Pergamon

Adv. Space Res. Vol. 22, No. 7, pp. 981–986, 1998
Published by Elsevier Science Ltd on behalf of COSPAR
Printed in Great Britain
0273-1177/98 \$19.00 + 0.00

PII: S0273–1177(98)00130–6

RADIO PULSARS OBSERVED AT X-RAY ENERGIES BY THE X-RAY TIMING EXPLORER

L.E. Peterson[1], D. Marsden[1], P. Blanco[1], D.E. Gruber[1], W.A. Heindl[1], M.R. Pelling[1], R.E. Rothschild[1], P.L. Hink[2], J. Swank[3], K. Jahoda[3] and A. Rots[3]

[1] *CASS 0424, UC San Diego, 9500 Gilman Dr., La Jolla, CA 92093, USA*
[2] *Washington University, Dept. of Physics, St. Louis, MO 63130, USA*
[3] *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

ABSTRACT

The Rossi X-Ray Timing Explorer observed a number of X-ray emitting radio pulsars soon after launch on 30 Dec. 1995. These included two plerionic systems formed in recent supernova events, the Crab Nebula with its 33 ms pulsar PSR 0531+21 and MSH 15–52 with its 151 ms pulsar PSR 1509–58. Observations of these sources for 20–30 ksec with both the PCA and HEXTE allowed precision phase resolved spectroscopy for the Crab Nebula, confirmation of the light curve and pulsed spectrum for PSR 1509–58, and separation of the Nebular emissions from the pulsed X-rays over the 18–250 keV range for both sources. Within statistical uncertainties, a power law spectrum fits all the observations over this limited energy range. The nebular region for both sources has a photon index of about -2.1, while the pulsed spectra are considerably harder. Significant differences in spectral index are observed for the first pulse, the second pulse, and the interpulse of PSR 0531+21. Published by Elsevier Science Ltd on behalf of COSPAR.

INTRODUCTION

Only a handful of isolated, rotation-powered radio pulsars have been observed in the X-ray and gamma-ray range. In particular, two of these so far observed are embedded in a remnant produced in a supernova explosion which has occurred within the past several thousand years. These so-called plerionic systems are of considerable interest because the nebular regions are believed powered by the rapidly rotating magnetized neutron star, which also emits the pulsed electromagnetic emissions. In this paper we report results observed with the Rossi X-Ray Timing Explorer (RXTE) on the Crab Nebula and its 33 ms pulsar PSR 0531+21, and on MSH 15–52 and its 151 ms pulsar PSR 1509-58. Results obtained include precision phase resolved spectroscopy of the X-ray pulsars in the 2–250 keV range, of interest to determine the geometry of the emitting region, and to infer its nature in terms of the "polar cap" and "outer gap" emission models. Also results were obtained on the off-pulse, presumably nebular, spectra of both sources over the 18–250 keV range. These spectra are relevant to the injection acceleration and transport of the relativistic electrons in the nebular region. These electrons presumably produce the diffuse X-ray continuum by synchrotron radiation.

OBSERVATIONS

The observations reported here were obtained with instruments on the RXTE during the Initial Orbital Calibration phase (IOC) immediately following the launch on 30 December 1995. Data were obtained with both the 15,000 cm^2 Proportional Counter Array (PCA) which operates over the 2–30 keV range, and with the 1600 cm^2 High Energy X-Ray Timing Experiment (HEXTE) which operates over the 15–250 keV range. Both instruments and the RXTE are described elsewhere (Bradt *et al.* 1991; Gruber *et al.* 1995; Jahoda *et al.* 1996).

Table I indicates intervals the Crab Nebula and MSH 15–52 were observed during January 1996. A total of about 20 ksec were obtained on MSH 15–52 and about 30 ksec on the Crab Nebula. The HEXTE was operated in a rocking on-source, off-source mode so direct background subtraction was obtained. Both the Crab Nebula and MSH 15–52 extend on the order of a few arc minutes, so the entire source region, pulsar + nebula, were in the one degree field of view of the instruments, when observing each source.

Table 1. RXTE Observations of the Crab and PSR 1509-58.

