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A NEW TRANSIENT PULSAR IN THE SMALL MAGELLANIC CLOUD WITH AN UNUSUAL X-RAY SPECTRUM

JOHN P. HUGHES[1]
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
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ABSTRACT

This article reports the discovery of a luminous (3.5×10^{37} ergs s^{-1} over the 0.2–2 keV band) transient X-ray pulsar in the Small Magellanic Cloud (SMC) with an extremely soft component to its X-ray spectrum. This is the first time that a spectrum of this type has been seen in this class of X-ray source. The pulse period is 2.7632 s, and the pulse modulation appears to vary with energy from nearly unpulsed in the low-energy band of the *ROSAT* PSPC (0.07–0.4 keV) to about 50% in the high-energy band (1.0–2.4 keV). The object, RX J0059.2−7138, also shows flickering variability in its X-ray emission on timescales of 50–100 s. The pulse-phase–averaged PSPC X-ray spectrum can be well described by a two-component source model seen through an absorbing column density of $\sim 10^{21}$ atoms cm^{-2}. One spectral component is a power law with photon index 2.4. The other component is significantly softer and can be described by either a steeply falling power law or a blackbody with a temperature $kT_{\mathrm{BB}} \sim 35$ eV. This component is transient, but evidently unpulsed, and, for the blackbody model fits, requires a large bolometric luminosity: near, or even several times greater than, the Eddington luminosity for a 1.4 $M_{\odot}$ object. When these characteristics of its soft emission are considered, RX J0059.2−7138 appears quite similar to other X-ray sources in the Magellanic Clouds, such as CAL 83, CAL 87, and RX J0527.8−6954, which show only extreme ultrasoft (EUS) X-ray spectra. The discovery of RX J0059.2−7138, a probable high-mass X-ray binary, clearly indicates that EUS spectra may arise from accretion-powered neutron-star X-ray sources. This result lends support to the idea that some of the "pure" EUS sources may be shrouded low-mass X-ray binaries rather than accreting white dwarfs.

Subject headings: binaries: general — pulsars: individual (RX J0059.2−7138) — stars: emission-line, Be — stars: neutron — X-rays: stars

1. INTRODUCTION

A possible new class of celestial X-ray sources, characterized by soft blackbody X-ray emission with temperatures in the range 30–100 eV, has recently been recognized based on observations by the *Einstein Observatory* (Long, Helfand, & Grabelsky 1981; Wang et al. 1991; Wang & Wu 1992) and *ROSAT* (Trümper et al. 1991; Greiner, Hasinger, & Kahabka 1991; Kahabka & Pietsch 1993; Pietsch & Kahabka 1993; Cowley et al. 1993; Schaeidt, Hasinger, & Trümper 1993; Orio & Ögelman 1993). In the several cases known, there is no measurable X-ray flux above 0.5 keV, and so these objects have been referred to as supersoft or, in the nomenclature I will use, extreme ultrasoft (EUS) sources. Several models have been proposed to explain the high luminosities and soft spectra seen from these objects: scattering in an extended accretion disk corona (Fabian, Guilbert, & Callanan 1987), Compton scattering in an optically thick cocoon surrounding a compact object undergoing supercritical accretion (Greiner et al. 1991), or the steady thermonuclear burning of hydrogen on an accreting white dwarf (van den Heuvel et al. 1992). In this article, I report the discovery by *ROSAT* of a luminous, transient X-ray pulsar in the Small Magellanic Cloud (SMC) which clearly shows, in addition to the power-law spectral component which is typical for these sources, an EUS spectral component. A combination spectrum of this type is reminiscent of that observed from the Galactic X-ray binary pulsar Her X-1 during its high state. The presence of pulsars, i.e., rapidly rotating neutron stars, in the latter two sources argues convincingly against the accreting white dwarf model as the explanation for their EUS emission.

