting rate saturated the 125 per second telemetry capability, rendering temporal analysis of the pulsar data virtually impossible. Temporal analysis of the Crab pulsar has therefore been based entirely on HRI data, whereas both HRI and IPC temporal analyses have been carried out for the Vela pulsar.

TABLE I

EINSTEIN Imaging Observations

Crab Nebula			Vela Pulsar Region		
Exp.Time	Date	Notes	Exp.Time	Date	Notes
45760	1979 Mar 3	H	31460	1978 Nov 29	H,2,3
20784	1979 Sep 14	H	5607	1978 Dec 18	I
5795	1981 Mar 27	H,1-25	12259	1979 May 31	H
8083	1981 Mar 27	I,2,1-25	1626	1979 Oct 25	I,1-3
2583	1981 Mar 27	I,2	18333	1979 Oct 31	H
1024	1981 Mar 27	I	17035	1980 Apr 27	H
			2038	1980 Jun 5	I,1-26
			1100	1980 Jun 6	I,1-35

Notes:
- H observed with HRI
- I observed with IPC
- 1-n offset from target by n arcmin
- 2 Al filter inserted in X-ray path
- 3 Observed with HRI-2 (instead of HRI-3)

Exp.Time in seconds (uncorrected for deadtime)

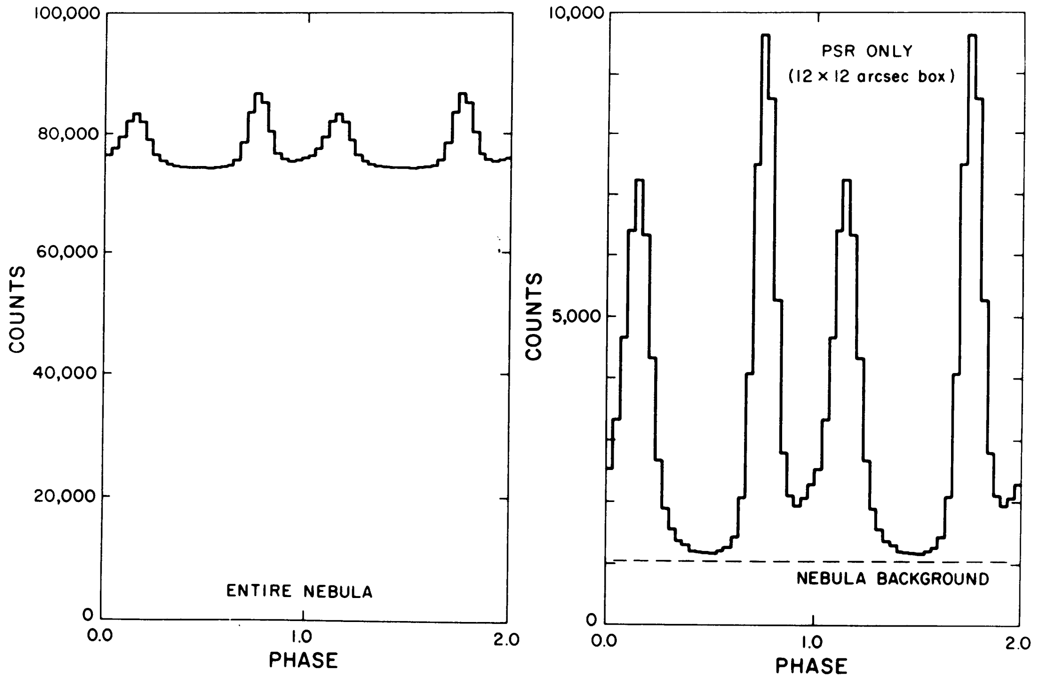

Figure 1: Light curve of the Crab Nebula X-ray data folded at the pulsar period of 33 msec. and plotted twice on each slide of the graph; left, all emission from the entire nebula; right, photons from the pulsar itself. Each curve has been corrected for a phase-dependent telemetry deadtime.

THE CRAB PULSAR

Temporal analysis for the Crab pulsar 1979 March data has yielded the light curve shown in Figure 1. An image made during the lowest phase interval, the next to last one of the 10 frames shown in Figure 2, reveals that a point source contribution from the pulsar is not statistically significant during this interval. The "3 σ" HRI count rate upper limit during this "off phase" is 0.22 counts per second.

This rate can be interpreted as an upper limit to the surface temperature of the neutron star; provided that the emission is assumed to be blackbody radiation. If a 10 km radius is assumed, an upper limit of ~ 2.5 million K results. Such a temperature is consistent with so-called cooling curves based upon a conventional equation of state for nuclear matter (cf. Nomoto and Tsuruta 1981). The corresponding 0.1 to 4.5 keV X-ray luminosity upper limit is 2.6×10^{34} erg sec^{-1}, but the use of such upper limits to constrain neutron star cooling curves seems rather ambiguous in view of the many possible heating mechanisms which could alter such curves (cf. Helfand et al. 1980).

