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EVIDENCE FOR SHOCK ACCELERATION IN THE BINARY PULSAR SYSTEM PSR B1259−63

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ABSTRACT

The PSR B1259−63 system (Johnston et al. 1992, 1994) was observed near periastron by the *Compton Gamma-Ray Observatory* in 1994 January. This system contains a rapidly rotating pulsar and a Be star in a highly eccentric binary orbit. We report the discovery by the OSSE instrument of unpulsed emission with a hard power-law spectrum between 50 and 200 keV from the direction of this system. Neither diffuse Galactic background emission nor nearby X-ray binaries contribute significantly to the detected flux. Our results are particularly important for the theory of interaction of pulsars with gaseous environments. We interpret the hard X-ray emission as synchrotron radiation from relativistic particles of the PSR B1259−63 wind being shocked and accelerated within the binary. Our results indicate, for the first time in a binary pulsar, that shock acceleration can increase the original energy of pulsar wind particles by a factor $\gtrsim 10$, despite the high synchrotron and inverse Compton cooling rates near periastron. The derived shock properties (efficiency, radiation spectrum, timescale) are relevant for a broad class of high-energy astrophysical sources characterized by shocked relativistic plasmas subject to strong radiative cooling.

Subject headings: acceleration of particles — gamma rays: observations — pulsars: individual (PSR B1259−63)— shock waves

1. INTRODUCTION

The PSR B1259−63 system contains a rapidly rotating radio pulsar with spin period $P = 47.76$ ms and spin-down luminosity $L_p \simeq 9 \times 10^{35}$ ergs s^{-1} orbiting around a massive Be star companion in a highly elliptical orbit with orbital period ~3.4 yr (Johnston et al. 1992, 1994). The interest in a detailed study of high-energy emission from the PSR B1259−63 system near periastron is manifold. Be stars are known to produce substantial gaseous outflows mainly concentrated in their equatorial planes (e.g., Waters et al. 1988), and the interaction of nebular material with a radio pulsar can in principle lead to accretion-powered high-energy emission or detectable shock emission. High-energy emission from the PSR B1259−63 system is likely to be enhanced near periastron, since the pulsar approaches its Be star companion at an orbital distance $a \sim 10^{13}$ cm, corresponding to ~10–20 stellar radii of the companion. Typical orbital distances near apastron of the PSR B1259−63 system are a factor of 10 larger. Radio pulsars lose their rotational energy by the emission of an electromagnetic and relativistic particle wind composed of electrons and positrons (Kennel & Coroniti 1984). It is also likely that the relativistic winds from radio pulsars contain heavy ions (see Gallant & Arons 1994, and references therein, for evidence supporting this view). In the PSR B1259−63 system the interaction of a relativistic pulsar wind and a mass outflow from a Be star can be studied for the first time in a time-variable environment with a shock radius $r_s \lesssim 10^{13}$ cm (Tavani, Arons, & Kaspi 1994).

High-energy emission (i.e., X-rays and gamma-rays) can be radiated by a pulsar wind termination shock during the periastron passage of PSR B1259−63, and this possibility motivated a long (3 week) observation by the *Compton Gamma-Ray Observatory* (*CGRO*). The *CGRO* instruments cover a broad energy range between 30 keV and ~30 GeV. Here we focus on the positive detection of hard X-rays in the direction of the PSR B1259−63 system by the OSSE instrument. We briefly comment on how the detected emission can be used to sensibly constrain models of high energy emission from pulsar termination shocks. A more detailed theoretical analysis of our results will appear elsewhere (Tavani & Arons 1995).

2. OBSERVATIONS

OSSE observed PSR B1259−63 for the 3 week period 1994 January 3–23 chosen to cover the periastron passage (1994 January 9; Johnston et al. 1994). The OSSE instrument consists of four nearly identical large-area NaI(Tl)–CsI(Na) phoswich detector systems (Johnson et al. 1993). It covers the energy range from 50 keV to 10 MeV with good spectral resolution. A tungsten slat collimator defines the $3\overset{\circ}{.}8 \times 11\overset{\circ}{.}4$ field of view, which was chosen as a compromise allowing high sensitivity to both diffuse emission and point sources. Spectra are accumulated in a sequence of 2 minute measurements of the source field alternated with 2 minute, offset-pointed measurements of background.