2. ANALYSIS

RX J0059.2−7138 appeared as a serendipitous source in a short pointing (4900 s) of the bright supernova remnant 0102−72.2 in the SMC carried out on 1993 May 12 with the *ROSAT* Position Sensitive Proportional Counter (PSPC). It was some 33′ off-axis and had an exposure-corrected counting rate of 7.826 ± 0.047 s^{-1}. The best estimate of its position is $00^{\mathrm{h}}59^{\mathrm{m}}12^{\mathrm{s}}.9$, $-71°38'50''$ (J2000), after accounting for (1) a translational shift of $6''.4$ using the optical positions of two known sources near the center of the field; (2) a shift of $6''.9$ to correct for the recently discovered roll angle error in the *ROSAT* standard processing; and (3) a shift of $7''.4$ to compensate for the asymmetric shape of the coma-distorted image, due to the large field angle. This latter effect was "calibrated" using off-axis observations of LMC X-1 in other PSPC fields, and it was verified by applying the technique to another source in the 0102−72.2 field (see below). The positional uncertainty is limited by these systematic effects and is estimated to be no more than about 10″ in each coordinate. Within the X-ray source error circle there is a $B_J \sim 14.1$ mag *HST* guide star at position $00^{\mathrm{h}}59^{\mathrm{m}}12^{\mathrm{s}}.74$, $-71°38'44''.7$ (J2000), only 6″ from the X-ray position. Comparison of the *B*- and *V*-band images in the Hodge & Wright (1977) atlas of the SMC suggests that this star is bluer than its neighbors. The atlas also reveals another star fainter by about 1 mag approximately 11″ northwest of the *HST* guide star and about 16″ from the X-ray position. Any other plausible optical candidates within 20″ of the X-ray position must be significantly fainter ($m_V \gtrsim 16$) than these two.

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[1] E-mail: jph@cfa.harvard.edu.

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The *ROSAT* standard processing detected this source and indicated the presence of variability on a timescale of about 2.7 s. Using standard IRAF/PROS tasks, I confirmed this periodicity and refined the value of the pulse period (using period folding techniques and including barycenter corrections) to be 2.7632 ± 0.0002 s. Of the 32 known X-ray pulsars, only three have periods shorter than this value (White, Nagase, & Parmar 1994). The pulse profile is shown in Figure 1 in three separate energy bands (two cycles are shown). One single broad pulse is seen. The pulse modulation (defined as maximum minus minimum divided by the average) apparently increases with energy: 0.13 ± 0.15 over the 0.07–0.40 keV band, 0.27 ± 0.20 over 0.40–1.0 keV, and 0.52 ± 0.17 over 1.0–2.4 keV.

The observation consisted of four nearly equal time intervals, nearly equally spaced over a period of 18,438 s. I determined the pulse period independently for each of the four data intervals and obtained values which were consistent with the period derived from the entire data set. The source count rates, averaged over each of these four intervals, were constant within the errors, varying by less than ± 3% from the mean. On shorter timescales (50–100 s), however, RX J0059.2−7138 showed variability with excursions from the mean rate up to ~30%. Because of the large image size (FWHM ~1'.5), the wobble motion is not expected to introduce such a large modulation, and a direct comparison reveals that the wobble motion (at a period of 400 s) and the source variability were indeed uncorrelated. The variation in the soft (0.07–0.40 keV) and hard (0.40–2.40 keV) bands was weakly correlated (linear correlation coefficient ~0.2), but a definitive conclusion on this correlation is limited by the statistical error.

Examined over longer timescales, years to decades, the source is transient. It was not detected by *SAS 3*, which discovered SMC X-2 and SMC X-3 (Clark et al. 1978). It did not appear in three separate pointings with the *Einstein Observatory* in 1979 and 1980, and *EXOSAT* failed to detect it in 1983 (Jones et al. 1985). As for previous observations with the *ROSAT* PSPC: the all-sky survey (Kahabka & Pietsch 1993) in 1990 November and pointed observations (Pietsch & Kahabka 1993) in 1991 November also showed no evidence for a source this bright at the appropriate position. The 3 σ upper limit to the flux (0.2–2 keV band) of the new source (assuming the same intrinsic spectrum as used below) was 1.5×10^{-13} ergs s^{-1} cm^{-2} on 1979 November 13 based on *Einstein* imaging proportional counter (IPC) data. On 1980 December 26 the upper limit was 5.3×10^{-14} ergs s^{-1} cm^{-2} based on data from the *Einstein* high-resolution imager (HRI). This is over a factor of 1500 less than the flux quoted here.

