

THE PULSED HARD X-RAY SPECTRUM OF PSR B1509–58

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ABSTRACT

OSSE observed the 150 ms X-ray pulsar PSR B1509–58 in the supernova remnant MSH 15–52 for four weeks in 1992. The pulsed spectrum from 50 keV to 5 MeV is well-fit by a single power law photon spectrum of the form $(3.14 \pm 0.16) \times 10^{-6} \times (E/118.5 \text{ keV})^{-1.68 \pm 0.09} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$. This is significantly harder than the Crab pulsar spectrum in this energy range. The *Ginga* soft X-ray spectrum (2 – 60 keV) reported by Kawai et al. is significantly harder than the observed OSSE spectrum and predicts a flux two times higher than we observe in the $\sim 55 - 170$ keV energy band. This requires a break to a steeper spectrum somewhere in the intermediate energy range ($\sim 40 - 80$ keV). The spectrum must soften again at higher energies or the pulsar would have easily been detected by EGRET, *COS B*, and SAS-2.

Subject headings: gamma rays: observations — pulsars: individual (PSR B1509–58) — X-rays: stars

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1. INTRODUCTION

PSR B1509–58 is a rotation powered pulsar with a period of approximately 150 ms and the largest measured period derivative (Lyne & Graham-Smith 1990). It was first discovered in soft X-rays in data from the *Einstein Observatory* (Seward & Harnden 1982). Using the known period and approximate position, Manchester, Tuohy, & D’Amico (1982) then found the radio signal. The pulsar is positionally coincident with the optical supernova remnant MSH 15–52; however, it is not certain that the pulsar and SNR are actually related, due to an apparent difference in age (Manchester et al. 1982; van den Bergh & Kamper 1984). Seward et al. (1984) found an extended X-ray source coincident with the pulsar which they identify as a synchrotron nebula like that surrounding the Crab pulsar. In the *Einstein* energy range (0.2 – 4 keV) the pulsed emission is only about 5% of the flux from the extended source. The light curve consists of a single pulse in both the radio and soft X-rays; however, using *Ginga* data, Kawai et al. (1991) determined that the soft X-ray pulse lagged the radio pulse by about 0.25 periods.

In 1991 the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory (GRO)* detected the pulse from PSR B1509–58 to greater than 200 keV in epoch-folded hard X-ray data (Wilson et al. 1992). This made it one of only three pulsars, along with the Crab (Ulmer et al. 1993a and references therein) and Vela (Strickman et al. 1993), to be detected in this energy range (~ 100 keV – 1 MeV). The pulsar was subsequently observed by the Oriented Scintillation Spectrometer Experiment (OSSE), also on *GRO*. The combined BATSE and OSSE data were used to confirm the radio/X-ray pulse offset seen by *Ginga*, and determine a phase difference of 0.32 ± 0.02 , independent of energy between ~ 20 and 500 keV (Ulmer et al. 1993b). We report here on a further analysis of the OSSE data and derive a photon spectrum for the pulsed emission above 50 keV.

2. OBSERVATIONS

The OSSE instrument is described in detail by Johnson et al. (1993). It consists of four independent cylindrical NaI/CsI phoswich scintillators, actively shielded on the sides by NaI. The front of each detector is covered by a tungsten collimator, which defines a rectangular ($11.4^\circ \times 3.8^\circ$ FWHM) field of view. Each detector may be positioned independently about an axis parallel to the long direction of the collimator.

OSSE observed PSR B1509–58 in two separate viewing periods: 1992 March 19 – April 2 and October 15 – 29. During the observations two of the detectors pointed continuously

Table 1: RADIO EPHEMERIS FOR PSR B1509–58

ν	$6.6371895831124 \text{ s}^{-1}$
$\dot{\nu}$	$-6.76844 \times 10^{-11} \text{ s}^{-2}$
$\ddot{\nu}$	$1.97 \times 10^{-21} \text{ s}^{-3}$
$t_0(TDB)$	48420.0
$t_{0geo}(MJD)$	48420.000000121
$R.A. (J2000)$	$15^h 13^m 55^s.667$
$Dec (J2000)$	$-59^\circ 08' 9''.42$

at the pulsar while the other two viewed the pulsar and background regions alternately every 2 minutes. Pulsar data were only collected from a detector when it was pointing at PSR B1509–58. Due to bandwidth limitations, the high time resolution data required for pulsar analysis cannot be accumulated for the entire energy range of the instrument at the normal spectral energy resolution. For PSR B1509–58 we collected data as 8-ms rate samples in eight broad energy bands from ~ 50 to 5000 keV.