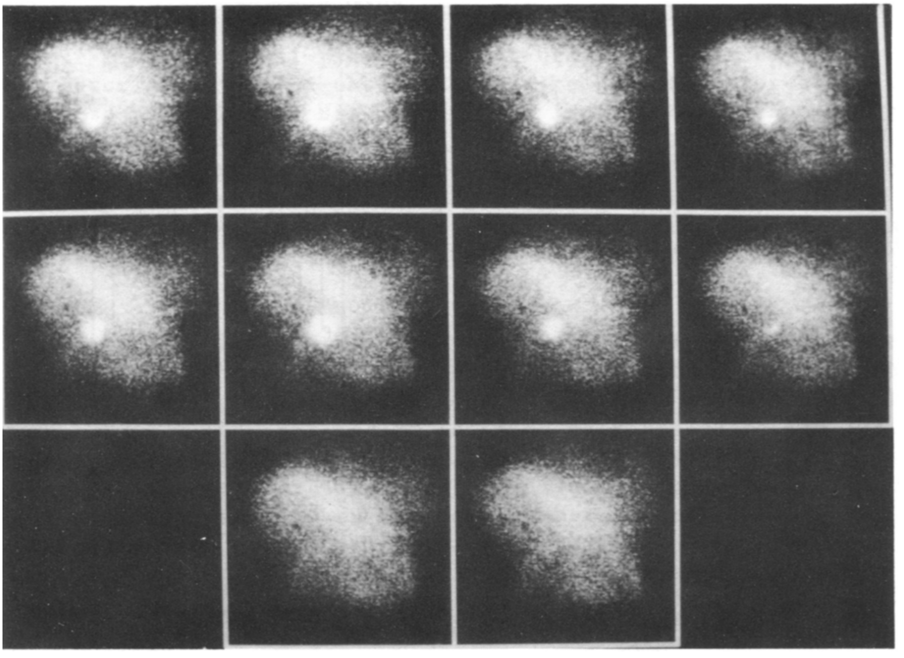

Figure 2: HRI images of the Crab Nebula and its pulsar. March 1979 data from a 20,000 second exposure have been folded at the pulsar period (33 msec.) and imgaged in 10 phase intervals. The main pulse occurs in the second interval, the interpulse falls in the sixth, and the pulsar is faintest in the ninth image.

THE VELA PULSAR

Because of previous reports of variability (Smith and Pounds 1975) and earlier reports of possible X-ray pulsations (Harnden and Gorenstein 1973), it was important to observe the Vela pulsar (PSR 0833-45) several times. However, all Einstein observations of this pulsar (see Table I) are consistent with a constant flux. Furthermore, none of the data exhibits pulsations at the 89 millisecond radio-optical-gamma-ray period. The most sensitive upper limit (95 per cent confidence, from IPC data) on pulsations is 3.2×10^{-13} ergs cm^{-2} sec^{-1} for the 0.2 to 4.0 kev passband. (Note that intercomparisons of fractional limits from experiments with different fields of view can be misleading since there is complicated spatial structure in the X-ray emission from the vicinity of the pulsar - see below.)

The Vela pulsar is a relatively strong X-ray source despite the absence of pulsations. It appears "unresolved" to the IPC (~1 arcmin resolution), at a flux level of 3.9×10^{-11} erg cm^{-2} sec^{-1} in the 0.2 to 4.0 keV bandpass. The emission from this source is decidedly non-thermal: the IPC spectrum is well fit by a power law model but

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produces unacceptably high chi-square values for attempts to fit it to with a thermal model. This is in contrast to the spectra of nearby, bright, diffuse emission regions, which are well fit by the thermal model but reject the power law. One such region, nearly a degree in extent, partially overlaps the position of the pulsar and may account for the extended source observed at the pulsar position by previous, non-imaging experiments. On the basis of the spectral differences, however, it seems unlikely that the pulsar is directly responsible for this diffuse emission. Indeed, there are at least half a dozen other localized, diffuse emission regions, throughout the 5 degree remnant, which can characterized as knots and filaments.

Yet there is another scale to the pulsar source. With the HRI, what was unresolved in the IPC becomes resolved into a point-like component surrounded by a small nebula. The unresolved HRI source accounts for ~1/3 to 1/2 of the emission, with the remainder coming from a centrally condensed nebula of ~80 arc second extend.

STRUCTURE OF THE CRAB NEBULA

The shape of the X-ray Crab Nebula can be seen in Figure 2. Except for the point-like pulsar, which contributes only ~ 5% of the time-averaged image, there are no sharp features. The most intense emission region is, like the optical wisps, to the northwest of the pulsar. When subjected to a maximum entropy deconvolution procedure, this region tends to coalesce into knot-like features, but the reality of such features is not convincing, even though one such "knot" coincides with the position of a 17th magnitude "stellar" object. (Optical observations of this and other stellar objects within the nebula are underway.)

SHOCKWAVE SHELL AROUND THE CRAB?