Object	Obs. Date m/d/y	Start (U.T.) hh:mm:ss	End (U.T.) hh:mm:ss	Livetime (s)
Crab	1/10/96	14:46:40	20:17:51	7740
Crab	1/11/96	13:05:20	17:05:04	6855
Crab	1/12/96	13:10:08	15:29:52	4620
Crab	1/15/96	16:33:36	21:57:52	9405
1509-58	1/6/96	00:06:40	03:24:00	7905
1509-58	1/17/96	20:05:51	22:34:40	5865
1509-58	1/26/96	18:48:00	21;08:00	5820

CRAB NEBULA AND PSR 0531+21

Pulsed spectral data on the Crab Nebula and PSR 0531+21 were folded at the radio period, ~ 33.3901 ms. This period was verified with a power spectral analysis, which showed a very strong narrow peak at the expected frequency. Figure 1 shows the light curves of the PCA data, and the HEXTE data in four energy ranges. The light curves confirm previous observations in this X-ray range (Knight 1982; Ulmer *et al.* 1994) which shows a narrow first pulse phase with the radio pulse, a broader second pulse, and considerable emission in the interpulse or bridging region. The region of the lowest emission, phase 0.7–1.0, which we call the off-pulse region, is probably the true flux from the nebula for the HEXTE data, since the detector background is corrected out by the on-source, off-source nature of the measurement. Clearly the second peak has a harder, i.e. less steep, spectrum in this energy range, since the ratio of the fluxes at the peaks reverses with increasing energy. This is consistant with recent observations by OSSE in the 50–550 keV range (Ulmer *et al.* 1994).

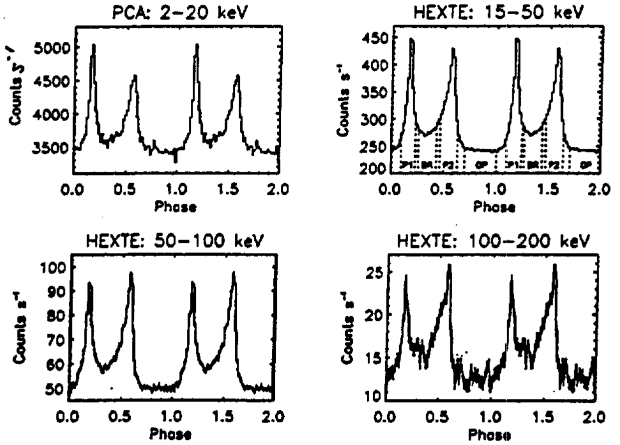

Fig. 1. The Crab Nebula system folded light curve as seen by RXTE in various energy bands. The dotted lines in the top-right panel show the phase regions used in the spectral analsis.

The precision data with its high statistical significance permits pulse phase spectroscopy to an accuracy unavailable in previous work. Also shown in Figure 1 are the regions the 60 phase bins were accumulated over to allow spectral fitting to the data. These regions are consistant with those identified in previous work (Knight 1982; Ulmer *et al.* 1994). The count rate data, after being accumulated in the defined intervals, were converted to a photon spectrum, using the response matrix in the HEXTE analysis tool XSPEC. Because of the uncertain background correction and response matrix, the PCA data were not included in the spectral analysis. Figure 2 shows the spectral data in the various regions with $\pm 1\ \sigma$ statistical errors indicated. The best bit fit power law is indicated as a histogram, computed over the width of the pulse height data channels.

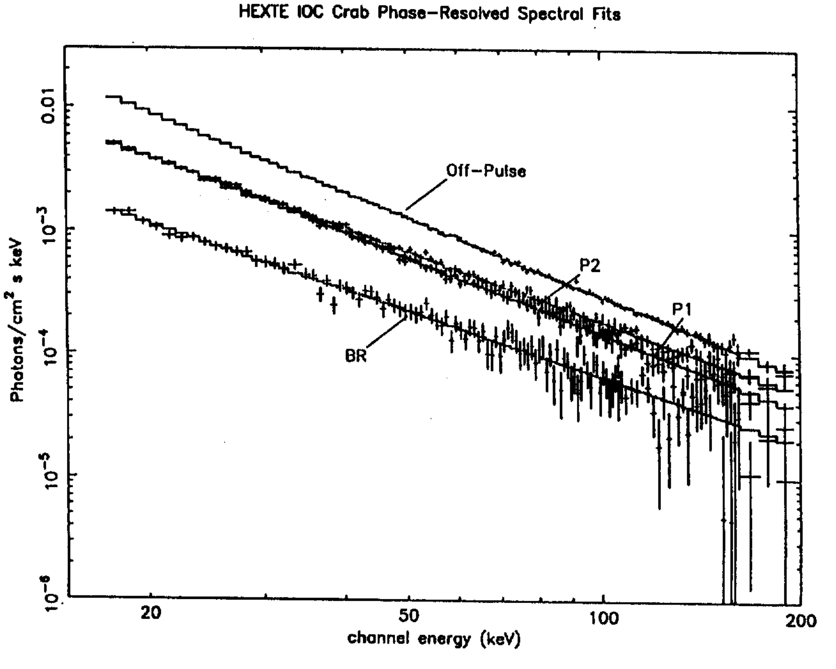

Fig. 2. HEXTE inferred incident photon spectra for the various phase intervals of the Crab Nebula and its pulsar. The best-fit power law component is indicated by a solid line.

