

## X-RAY EMISSION FROM THE DOUBLE PULSAR SYSTEM J0737–3039

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### ABSTRACT

We report on a 10 ks observation of the double pulsar system J0737–3039 obtained with the *Chandra X-Ray Observatory*’s Advanced CCD Imaging Spectrometer. We detect the system as a point source with coordinates (J2000.0) R.A. = 07<sup>h</sup>37<sup>m</sup>51<sup>s</sup>.23, decl. = –30°39′40″.9, making this the first double neutron star system to be detected at X-ray energies. Only 77 source counts are detected. The data are represented satisfactorily by a power-law spectrum with photon index  $\Gamma = 2.9 \pm 0.4$ . The inferred 0.2–10 keV luminosity is  $\approx 2 \times 10^{30}$  ergs s<sup>–1</sup> for a distance of 0.5 kpc. We do not detect any significant variability with orbital phase in these data, which span one full orbit. These results are consistent with the X-ray emission originating solely from the magnetosphere of the energetic A pulsar, with an efficiency for conversion of rotational energy to X-rays in this band of  $\sim 0.04\%$ , although we cannot exclude other possibilities.

*Subject headings:* stars: neutron — X-rays: stars

*On-line material:* color figure

### 1. INTRODUCTION

Thirty years following the discovery of the first double neutron star (Hulse & Taylor 1975), only eight such systems are known. A few of these rare binaries are wonderful laboratories for the study of relativistic gravity and gravitational radiation. One of the more recently discovered of these systems, J0737–3039 (Burgay et al. 2003), is fundamentally different from all of the others observationally, in that it contains *two* detected pulsars (Lyne et al. 2004). The first pulsar discovered in the system (A) spins every 22 ms and has a low inferred surface magnetic field strength, a characteristic age of 210 Myr, and a relatively high rate of rotational energy loss,  $\dot{E} = 5.8 \times 10^{33}$  ergs s<sup>–1</sup>. Pulsar B has a period of 2.7 s, a characteristic age of 50 Myr, and an  $\dot{E}$  that is 3600 times smaller than that of A. Its mass,  $1.25 M_{\odot}$ , is the lowest known for any neutron star and is  $0.09 M_{\odot}$  less than that of A. Both pulsars orbit their common center of mass every 2.4 hr with eccentricity of 0.09. We observe the system nearly edge-on, with an orbital inclination of 87°.

A unique aspect of the system is that radio emission from pulsar B is only detected strongly in two repeatable orbital phase ranges, each of duration  $\sim 10$  minutes. A  $\sim 30$  s long eclipse of pulsar A is also observed at its superior conjunction. Both of these effects most likely result from the interaction of the fast-spinning pulsar’s relativistic wind with the magnetosphere of its much less energetic companion (Lyne et al. 2004).

This system will be an exceptional laboratory for relativistic astrophysics and should provide unique insights into the mag-

netospheres and the local environment of both neutron stars. High-energy observations, particularly at X-ray energies, could be especially valuable for understanding the energetics of the system. Whether resulting from magnetospheric or thermal processes, most pulsars emit of the order of  $10^{-3}\dot{E}$  in soft X-rays (Becker & Trümper 1999). This translates to an expected luminosity of the order of  $10^{31}$  ergs s<sup>–1</sup> for pulsar A and means that B should be undetectable because of its very low  $\dot{E}$  and relatively large age. But in this particular system, while still unlikely, it is conceivable that a portion of A’s relativistic Poynting/particle flux might heat the surface of B, perhaps causing it to emit detectable radiation. Such emission could prove invaluable for probing the atmosphere of B, which is likely to deviate significantly from standard models. A more likely source of “unusual” X-ray emission might be the shock that undoubtedly forms near pulsar B owing to the collision between A’s relativistic wind and B’s magnetosphere. Some of this emission could be time variable, for instance because of Doppler boosting.