The pulsar is located in the Galactic plane at $304\overset{\circ}{.}2$ longitude, where Galactic diffuse continuum emission is detectable by OSSE. To minimize the effect of the Galactic emission, the observation of PSR B1259−63 was performed with the long axis of the collimator oriented perpendicular to the plane and centered on the pulsar. Background fields on either side, centered at $308\overset{\circ}{.}7$ and $296\overset{\circ}{.}4$ longitude, were selected to avoid nearby point sources such as the X-ray binaries GX 301−2, Cen X-3, and 2S 1417−624. These objects, shown by the BATSE instrument on *CGRO* to be occasional emitters in the

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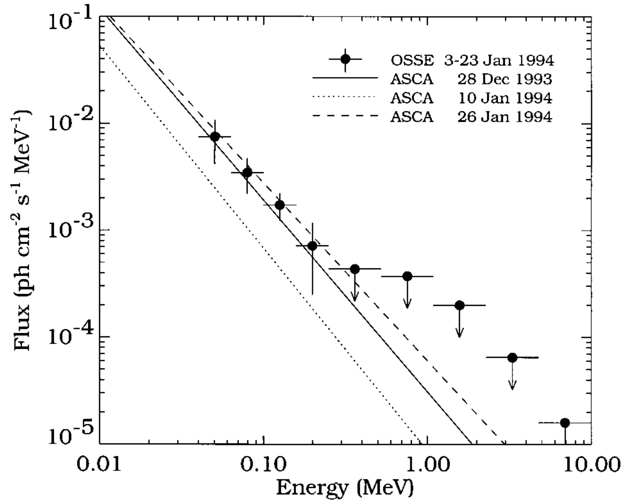

FIG. 1.—OSSE spectrum of emission from the region of PSR B1259−63. Schematic extrapolations to the power-law spectra of *ASCA* observations from 1993 December 28 (*solid line*), 1994 January 10 (*dotted line*), and 1994 January 26 (*dashed line*) are also shown. *ASCA* extrapolations obtained from the analysis of Kaspi et al. (1995).

20–50 keV band (R. Wilson 1994, private communication), are each suppressed by a factor of more than 10^2 by the collimator and account for no detectable emission in the source field. Unavoidably, the source field contained the Be star binary pulsar GX 304−1; however, this X-ray pulsar has not been detected by BATSE in 3 years of daily observation (M. Finger 1994, private communication), and it was shown by *EXOSAT* to be in an off state in 1984 (Pietsch et al. 1986). A total exposure time $T = 1.9 \times 10^5$ s of highest quality data were collected in two OSSE detectors on the PSR B1259−63 source field, with approximately an equal time on the background fields.

3. RESULTS

The energy spectrum from the PSR B1259−63 region is shown in Figure 1. Emission is detected from 50 to ∼200 keV, with a total statistical significance of 4.8 σ, at a level of ∼5 mcrab (total) flux units.

The best-fit power-law photon number spectrum for photon energies E in the 50–300 keV band is $dN_\gamma/dE = (2.8 \pm 0.7) \times 10^{-3} E_2^{-\alpha}$ γ cm^{-2} s^{-1} MeV^{-1}, with photon index $\alpha = 1.8 \pm 0.6$ and $E_2 = E/(100$ keV). The power-law fit is good ($\chi^2_{\rm dof} = 0.90$ for 40 degrees of freedom). Also shown in Figure 1 are schematic extrapolations from the power-law fits to the *ASCA* data from 1993 December 28, 1994 January 10, and 1994 January 26 (Kaspi et al. 1995). We note that the uncertainties in *ASCA*'s fit parameters are such that the three models are essentially equivalent at 100 keV. The emission in the OSSE band is, therefore, consistent in intensity and spectral shape with a simple power-law extrapolation of the *ASCA* observations. The continuation of the power-law spectrum to hard X-ray energies is very significant for the interpretation of the emission (see § 4). At 2.0 kpc (Johnston et al. 1994), the inferred 50–200 keV luminosity of the PSR B1259−63 system is $L_X \simeq 3 \times 10^{34}$ ergs s^{-1}, and the hardness of the OSSE spectrum suggests that the luminosity per energy decade peaks near or above 200 keV.

There is no evidence for variability in the OSSE data; however, because of the relatively low statistical significance of the detection, the constraints on variability are not stringent. The 95% confidence upper limits on 50–200 keV variability on daily or weekly timescales are ∼190% and ∼70%, respectively. Any flux decrease by ∼50% during the 3 week observing period, as suggested by the *ASCA* data, is undetectable by OSSE. Because of the brevity of our observation in relation to the 3.4 yr binary period, we are unable to place a meaningful limit on modulation at orbital timescales.