The results of the fitting, shown in Table 2, indicate that a power law provides a statistically satisfactory fit to each phase region. This data confirms and quantifies the inference that the leading pulse P1 is significantly softer than the second pulse P2 by 0.15±0.02 of a power law index in photon space. The bridging region, BR, is harder yet in this spectral range, and the off-pulse data are consistent with previous measurements of the nebular flux (Knight 1982; Jung 1989).

Table 2. Phase-Resolved Spectral Fit Results.

Object	Phase	Energy Range (keV)	Photon Index	χ_ν^2	ν
Crab	P1	18 – 250	2.07 ± 0.01	1.141	230
Crab	BR	18 – 250	1.79 ± 0.02	1.015	230
Crab	P2	18 – 250	1.92 ± 0.01	1.131	230
Crab	Off-Pulse	18 – 250	2.130 ± 0.002	1.217	230
1509-58	P1	18 – 256	1.38 ± 0.12	0.914	237
1509-58	Off-Pulse	18 – 256	2.15 ± 0.18	0.977	237

Pulsed emissions of rotating magnetized neutron stars are generally explained in terms of the polar cap model (Daugherty & Harding 1982) or the outer gap model (Cheng, Ho & Ruderman 1985a,b). For the latter, Ho (1989) has reduced the spectrum descriptor of hard X-rays to a single parameter, which represents the linear fraction of the magnetosphere occupied by the magnetosphere gap. According to the results obtained by OSSE (Ulmer *et al.* 1994) in the 50–550 keV range, the spectrum of the pulsed emission is consistent with the outer gap model if the gap parameter f_G, is 0.46. Our results are in agreement with this supposition.

MSH 15–52 AND PSR 1509–58

The 150.689 ms pulsar in MSH 15–52 was first detected in X-rays by Seward and Harnden (1982), and confirmed in the radio by Manchester *et al.* (1985). The ROSAT image (Greiveldinger 1995) of MSH 15–52 is dominated by a nebular region several arc minutes in size surrounding the pulsar in the center of the image, and a more compact source, associated with an Hα region, ∼ 10′ minutes to the North. ASCA observations (Tamara *et al.* 1996) have confirmed that the hot Hα is heated by a relativistic jet extending from the region containing the pulsar. The supernova which produced the system is believed to be about 1500 years old (Thorsett 1992; Chin & Huang 1994).

The light curves of PSR 1509–58 obtained by RXTE during January 1996 are shown in Figure 3. Since the total emission of the MSH 15–52 system is only about 60 mCrab at 30 keV, the statistical significance of the data obtained in the 20 ksec observation is appreciably less than on the Crab Nebula and its pulsar. Nevertheless, the observations confirm a single broad hard X-ray pulse, and on "off-pulse" region of about 0.5 phase. Because of the limited exposure time, significant data was not obtained at energies above about 150 keV and phase resolved spectroscopy could be accomplished only over two phase intervals, as shown in Figure 3.

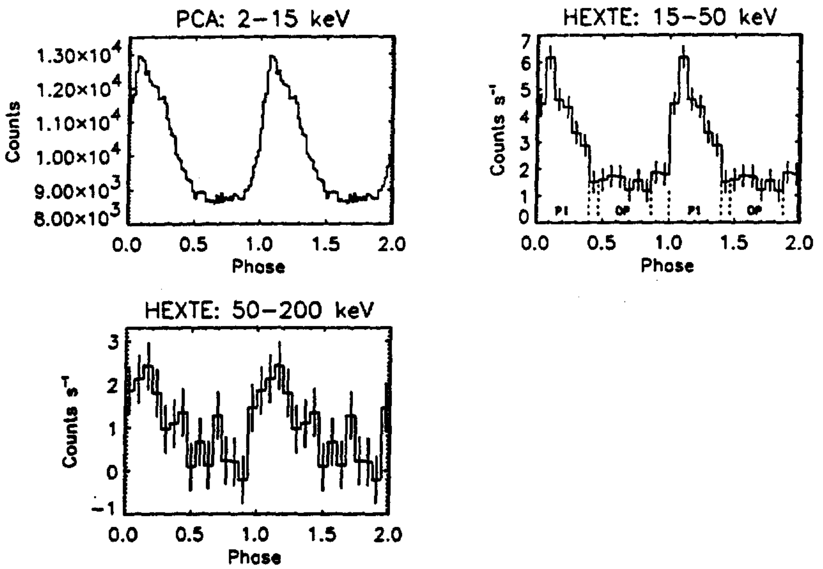

Fig. 3. The folded light curves of the PSR 1509–58/MSH 15–52 system in various energy bands. The dotted lines in the top right hand panel show the phase regions used in the spectral analysis.