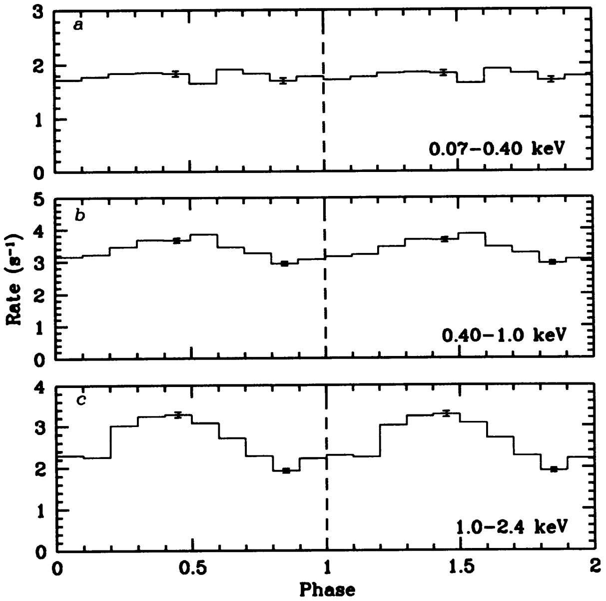

FIG. 1.—The pulse profile of RX J0059.2−7138 folded modulo the pulse period (2.7632 s) for three different energy ranges: (*a*) 0.07–0.40 keV, (*b*) 0.40–1.0 keV, and (*c*) 1.0–2.4 keV. In each panel two complete cycles are shown. The data have been background subtracted and exposure corrected.

Below a cutoff energy of roughly 10–20 keV, X-ray pulsars tend to show power-law spectra (White et al. 1994) with photon indices $\alpha_P \sim 1.0$–2.0. The pulse-phase–averaged soft X-ray spectrum of RX J0059.2−7138 is not well described by such a single power law observed through a line-of-sight absorbing column with solar abundances (using the photoelectric absorption cross sections from Balucinska-Church & McCammon 1992, including more recent updates to the cross sections of helium). The minimum χ^2 for this model is 46.57 for 24 degrees of freedom (including in each channel a 1% systematic error added in quadrature with the statistical error), which can be rejected at the 99.6% confidence level. The residuals from this fit are at the level of 15%–20%, significantly more than the calibration uncertainties in the PSPC spectral response function. Other simple, single-component models, such as blackbody, exponential, or thermal plasma emission (Raymond & Smith 1977), also can be rejected with high confidence. Reducing the metal abundance of the absorbing material in the line-of-sight (as might be indicated by the lower metallicity of the SMC) does not yield a better fit. I obtain an acceptable fit (reduced $\chi^2 \sim 1.03$ for 22 degrees of freedom) with a two-component model, either two power-law models or a power law and blackbody, provided that the second component is quite soft. This represents a highly significant reduction in χ^2 ($\gg$99.95% confidence level) for introducing two additional free parameters. Results of spectral fitting with a power-law plus blackbody model are given in Table 1, and the data and model are plotted in Figure 2.

The best-fit column density for RX J0059.2−7138 is greater than the Galactic column in this direction [$(3–7) \times 10^{20}$ cm^{-2}], but it is also less than the total integrated column through this part of the SMC ($\sim 4 \times 10^{21}$ cm^{-2}; see Hindman 1967). This result holds true even when different spectral models for the X-ray emission are used. This confidently places RX J0059.2−7138 within the SMC and also demonstrates that

TABLE 1

TWO-COMPONENT SPECTRAL MODEL FITS TO PULSE-PHASE–AVERAGED PSPC SPECTRUM

Parameters	Best-Fit Values[a]
N_H (atoms cm^{-2})	$(8.8^{+2.7}_{-2.1}) \times 10^{20}$
$F_{1\,keV}$[b] (photons s^{-1} cm^{-2} keV^{-1})	$(3.89^{+0.34}_{-0.26}) \times 10^{-2}$
α_P	$2.44^{+0.19}_{-0.16}$
L_{BB}[c] (ergs s^{-1})	$(6.7^{+43.1}_{-5.4}) \times 10^{38}$
kT_{BB} (eV)	$35.6^{+8.5}_{-7.2}$
χ^2 (dof)	22.68 (22)

[a] Statistical errors at 90% confidence.