Many of these emission modes are clearly speculative and hard to quantify with the present understanding of the system. Nevertheless, given the potential for unusual insights into the physics of this unique interacting binary, we have obtained a short X-ray observation of this system, awarded through the *Chandra* Director’s Discretionary Time program, in order to better plan future multiwavelength studies. In this Letter we report the detection of a point source at the position of the J0737–3039 system and describe its properties.

### 2. X-RAY OBSERVATIONS AND ANALYSIS

The double pulsar system J0737–3039 was observed with the Advanced CCD Imaging Spectrometer S-array (ACIS-S) instrument on board *Chandra* on 2004 January 18 for 10 ks (corrected exposure time was 10,009 s). The system’s position was located on the aim point of the ACIS S3 chip. We used the CIAO package,<sup>8</sup> version 3.0.2, to perform much of the analysis of these data, using the most recent release of the calibration software, CALDB 2.26, which corrects for the loss

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<sup>8</sup> Available at <http://asc.harvard.edu/ciao>.

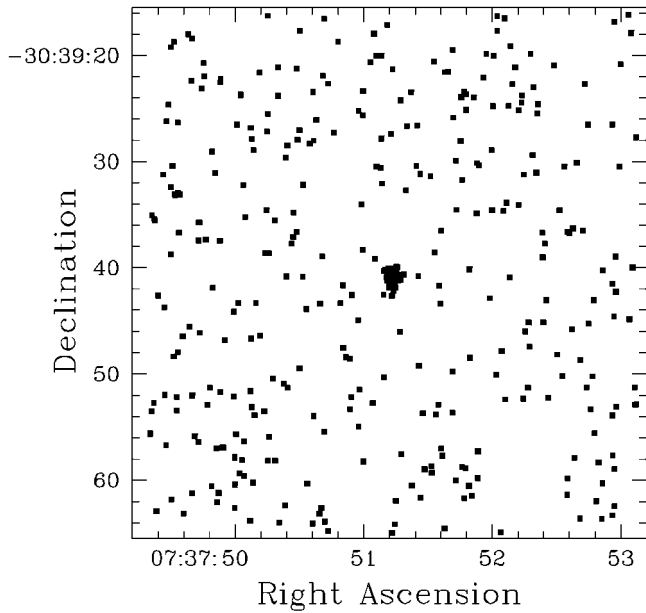


FIG. 1.—A  $50' \times 50'$  portion of the ACIS-S3 chip in the 0.2–10 keV band, with the double pulsar J0737–3039 at its center. No other sources were detected in the entire  $16' \times 16'$  area of the chip.

of quantum efficiency at low energies due to molecular contamination. As shown in Figure 1, we detect a source at (J2000.0) R.A. =  $07^{\text{h}}37^{\text{m}}51^{\text{s}}.23$ , decl. =  $-30^{\circ}39'40''.9$ . No other sources are detected in the entire S3 chip. This position is  $0''.3$  away from that derived from radio timing of the pulsars (Lyne et al. 2004), well within the X-ray  $1 \sigma$  position uncertainty of  $0''.8$ , dominated by the satellite pointing error of approximately  $0''.7$ . We have therefore detected the J0737–3039 system in X-rays. Using a circular aperture of radius  $2''$  centered on the position of the system and four background regions, we determine that  $77 \pm 9$  counts originate from the pulsar, corresponding to a rate of  $(7.7 \pm 0.9) \times 10^{-3}$  counts  $\text{s}^{-1}$ . The system is detected as a point source, with the spatial spread consistent with the point-spread function of the instrument.