The spectra obtained in the "on-pulse" region P1, and the "off-pulse" region OP are also shown in Figure 4. The results of fitting a single power law to each phase interval of the HEXTE data are also shown as a continuous histogram in the Figure. The PCA data was only fit to the main pulse, because of the uncertain background correctic in the off-pulse intervals. The results for the on-pulse intervals in the 18 to ∼ 150 keV range are consistent with the measurements reported at lower energies by Seward *et al.* (1984) and are consistent with the less significant spectra index of 1.64±0.4 obtained over the 94–240 keV range from a balloon observation by Gunji *et al.* (1994).

Assuming the off-pulse spectrum shown in Figure 4 is indeed that of the integrated nebula, the HEXTE on RXTE has produced the first measurement of the nebular component spectrum in its energy range. The nebular spectral index, where a statistically significant fit could be obtained is -2.15±0.18. The data do not permit fitting a second power law to determine if a break in the nebular spectrum exists. Changes in the power law shape are indicative of acceleration and transport mechanisms associated with the relativistic electrons presumably injected in the nebular region by the pulsar. The off-pulse, presumably nebular spectrum is remarkably similar in shape to that in the Crab Nebula in this region (Jung 1989). He found that spectrum to be about -2.08 in the 1–100 keV region, with a break at about 150 keV to a slope of ~ 2.5. This data is consistent with more recent observations by OSSE (Ulmer *et al.* 1994) on the Crab Nebula. It is of considerable interest to determine if a similar break occurs in MSH 15–52. Clearly a much longer observation is needed to settle this important question.

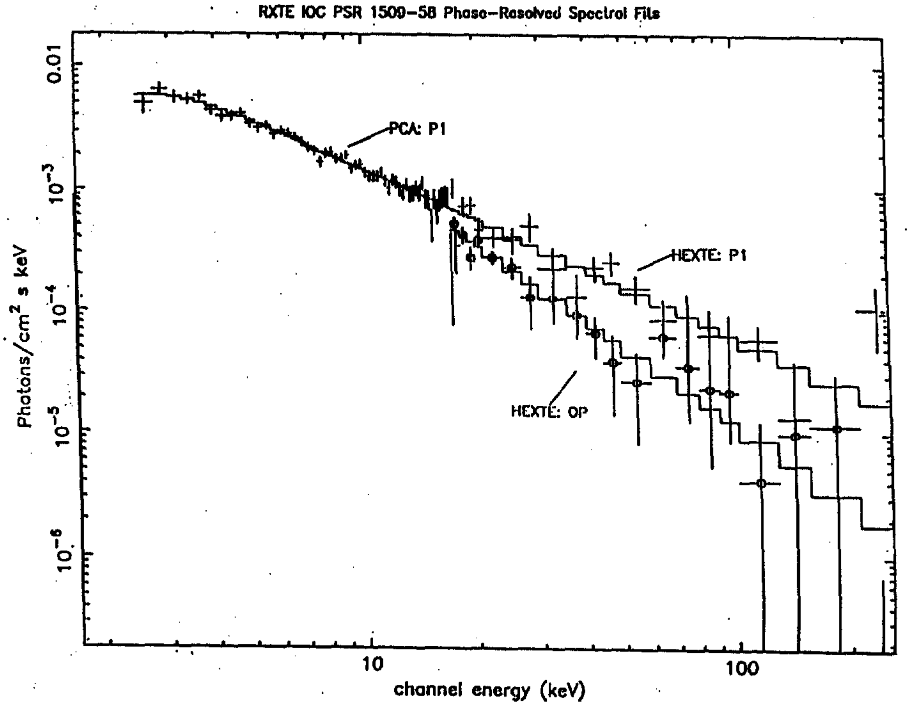

Fig. 4. Inferred incident photon spectra from PSR 1509–58/MSH 15–52, showing the pulsed component (PCA & HEXTE) and the off-pulse component (HEXTE only). The best-fit power law models for the pulsed and off-pulse components are indicated by the solid lines.