For weak detections such as that from the PSR B1259−63 field, it is important to address possible systematic errors or alternate sources for the emission. A study of residuals in the 50–200 keV band from an aggregate of many OSSE pointings indicates that the systematic errors are smaller than the statistical errors and, therefore, that the ∼5 σ excess reported here should be exceedingly rare. The background fields of view were chosen to exclude known point sources of hard X-rays in the region, and the source field otherwise contained only GX 304−1, which is apparently in an off state (see § 2). Furthermore, we find no evidence for pulsations from GX 304−1 in the OSSE data at periods between 267 and 275 s, which reasonably bound extrapolations of the historical period.

OSSE is conducting an extensive survey of the galactic diffuse line and continuum emission (e.g., Purcell et al. 1994). To date, measurements appropriate to estimating the diffuse emission in the PSR B1259−63 region, i.e., those at similar separation from the Galactic center and without significant contributions from known point sources, are available only on the opposite side of the Galactic center, at longitudes 40° and 58°. From these measurements and a simple one-dimensional Galactic plane model, we estimate that the large-scale (i.e., ∼10°) longitudinal gradient in the emission per degree in the 50–200 keV band is $\sim -3 \times 10^{-5}$ γ cm^{-2} s^{-1} MeV^{-1} deg^{-2}. Assuming that the diffuse emission is generally symmetric about the Galactic center and convolving this emission through the instrument response, we estimate that the residual diffuse 50–200 keV flux for our viewing strategy of the PSR B1259−63 region is $\sim 2 \times 10^{-4}$ γ cm^{-2} s^{-1} MeV^{-1}, a factor of ∼10 less than the observed flux. We note, however, that the level of small-scale, local fluctuations in the diffuse emission is somewhat uncertain and not easily measured, given the presence of nearby point sources. Such fluctuations are the most likely alternative explanation for the observed flux.

Using the radio ephemeris (Manchester et al. 1995) for the spin and binary orbital parameters of PSR B1259−63, we searched for pulsed emission at the rotation period of the neutron star in OSSE's high time resolution data channels, which provided 8 ms (or faster) rate samples over 50–180 keV. No pulsed emission was detected on any day or for the total observation. However, we caution that because of the long integrations required in the hard X-ray regime, small errors in the pulsar ephemeris could smear coherent pulsations. The 95% confidence upper limits for pulses of phase width 0.15 or 0.5 in the 50–180 keV band over the 21 day observation period are $\Phi_{0.15} = 3 \times 10^{-4}$ and $\Phi_{0.5} = 7 \times 10^{-4}$ γ cm^{-2} s^{-1} MeV^{-1}, respectively. The former corresponds to 3 mcrab pulsar flux units. Upper limits for individual days are typically a factor of $\sqrt{21}$ higher.

The region of PSR B1259−63 was also observed by OSSE in 1992 September 19–1992 October 3 (TJD 8518–8532), when the pulsar was far from periastron, as part of OSSE's Galactic plane survey. However, the sensitivity was reduced by the placement of the pulsar in the wing of the collimator, which was aligned with the plane. Any unpulsed emission from the pulsar was masked by GX 301−2 and Cen X-3 (both at high sensitivity near the center of the field of view) as well as by diffuse emission from the plane. While these data therefore cannot provide a useful limit on unpulsed emission from PSR B1259−63 away from periastron, they have been used in a search for pulsed emission (Ray et al. 1992). The resulting 99.9% confidence limit of 6×10^{-3} γ cm^{-2} s^{-1} MeV^{-1} in the 64–150 keV band was achieved through a search of a large volume of acceleration space, as an adequate binary ephemeris was not then available in the radio. We have reanalyzed these data with the ephemeris of Johnston et al. (1994) and set an upper limit of 1.4×10^{-3} γ cm^{-2} s^{-1} MeV^{-1}.