The Einstein data may be capable of answering this important question, but the intricate analysis required has not yet been completed. Two effects, one instrumental and the other astrophysical make the detection of a possible, low-surface-brightness, blast wave shell very difficult.

Scattering from surface imperfections of the telescope mirror makes even a point source appear to have extended emission surrounding it at a low level. The possibility of surface degradation between the preflight calibration and the inflight observations necessitates caution in applying the instrumental response function.

Scattering from interstellar dust grains has long been discussed as a scientifically interesting effect which would produce a halo around a point X-ray source. In the case of the Crab Nebula, untangling such an effect (by subtle differences in spectral dependence) from mirror scattering is non-trivial. A simple comparison of three celestial sources, the Crab, 4U1658-48 (also known as GX339-4) and GX13+1, merely demonstrates that mirror or grain scattering can indeed spatially mimic what one might expect from a blast wave shell.

Another difficulty in detecting a Crab X-ray shell is the extreme intensity of the synchrotron emission from the 3 arcmin X-ray nebula. A simulated experiment (F. Seward, private communication) of placing the prominent shell of SN 1006 around the Crab revealed that such a shell would be undetectable in the Crab even if the scaled surface brightness were increased by an order of magnitude.

In concluding, it can be noted that although the Crab Nebula has long been recognized to be quite unique among SNR's, this has not prevented observers and theoreticians alike from using it as the archetype for type I supernova. This was perhaps understandable in the past, due to the lack of other such objects (except for Vela which is quite different in many respects); but Einstein observing programs carried out by guest observers and consortium members have now discovered other SNR's with compact objects (e.g., RCW 103, G 109, and MSH 15-52), as well as "Crab-like" SNR's in the LMC. The very fact that this Symposium has occurred is a hopeful sign that new progress in the understanding of SNR may lie just around the corner.

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DISCUSSION

KIRSHNER Is it correct to say that the point response function is a function of the incident energy, the position in the field and possibly even time? If that's true, can you give an idea whether it will be possible to place a firm limit on or possibly detect the shell around the crab that has been suggested in the past?

HARNDEN The unavoidable problem is the existence of three separate physical processes which produce similar observed features: (1) a blast wave shell, (2) interstellar dust grain scattering and (3) image degradation due to instrumental scattering from mirror-surface imperfections. No, it is not correct to say that the point response of the Einstein IPC is a function of time. The dependence upon incident energy and position is well understood and can be accurately modeled. Certainly a formal detection (or upper limit determination) will be possible, but it does require detailed analysis which has not yet been completed. With the Crab (whose spectrum is well determined) the major uncertainty is the possible existence of a dust grain halo; with sources whose spectra are not well determined, that uncertainty further complicates the analysis.

HELFAND The use of the minimum of the X-ray pulse profile to establish a neutron star temperature limit is a reasonable first approximation, but, in fact, the surface thermal conductivity is expected to be very nonuniform as a result of the strong magnetic field. Thus, the blackbody surface emission should be modulated, peaking at the nonthermal pulse peaks, if these represent the star's magnetic poles. Can you use the IPC/HRI rate as a function of pulse phase to get some spectral information? What about MPC/HRI?

HARNDEN Use of the IPC temporal information is hopelessly complicated by the very high count rate, which saturates the available telemetry, so I don't think the IPC data could help. The HRI rate is quite high, too, but the deadtime is well understood. I'm not sure what the MPC deadtime is as a function of pulsar phase, but if it can be accurately enough determined, perhaps the MPC/HRI ratio might shed some light on this question.

PRAVDO Is the temperature of the thermal X-rays near (within 1 degree) the Vela pulsar, the same as that of the X-rays in farther away regions of the SNR?

HARNDEN The Vela spectral analysis hasn't been completed yet so I can only give you a preliminary answer. As we saw in the slide of the 5-degree remnant, there are several localized regions of enhanced X-ray emission within the large remnant: the pulsar is one of these, as is a region ~ 20 arcmin to the north of the pulsar. If we fit a thermal plasma model to the IPC spectral data from these relatively intense regions, we can get acceptable fits with "reasonable" values of temperature for all regions (except for the region within ~ 3 arcmin radius of the pulsar, where a power law model is required to obtain an acceptable Chi-square value). These "reasonable" values definitely vary from one region to another. In fact, the intensity and the temperature appear to be correlated. The east-west filamentary structure which passes ~ 20 arcmin north of the pulsar has a temperature within the range of variation of the other bright spots, i.e., it's not particularly noteworthy except for its proximity to the pulsar.

DANZIGER On deep exposure direct plates, one has seen in the immediate vicinity of the Vela pulsar filamentary nebulosity belonging to the SNR. One also sees emission from diffuse nebulosity of a type characteristic of the SNR at the precise position of the pulsar. It could be either foreground or background material.

HARNDEN I think the X-ray data are consistent with that optical picture, namely foreground or background thermal emission from the blast wave are present at the pulsar position as elsewhere. But none of the really pronounced regions of thermal X-ray emission coincides with the pulsar, the nearest are being ~ 20 arcmin away.