CONCLUSION

In this work, we have reported new determinations of pulsed and non-pulsed X-rays for two recently formed plerion systems containing radio and hard X-ray pulsars: the Crab Nebula and its pulsar PSR 0531+21, and MSH 15–52 and its pulsar PSR 1509–558. Phase resolved spectra were obtained for each source, and could be fit with power law spectral shapes. The Crab pulsar is consistent with previous work in that the second pulse is harder than the leading pulse. The off-pulse, presumably nebular, component, is softer than the pulsed component, and is relatively more intense in the 18–250 keV range. The total flux (pulsed and non-pulsed) from MSH 15–52 is about 60 mCrab. The single broad pulse has a power law photon spectrum index of ~ 1.4, harder than the peak emissions of the Crab pulsar. The first measurements of the off-pulse component show the nebula to have a power law index of about 2.1 in the 18–150 keV range. The off-pulse components is softer, and relatively less intense than the Crab Nebula. Longer observations of MSH 15–52 are needed to accomplish phase-resolved spectroscopy in many phase bins, and to search for the possibility of a change in the power law slope in this spectral region.

ACKNOWLEDGEMENTS

This was supported by NASA contract NAS5–30720 at UCSD.

Note Added In Proof: A more complete analysis of the RXTE data on PSR 1509–58/MSH 15–52 has been published by Marsden, *et al.* (1997).

REFERENCES

Bradt, H.V., J.H. Swank, and R.E. Rothschild, The X-Ray Timing Explorer, *Adv. Space Res.*, **11**, No. 8, 243 (1991).

Cheng, K.S., C. Ho, and M. Ruderman, Energetic Radiation from Rapidly Spinning Pulsars. 1. Outer Magnetosphere Gaps, *Ap. J.*, **300**, 500 (1986).

Cheng, K.S., C. Ho, and M. Ruderman, Energetic Radiation from Rapidly Spinning Pulsars. II. Vela and Crab, *Ap. J.*, **300**, 522 (1986).

Chin, Y-N., and Y-L. Huang, Identification of the Guest Star of AD 185 as a Comet Rather than a Supernova, *Nature*, **371**, 398 (1994).

Daugherty, J.K., and Harding, A.K., Electromagnetic Cascades in Pulsars, *Ap. J.*, **252**, 337 (1982).

Greiveldinger, C., S. Caucino, S. Massaglia, H. Ögelman and E. Trussonl, PSR 1509–58 and Its Plerionic Environment, *Ap. J.*, **454**, 855 (1995).

Gruber, D.E., P.R. Blanco, W.A. Heindl, *al.*., The High Energy X-Ray Timing Experiment on XTE, *Astron. & Astrophy.*, 120, 641 (1996).

Gunji, S., *et al.*, Observation of Pulsed Hard X-Rays/γ-Rays from PSR 1509–58, *Ap. J.*, **428**, 284 (1994).

Ho, C., Spectra of Crab-Like Pulsars, *Ap. J.*, **342**, 396 (1989).

Jahoda, K. *et al.*, In Orbit Performance and Calibration of the Rossi X-Ray Timing Explorer (RXTE) Proportional Counter Array (PCA), *Proc. SPIE*, 2808, 59 (1996).

Jung, J.V., The Hard X-Ray to Low-Energy Gamma-Ray Spectrum of the Crab Nebula, *Ap. J.*, **338**, 972 (1989).

Knight, F.K., Observations and Interpretations of the Pulsed Emission form the Crab Pulsar, *Ap. J.*, **260**, 538 (1982).

Manchester, R.N., J.M. Durdin, and L.M. Newton, A Second Measurement of a Pulsar Braking Index, *Nature*, **313**, 374 (1985).

Marsden, D. *et al.*, The X-Ray Spectrum of the Plerionic System PSR B1509-58/MSH 15-52, *Ap.J. (Letters)*, 491, L39 (1997).

Seward, F.D., and F.R. Harnden, A New, Fast X-Ray Pulsar in the Supernova Remnant MSH 15–52, *Ap. J.*, **256**, L45 (1982).

Seward, F.D., F.R. Harnden, Jr., A. Szymkowiak, and J. Swank, The X-Ray Nebula Around PSR 1509–58, *Ap. J.*, **281**, 650 (1984).

Tamura, K., N. Kawai, A. Yoshida, and W. Brinkmann, Evidence for a Pulsar Jet Producing a Hot Nebula in the Supernova Remnant MSH 15–52, *PASJ*, **48**, L33 (1996).

Thorsett, S.E., *Nature*, **356**, 690 (1992).

Ulmer, M.P., *et al.*, OSSE Observations of the Crab Pulsar, *Ap. J.*, **432**, 228 (1994).