[b] Flux density of power-law model at 1 keV.

[c] Bolometric luminosity of blackbody assuming a distance of 57.5 kpc.

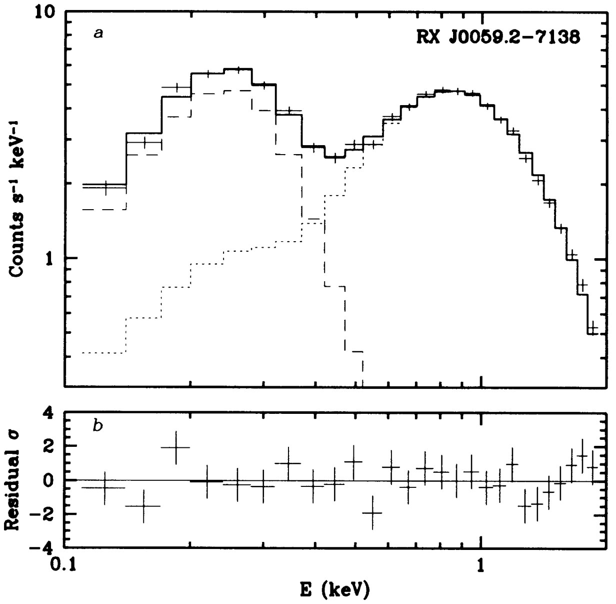

FIG. 2.—(*a*) The pulse-phase–averaged PSPC spectrum of RX J0059.2−7138 with the best-fit two-component model. The individual spectral components are shown as the dashed (blackbody) and dotted (power-law) histograms. (*b*) The difference between the observed data and the best-fit model expressed in terms of the statistical error in each energy channel.

it is not self-absorbed by a thick overlying corona. The flux in the 0.2–2 keV band is 8.7×10^{-11} ergs s^{-1} cm^{-2}, which implies a luminosity of 3.5×10^{37} ergs s^{-1} for a distance of 57.5 kpc (van den Bergh 1989).

As Table 1 indicates, the bolometric luminosity of the blackbody component itself is quite large. However, most of the luminosity from this component lies outside the *ROSAT* band; specifically, only some 15% of $L_{\rm BB}$ is above 0.2 keV, assuming the best-fit parameters in Table 1. In addition, the precise value of the blackbody component's luminosity is sensitive to the assumed shape of the higher energy spectral component. For example, substituting an exponential for the higher energy component resulted in a reduction of a factor of 8 in $L_{\rm BB}$, albeit with an increase in the best-fit χ^2 of 10.7 over the power-law plus blackbody model.

The results on the EUS spectral component are also sensitive to the X-ray absorption model used. When the data are fitted with Morrison & McCammon (1983) absorption cross sections and abundances, the derived luminosity of the blackbody component becomes about a factor of 2 larger than shown in Table 1. A more appropriate absorption model should consider the lower mean metal abundance of the SMC. If I assume that only part of the X-ray absorption (specifically, 3×10^{20} atoms cm^{-2}) comes from gas with solar composition while the remainder comes from gas with metallicity appropriate to the SMC (roughly 25% solar; see Russell & Dopita 1992), then the fits yield a luminosity of the blackbody component which is some 15% larger than that shown in Table 1. Therefore, all things being considered, the conclusion that RX J0059.2−7138 contains a highly luminous, extreme ultrasoft X-ray spectral component is nearly inescapable. The blackbody radii corresponding to the $L_{\rm BB}$ values quoted in Table 1 are $6^{+19}_{-4} \times 10^9$ cm. Finally, I note that the power-law index is slightly steeper than expected, based on extrapolating the spectral shape derived from 2–10 keV band observations of other X-ray pulsars.