We used PSEXTRACT to obtain a spectrum for this source and fit it using Sherpa, the CIAO modeling and fitting package. As shown in Figure 2, a steep power-law spectrum fits the data satisfactorily, with photon index  $\Gamma \approx 2.9$  and neutral hydrogen column density  $N_{\text{H}} \approx 5 \times 10^{20}$   $\text{cm}^{-2}$ . Because of the small number of counts we use the maximum likelihood method to fit these data, implemented in Sherpa with the CSTAT statistic (Cash 1979). This fit returns a  $Q$ -value (i.e., the probability that we would observe the measured CSTAT statistic or higher if the best-fit model is true) of 0.96. The best-fit blackbody and Raymond-Smith models return  $Q$ -values of  $3 \times 10^{-5}$  and  $2 \times 10^{-5}$ . A thermal bremsstrahlung model returns a  $Q$ -value of 0.55, but the best-fit value of  $N_{\text{H}} \sim 1 \times 10^{19}$   $\text{cm}^{-2}$  is unreasonably low. Fitting for multicomponent models or models with more free parameters is unreasonable because of the small number of counts available. While there are only two counts with energies greater than 3 keV, the fitted parameters do not change substantially if these counts are removed. Similarly, the fit does not change substantially if we exclude photons with energies less than 0.5 keV, where ACIS-S calibration is somewhat uncertain.

Figure 3 shows the contour plot of the CSTAT statistic for the best-fit model in the  $N_{\text{H}}-\Gamma$  plane. From the derived count

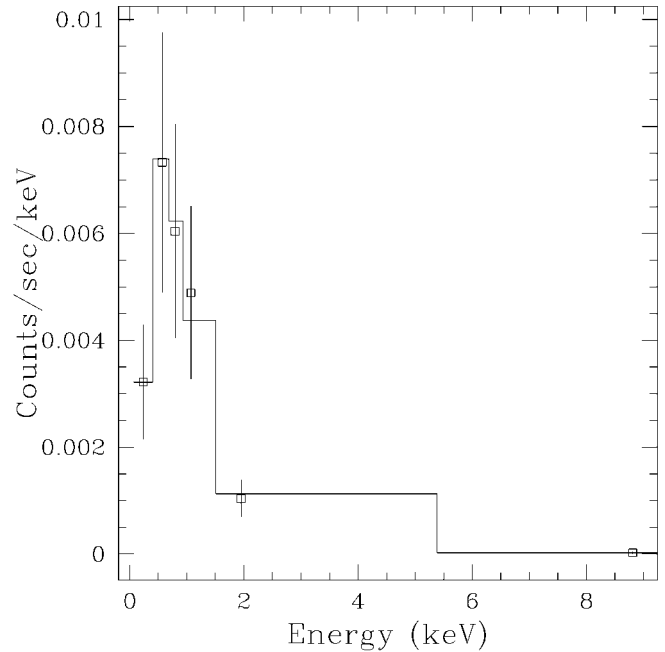


FIG. 2.—Background-subtracted spectrum of J0737–3039, with the power-law fit described in § 2. Each of the first five energy bins contains 15 counts; the last bin contains two counts. The squares are placed at the average energy of the photons in each bin, while the solid best-fit line illustrates each bin's full width. Error bars, calculated by Sherpa, account for uncertainties in both source counts and the instrumental model. [See the electronic edition of the *Journal* for a color version of this figure.]

rate and spectral fit, we calculate a 0.2–10 keV unabsorbed flux of  $f_{\text{x}} \approx 8 \times 10^{-14}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$ . Assuming isotropic emission and for a distance  $d \sim 0.5$  kpc, inferred from its dispersion measure (i.e., free electron column density) and a model for the Galactic electron density (Cordes & Lazio 2002), we obtain a