3. ANALYSIS

We have previously described the verification of the spacecraft clock and the epoch-folding procedure used to produce pulsar light curves for the 8 individual energy bands (Ulmer et al. 1993b). The pulsar ephemeris used in this analysis is given in Table 1 (Johnston et al. 1992).

In order to determine the pulsed spectrum we need to derive a pulsed intensity for each of the eight energy ranges for which we have high time resolution data. We have previously (Ulmer et al. 1993b) verified that the pulse shape seen by OSSE was consistent with that seen with greater significance at lower energies by *Ginga* (Kawai et al. 1991). We therefore normalized the *Ginga* $\sim 2 - 11$ keV light curve and used it as a template to fit our data in each energy range, varying the background (DC) intensity and the multiplicative scaling factor of the template to minimize chi-squared. The fluxes determined using this technique are consistent with those obtained from a simple pulse-on minus pulse-off difference, but are better constrained. Figure 1 illustrates the results of the fitting process for the two lowest pulsar energy ranges, using, for display purposes, combined data from both observations. The best-fit scaling factors for the eight energy windows, phase averaged, give the pulsed flux (in counts s^{-1}) as a function of energy.

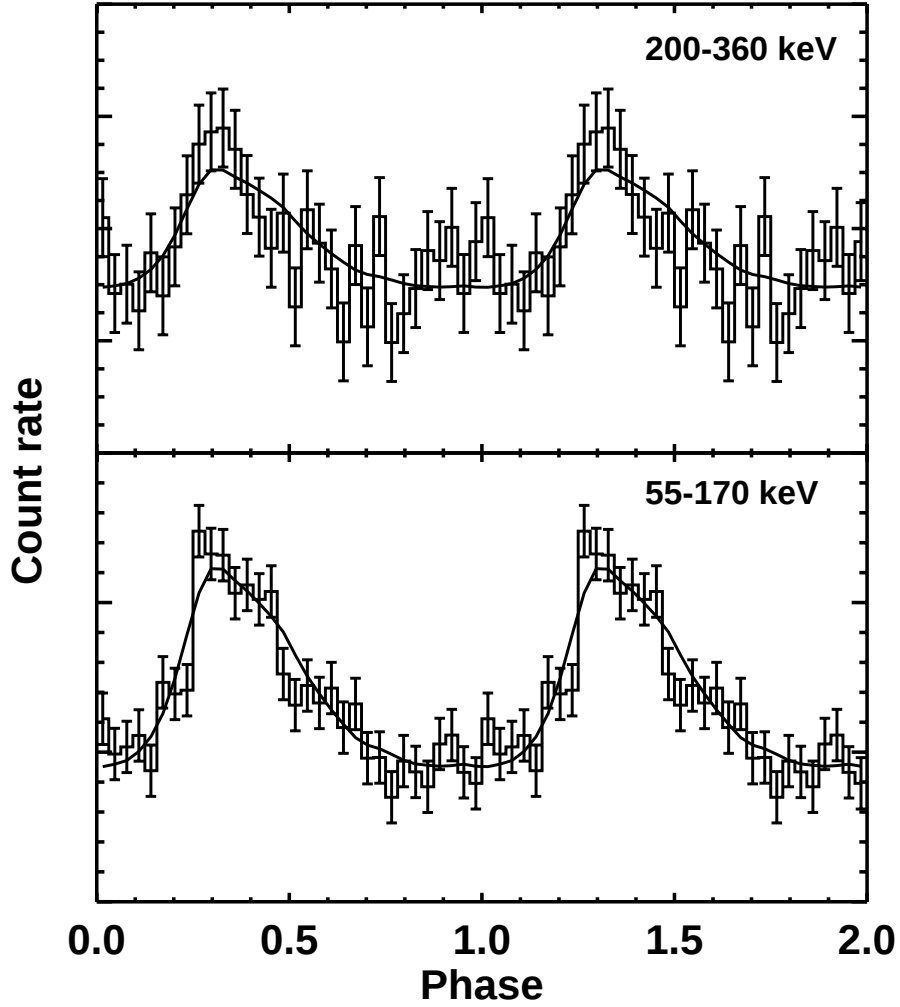


Fig. 1.— Plots of the pulsar light curves for the two lowest energy ranges, summed from the two observations. Overlaid on each of the plots is the fit of the normalized *Ginga* light curve.