4. DISCUSSION

Hard X-ray emission from a neutron star with a power-law extending up to ~200 keV and with photon index $\alpha \sim 1.8$–2 is a manifestation of energetic particle acceleration. Accreting neutron stars do not usually emit in the hard X-ray range (White, Nagase, & Parmar 1995) with photon energies $E_X \gtrsim 50$ keV. Only sporadic hard X-ray emission from a few accreting neutron stars has been reported (Barret & Vedrenne 1994), and a power-law fit to the spectrum typically gives a photon index ~2–3 or larger. In the case of emission from the direction of the PSR B1259−63 system, the lack of pulsations, the absence of detectable flux variations within the timescale of weeks, the relatively low hard X-ray luminosity, and the spectrum substantially harder than for accreting neutron stars (and consistent with an extrapolation to soft X-ray energies) all argue against accretion-powered emission (Tavani & Arons 1995; Kaspi et al. 1995).

Hard X-rays provide crucial information on the shock emission due to the interaction of the relativistic particle wind of PSR B1259−63 with the nebular gas of the Be star mass outflow. As in the case of the Crab nebula (Kennel & Coroniti 1984; Gallant & Arons 1994), shock acceleration and synchrotron radiation capable of producing unpulsed hard X-ray emission occurs at a shock radius within the PSR B1259−63 binary where pressure balance is established (Tavani et al. 1994) between the pulsar relativistic wind (electrons/positrons, possibly ions) and the ram pressure of the Be star outflow. The radiative environment near the shock radius within the PSR B1259−63 system is quite different from that of the Crab nebula, and the large synchrotron and inverse Compton cooling rates ($\sim 10^{-2}$–10^{-3} s^{-1}) at the PSR B1259−63 periastron make the detection of high-energy emission a unique diagnostic of shock acceleration subject to strong radiative cooling (Tavani et al. 1994; Tavani & Arons 1995). By comparing the OSSE and *ASCA* results a unified picture for the emission and spectrum emerges. Spectral calculations for models with a weak ram pressure of the Be star outflow show that the dominating inverse Compton spectrum is typically much too flat to agree with the OSSE data (Tavani & Arons 1995). Instead, the spectral shape and intensity of the power-law emission from the PSR B1259−63 system are consistent with synchrotron radiation of shock-accelerated electron-positron pairs for an intermediate value of the ram pressure of the Be star outflow and a shock distance relatively close to the pulsar rather than to the Be star. The inferred characteristics of the electron-positron pairs in the pulsar wind are a Lorentz factor of $\gamma_1 \sim 10^6$ and a ratio of electromagnetic energy density to particle kinetic energy density in the wind of $\sigma \sim 10^{-1}$–10^{-2} (Tavani & Arons 1995). The efficiency of conversion of the pulsar wind kinetic and electromagnetic energy into radiation in the 50–200 keV band is ~3% for a system distance of 2 kpc (Johnston et al. 1994). The absence of a spectral break—from the soft X-ray band above $\epsilon_{\min} \sim 1$ keV (Kaspi et al. 1995) through the lower limit on the high-energy cutoff, $\epsilon_{\max} \gtrsim 200$ keV, from the OSSE observations—strongly constrains the acceleration mechanism. The collisionless pulsar wind shock must produce a power-law particle distribution function of index δ between a minimum $e^{\pm}$ pair energy $E_1 = \gamma_1 m_e c^2$ and an upper energy cutoff $E_c = \gamma_c m_e c^2$, where m_e is the electron-positron mass and c is the speed of light. For a synchrotron model of shock emission, we obtain

$$\frac{\gamma_c}{\gamma_1} \gtrsim \left(\frac{\epsilon_{\max}}{\epsilon_{\min}}\right)^{1/2} \sim 10, \tag{1}$$

and $\delta = 2\alpha - 1 \sim 2$–3. The OSSE observation of the PSR B1259−63 system therefore demonstrates, for the first time in a Galactic source, the ability of shock acceleration to efficiently energize a relativistic plasma subject to radiative cooling with typical timescale $\tau_c \sim 10^2$ s. The important derived constraints on the radiation efficiency (~3%), acceleration timescale ($\lesssim \tau_c$), index of the postshock particle distribution ($\delta \sim 2$–3) are of crucial interest for any theory of relativistic shock acceleration.

Our results can have a broad range of applications to astrophysical sources with relativistic plasmas being shocked and accelerated in a strongly radiative environment. Our observations of the PSR B1259−63 system show that shock emission is an efficient mechanism of unpulsed high-energy radiation in pulsar binaries. Poorly understood, unidentified, and time-variable high-energy Galactic sources (e.g., Fichtel et al. 1994) may reveal energetic pulsars powering unpulsed emission in binaries.

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