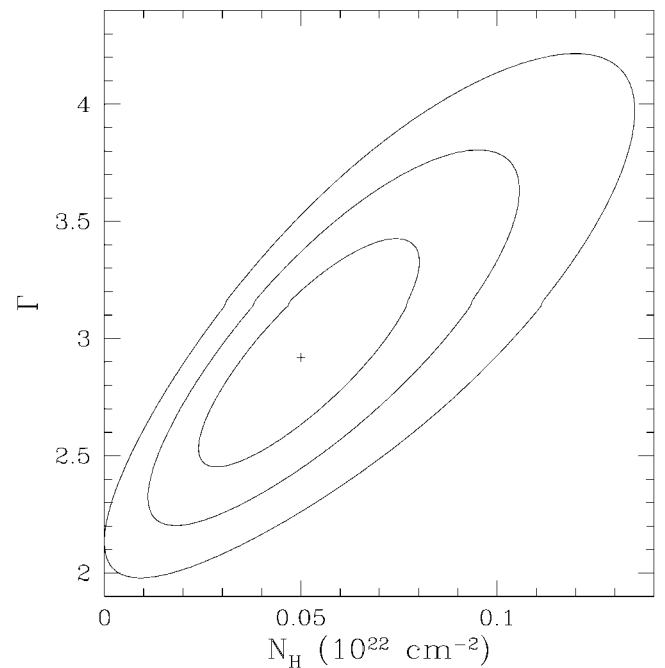


FIG. 3.—Contour plot of the CSTAT statistic as a function of the neutral hydrogen column density  $N_{\text{H}}$  and the photon index  $\Gamma$ . The plotted confidence levels are 1, 2, and 3  $\sigma$ .

TABLE 1  
X-RAY PROPERTIES OF THE J0737–3039 SYSTEM

Parameter	Value
$\Gamma$ , photon index .....	$2.9^{+0.4}_{-0.4}$
$N_{\text{H}}$ , neutral hydrogen column density ( $10^{20} \text{ cm}^{-2}$ ) .....	$4.8^{+3.4}_{-2.4}$
$f_{\text{X}}$ (0.2–10 keV), flux ( $10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ ) .....	$7.6^{+1.6}_{-1.2}$
$L_{\text{X}}$ (0.2–10 keV), luminosity ( $10^{30} \text{ ergs s}^{-1}$ ) .....	$2.3^{+0.5}_{-0.4}$
$L_{\text{X}}/E$ (0.2–10 keV) ( $10^{-4}$ ) .....	$4.0^{+0.8}_{-0.6}$

NOTES.—Results from a fit to ACIS-S3 data of the form  $dN \propto E^{-\Gamma} dE$ . Flux has been corrected for interstellar absorption. Luminosity assumes a distance of 0.5 kpc (see § 2) and is the same, within the errors, for the 0.2–3 keV energy range. Uncertainties correspond to  $1 \sigma$  confidence levels.

0.2–10 keV luminosity of  $L_{\text{X}} \approx 2 \times 10^{30} (d/0.5 \text{ kpc})^2 \text{ ergs s}^{-1}$ . In Table 1 we list all relevant spectral quantities and their uncertainties. We stress that  $d$ , and hence the derived luminosity, may be uncertain by a factor of 2 or more because of unmodeled electron density features associated with its position near the Gum Nebula (Mitra & Ramachandran 2001). VLBI observations will be important for determining the actual distance.

The value of  $N_{\text{H}}$  derived for the system, while rather uncertain, is much smaller than the total Galactic value of  $4.65 \times 10^{21} \text{ cm}^{-2}$  derived by Dickey & Lockman (1990) from neutral hydrogen measurements. It is also smaller (at greater than  $1 \sigma$ ) than the value of  $1.5 \times 10^{21} \text{ cm}^{-2}$  derived from its dispersion measure, assuming 10 H atoms for each  $e^-$ . Our derived  $N_{\text{H}}$ , however, is marginally greater than expected given the measured neutral hydrogen absorption to other sources with similar longitude, latitude, and  $\sim 0.5$  kpc distance<sup>9</sup> and is more consistent with the measurements if a distance of at least  $\sim 1$  kpc is assumed. Such discrepancies between  $N_{\text{H}}$  measurements and dispersion-measure derived distances for pulsars are not unusual (e.g., Nicastro et al. 2004). Also, since the source closest to J0737–3039 with a neutral hydrogen absorption measurement is a radial distance of  $\sim 0.1$  kpc away and because the errors on our  $N_{\text{H}}$  and distance measurements are large, further observations are necessary to determine if such a discrepancy exists.

In Figure 4 we plot the number of photons detected in each of 10 time bins over the 10 ks observation (i.e., 1.13 orbital periods). There is no significant evidence for variability, with a  $\chi^2$  test revealing only a 51% probability that the data were drawn from a nonuniform distribution. We also do not see any correlation between time and the energy of the photons. The small number of detected photons makes searching for variability on shorter timescales impossible.