A count rate vs. energy spectrum was obtained by this process for each of the two observations. The two spectra were then fit simultaneously to a single model spectrum using the standard OSSE spectral analysis procedure (Purcell et al. 1992): An instrument response matrix is generated giving the instrumental signal expected for incident photons of various energies, taking into account the position of the source in the collimator field of view. Model photon spectra are folded through this response to produce count rate spectra. These are integrated over the pulsar energy bands and the result compared to the observed count rate spectra. Chi-squared is minimized to determine the best values of the model parameters.

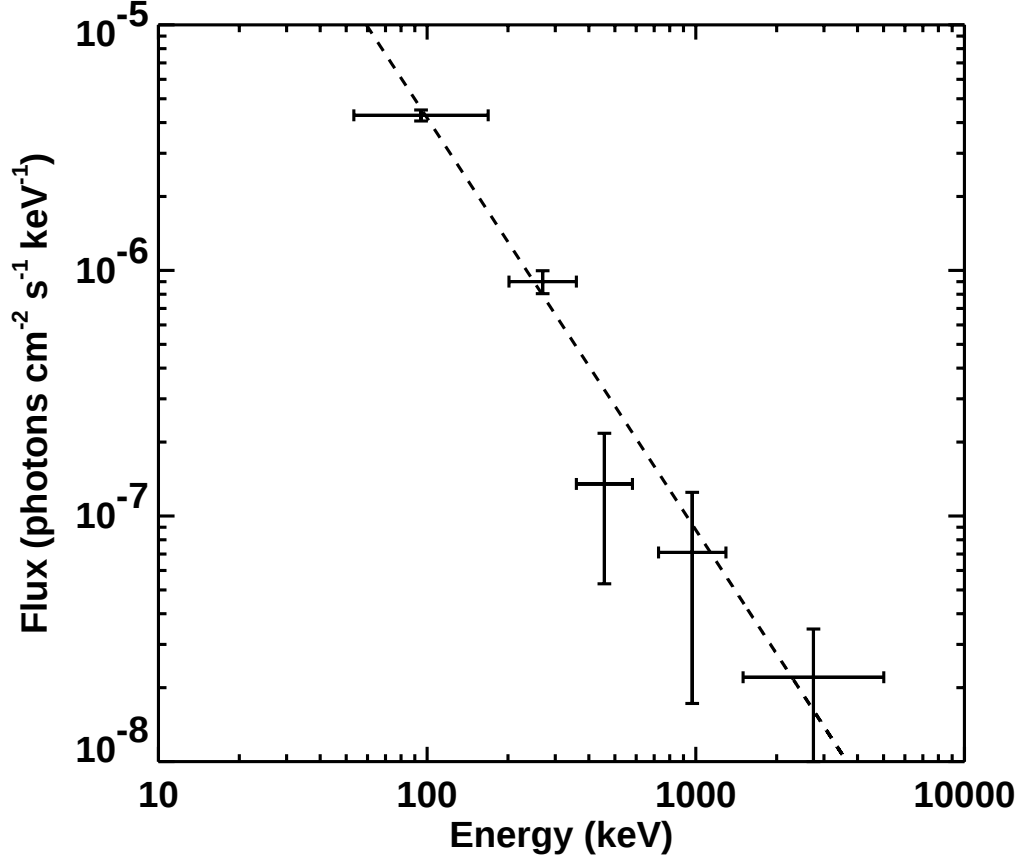


Fig. 2.— The deconvolved phase-averaged photon spectrum of the pulsar PSR B1509–58 along with the best fit power law. For display purposes *only* we have plotted the average spectrum from the two observations and combined some energy channels.

Fitting the two sets of data simultaneously to a single photon power law gives a best fit spectrum of $(3.14 \pm 0.16) \times 10^{-6} \times (E/118.5 \text{ keV})^{-1.68 \pm 0.09}$ photons cm⁻² s⁻¹ keV⁻¹, with a χ^2 of 17.3 for 14 degrees of freedom. The normalization energy has been chosen so that the errors in the two fitted parameters are uncorrelated. There was no evidence of any spectral variation between the two viewing periods; fits to the individual observations are consistent with the combined result. Figure 2 shows a plot of the fit and of the combined OSSE data converted to photon fluxes assuming the best-fit model spectrum. Note that the fit is largely driven by the two lowest energy bands since the higher energy points are all of low ($< 3\sigma$) significance. The derived spectral index is consistent with the preliminary result reported by BATSE (Wilson et al. 1993).

The spectral data from the two detectors which viewed both source and background regions allow us to place a limit on the non-pulsed emission from the pulsar and surrounding nebula. Using standard OSSE background estimation and subtraction techniques, we can produce an average difference spectrum for the source region. Because there are other sources of emission (including the galactic plane) within our field of view, the difference between the average and pulsed spectra gives only an upper limit on the non-pulsed emission. In the $\sim 55 - 170$ keV band this difference implies a 3σ limit on the non-pulsed flux of 1.5 times the pulsed flux. At lower energies ($0.2 - 4$ keV), Seward et al. (1984) reported an unpulsed flux 15 times higher than the pulsed flux. For comparison, the Crab non-pulsed flux is ~ 5 times the pulsed flux in this energy range (Knight 1982). More detailed analysis, including modelling the contribution from the diffuse galactic plane continuum, will be presented in a future work.

4. DISCUSSION

Ginga has recently reported (Kawai, Okayasu, & Sekimoto 1993) a power-law fit to the observed pulse spectrum from 2 to 60 keV of $(3.43 \pm 0.33) \times 10^{-3} \times (E/1 \text{ keV})^{-1.30 \pm 0.05}$ photons $\text{cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$. This fit is shown overplotted with our data and best power-law fit in Figure 3. Also shown is a flux value derived from the *Einstein* results as reported by Seward & Harnden (1982). A simple extrapolation of the *Ginga* fit to our energy range predicts a flux of $\sim 8.8 \times 10^{-6}$ photons $\text{cm}^{-2} \text{ s}^{-1}$ in the $55 - 170$ keV energy band, significantly higher than the value observed by OSSE, $(4.3 \pm 0.2) \times 10^{-6}$ photons $\text{cm}^{-2} \text{ s}^{-1}$. While the *Ginga* and OSSE instruments have not been directly cross calibrated, the uncertainties in the absolute efficiencies in these instruments (about 15% for *Ginga* (Kawai, private communication) and 5% for OSSE) are too small to explain this discrepancy in fluxes without a spectral break.

We can also directly compare the *Ginga* spectral shape with our data, independent of the normalization. We fit the OSSE pulsar spectrum with a photon power law with spectral index fixed at the *Ginga* value and with the normalization free. The best-fit had a χ^2 of ~ 45 for 14 DOF; this corresponds to a probability of $\sim 3 \times 10^{-5}$ that the *Ginga* spectral index actually describes our data. Like the intensity comparison, this indicates that a softening of the spectrum is required in a fairly narrow energy range ($\sim 40 - 80$ keV).

The pulsar spectrum is also constrained at high energies. An unbroken extrapolation of our fit to higher energies implies a flux of $\sim 7 \times 10^{-6}$ photons $\text{cm}^{-2} \text{ s}^{-1}$ from 30 to 100 MeV; Brazier et al. (1993) report a 99.9% upper limit based on EGRET observations of