### 3. DISCUSSION

We have detected the J0737–3039 system as a faint X-ray source that is best described by a steep power-law spectrum with  $\Gamma \approx 2.9$  and  $L_{\text{X}} \approx 2 \times 10^{30} (d/0.5 \text{ kpc})^2 \text{ ergs s}^{-1}$  (see Table 1). This result is compatible with the emission originating solely from the magnetosphere of pulsar A: Becker & Trümper (1999) find that for recycled radio pulsars that are detected at X-ray energies,  $L_{\text{X}} \sim 10^{-3} \dot{E}$ , and that when their spectra can be fitted by a power law,  $2 \lesssim \Gamma \lesssim 2.4$ . While by comparison our spectral index is a bit steep and our efficiency for conversion of rotational to X-ray energies is a little small [ $4 \times 10^{-4} (d/0.5 \text{ kpc})^2$ ], un-

<sup>9</sup> See the ISM Hydrogen Column Density Search Tool at <http://archive.stsci.edu/eu/ism/ismform.html>.

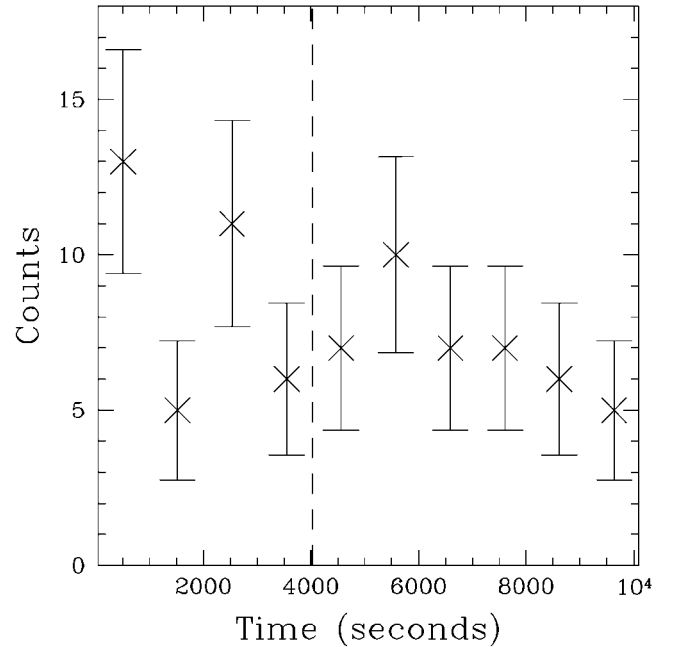


FIG. 4.—Number of counts (shown with Poisson error bars) vs. elapsed time (since the start of the observation) with 10 bins across the 10 ks observation. The orbital period of the system is 8835 s. Orbital phase calculated from barycentered data (with respect to the ascending node of pulsar A) ranged from  $281^\circ$  at the start of the observation to  $328^\circ$  at the end, with the dashed line marking the superior conjunction of A.

certainties in spectral parameters and distance make this interpretation perfectly plausible. The steepness of the spectrum suggests that it may consist of both magnetospheric and blackbody components. However, more sensitive observations are needed to test this hypothesis. We note in passing that the X-ray luminosity detected from the system is roughly equal to the entire spin-down luminosity of pulsar B.

Another intriguing possibility is that these X-rays are produced when the relativistic winds of A and B collide. As shown by Arons & Tavani (1993), the synchrotron emission produced in such interactions would also be expected to have a power-law X-ray spectrum with  $\Gamma \sim 2$ . Unfortunately, the data from this short observation are not sufficient to discriminate between these two possibilities. More sensitive observations with better time resolution are necessary in order to obtain a better spectral fit, determine what portion of the detected X-ray flux is pulsed at the rotation period of pulsar A, quantify better any possible time variability (the observed radio flux density of B varies dramatically on  $\sim 5$ – $10$  minute timescales that are impossible to investigate with the present data), and measure any thermal component that may be contributing to the total X-ray flux of this system.

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