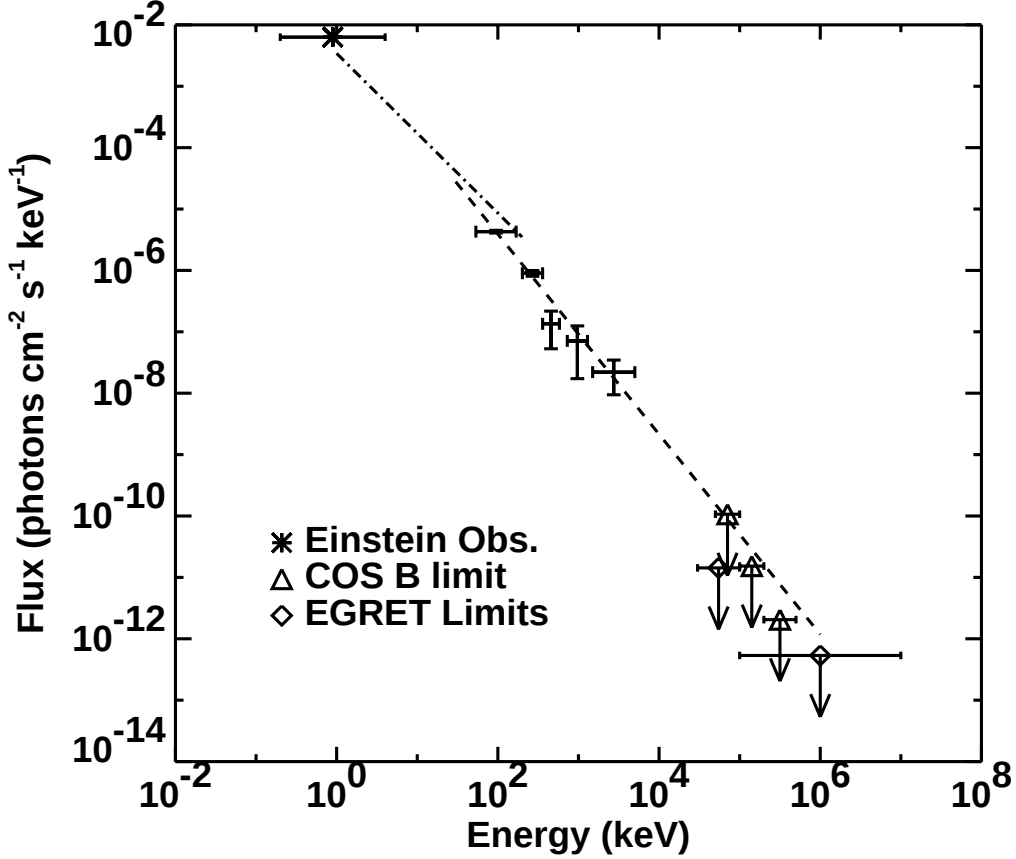


Fig. 3.— The OSSE data and spectral fit (dashed line) for PSR B1509–58 along with the *Einstein* flux measurement, the best-fit power law reported by *Ginga* (dash-dotted line), and upper limits from *COS B* (2σ) and EGRET (99.9%).

$\sim 1 \times 10^{-6}$ in the same energy range. Hartmann et al. (1993) analyzed the *COS B* data for this pulsar and report a marginal detection, which the authors interpret as upper limits. From their Figure 1b, the 2σ limits are about 1.5×10^{-6} and 6.2×10^{-7} photons $\text{cm}^{-2} \text{s}^{-1}$ in the 100 – 200 and 200 – 500 MeV energy ranges, respectively. These again are lower than the flux predicted by the extrapolation of our spectral fit: 2.1×10^{-6} and 1.7×10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ in the same energy bands. The spectrum must steepen somewhere above several hundred keV to agree with these high-energy limits. Figure 3 shows these limits compared to the power-law fit to the OSSE data.

PSR B1509–58 is only the third example of a rotation powered pulsar with a well-measured hard X-ray spectrum. The spectrum of PSR B1509–58 is significantly

harder than that of the Crab in this energy range ($\sim E^{-2.1}$, see, e.g., Knight 1982, Ulmer et al. 1993a). The Vela pulsar appears somewhat harder, about $E^{-1.3}$ from COMPTEL and OSSE data (Strickman et al. 1993; Hermsen et al. 1993). However, the spectra of these pulsars have important qualitative similarities. The Crab, Vela, and PSR 1509–58 are all consistent with power law photon spectra in the hard X-rays but require a broken power law to fit the data over a broader energy range: the Crab shows a change from $E^{-1.8}$ below ~ 20 keV to $E^{-2.1}$ above ~ 100 keV (Ulmer et al. 1993a); Vela softens from $\sim E^{-1.3}$ to $\sim E^{-1.7}$ in the MeV range (Hermsen et al. 1993); and PSR B1509–58 changes from $\sim E^{-1.3}$ for *Ginga* (2 – 60 keV) to $\sim E^{-1.7}$ for OSSE (> 55 keV). In each case the break is of about the same magnitude, ~ 0.4 in the spectral index. As noted above, a further softening at higher energies is required for PSR B1509–58 and there is also evidence for another break (at ~ 300 MeV) in the Vela spectrum (Grenier, Hermsen, & Clear 1988).

5. SUMMARY AND CONCLUSIONS

The pulsed spectrum of PSR B1509–58 measured by OSSE is well-represented by a photon power law of the form $(3.14 \pm 0.16) \times 10^{-6} \times (E/118.5 \text{ keV})^{-1.68 \pm 0.09}$ photons $\text{cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ from 50 keV to 5 MeV. The spectrum must flatten at lower energies to agree with the *Ginga* results and soften at higher energies to agree with measured upper limits > 30 MeV. The energies of these spectral changes are not well-determined; in particular, the softening at high energies could occur within the OSSE spectral range. COMPTEL has reported a marginal ($3 - 4\sigma$) detection of this pulsar in the 0.7 – 1.0 MeV range (Bennett et al. 1993); it is possible that their flux in this band and their higher energy limits may provide a better constraint on the spectrum above 700 keV.

It is not clear from the available data whether the required changes in power-law index occur at discrete energies (producing breaks) or over a broad energy range. While we have followed previous authors in using a power law to describe our results, the data do not *require* this shape, nor do they require sharp breaks at lower and higher energies. A model with a continuously steepening spectrum could describe the observed spectral softening yet roughly conform to power-laws over the energy ranges of *Ginga* and OSSE. Further observations of this and other hard X-ray pulsars are necessary to determine more precisely the spectral shapes of the pulsed emission and guide the makers of pulsar emission models.

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REFERENCES

- Bennett, K., et al. 1993, 23rd International Cosmic Ray Conference, 1, 172
- Brazier, K. T. S., et al. 1993, MNRAS, submitted
- Grenier, I. A., Hermsen, W., & Clear, J. 1988, A&A, 204, 117
- Hartmann, D. H., Brown, L. E., Clayton, D. D., Schnepf, N., Cordes, J. M., & Harding, A. 1993, in *Isolated Pulsars*, ed. K. A. Van Riper, R. Epstein, & C. Ho (Cambridge: Cambridge University Press), 405
- Hermsen, W., et al. 1993, in *Compton Gamma-Ray Observatory* (AIP Conf. Proceedings 280), ed. M. Friedlander, N. Gehrels, & D. J. Macomb (New York: American Institute of Physics), 204
- Johnson, W. N., et al. 1993, ApJS, 86, 693
- Johnston, S., Kaspi, V. M., Manchester, R. N., Lyne, A. G., & D'Amico, N. 1992, GRO/radio timing data base, Princeton University
- Kawai, N., Okayasu, R., Brinkmann, W., Manchester, R., Lyne, A. G., & D'Amico, N. 1991, ApJ, 383, L65
- Kawai, N., Okayasu, R., & Sekimoto, Y. 1993, in *Compton Gamma-Ray Observatory* (AIP Conf. Proceedings 280), ed. M. Friedlander, N. Gehrels, & D. J. Macomb (New York: American Institute of Physics), 213
- Knight, F. K. 1982, ApJ, 260, 538
- Lyne, A. G., & Graham-Smith, F. 1990, *Pulsar Astronomy* (Cambridge: Cambridge University Press)
- Manchester, R. N., Tuohy, I. R., & D'Amico, N. 1982, ApJ, 262, L31
- Purcell, W. R., et al. 1992, in *The Compton Observatory Science Workshop* (NASA Conference Publication 3137), ed. C. R. Shrader, N. Gehrels, & B. Dennis (Washington, D.C.: NASA), 15
- Seward, F. D., & Harnden, F. R. 1982, ApJ, 256, L45
- Seward, F. D., Harnden, F. R., Szymkowiak, A., & Swank, J. 1984, ApJ, 281, 650

- Strickman, M. S., et al. 1993, in Compton Gamma-Ray Observatory (AIP Conf. Proceedings 280), ed. M. Friedlander, N. Gehrels, & D. J. Macomb (New York: American Institute of Physics), 209
- Ulmer, M. P., et al. 1993a, ApJ, in press
- Ulmer, M. P., et al. 1993b, ApJ, 417, 738
- van den Bergh, S., & Kamper, K. W. 1984, ApJ, 280, L51
- Wilson, R. B., Finger, M. H., Fishman, G. J., Meegan, C. A., & Paciesas, W. S. 1992, IAU Circ. 5429
- Wilson, R. B., Finger, M. H., Pendleton, G. N., Fishman, G. J., Meegan, C. A., & Paciesas, W. S. 1993, in Isolated Pulsars, ed. K. A. Van Riper, R. Epstein, & C. Ho (Cambridge: Cambridge University Press), 257