A spectrum of the pulsed emission was made from phase bins 3–7 (see Fig. 1) using phase bins 1–2 and 8–10 for background. A single absorbed power law was an excellent fit to these data, $\chi^2 = 25.35$ for 24 degrees of freedom (confidence level for rejection being merely 61%). Both the line-of-sight column density, $N_{\rm H} = 0.6^{+1.9}_{-0.4} \times 10^{21}$ cm^{-2}, and the power-law index, $\alpha_P = 1.0^{+1.0}_{-0.7}$, were consistent with the values from the phase-averaged spectrum. The lack of an EUS spectral component to the pulsed emission is consistent with the lack of observed modulation in the lowest PSPC band and supports the conclusion that the EUS component is nearly unpulsed.

The nearest known X-ray source to the position of RX J0059.2−7138 is the EUS source 1E 0056.8−7154 discovered by the *Einstein Observatory* (Seward & Mitchell 1981; Bruhweiler et al. 1987; Wang & Wu 1992). This source was detected in both the *ROSAT* all-sky survey (Kahabka & Pietsch 1993) and in PSPC pointed observations (Pietsch & Kahabka 1993). I, too, clearly detect it about 4′ northwest of the new transient at a counting rate of 0.372 ± 0.011 s^{-1}. Its usefulness to the current analysis rests mainly on the independent check it provides for the procedure used to determine the position of RX J0059.2−7138. The position of 1E 0056.8−7154 derived from the PSPC data, after correcting for the three effects listed above, is within 5″ of the HRI position. This agreement verifies the procedure used to determine accurate positions of off-axis sources in this PSPC field and establishes the level of positional accuracy obtained.

This source is indeed soft: there are almost no photons detected above an energy of 0.5 keV. A fit of a blackbody spectrum to the PSPC data yields a temperature of $kT_{\rm BB} = 24$ eV and column density of 4.4×10^{20} atoms cm^{-2} for a source at a distance of 57.5 kpc emitting at the Eddington luminosity ($\sim 10^{38}$ ergs s^{-1}) for a 1.4 $M_\odot$ object. Comparison to the *Einstein* IPC and HRI data from 1979 and 1980 indicates possible long-term variability at the level of 20%–40%. These characteristics are very similar to those from other EUS sources in the LMC (Greiner et al. 1991).

3. DISCUSSION

Most known X-ray pulsars in binaries occur in high-mass systems, i.e., where the companion is an O or B star. These systems also show transient X-ray outbursts and flaring behavior on timescales of minutes. Since RX J0059.2−7138 displays all these properties, I tentatively identify it as a high-mass X-ray binary and perhaps even a Be/X-ray binary. This would suggest that the optical counterpart is indeed the 14.1 mag *HST* guide star mentioned above. The brightness of this star is similar to that of other optically identified high-mass X-ray binaries in the Magellanic Clouds and would indicate a spectral type around B0 (for luminosity classes III–V). Narrow-band optical images of this part of the SMC from an observing session at the CTIO Schmidt telescope on 1993 December 11 indicate the presence of Hα emission from the star at a level of about 15 Å equivalent width (R. C. Smith, 1994 private communication). Additional optical follow-up observations of the proposed counterpart, which should be able to confirm the identification, are underway.

The new SMC transient shares some characteristics of its X-ray emission with the well-studied Galactic low-mass X-ray binary, Her X-1. Like RX J0059.2−7138, Her X-1 is a short-period (1.24 s) X-ray pulsar. Perhaps one of the most interesting and relevant features of the X-ray emission of Her X-1 is the highly luminous EUS spectral component ($kT_{\rm BB} \sim 100$ eV), which it shows during high state (Shulman et al. 1975; Catura & Acton 1975). This intense soft X-ray emission has been attributed to reprocessing of the hard X-ray emission from the neutron star surface by either (1) an opaque partial shell of gas near the Alvén radius (Basko & Sunyaev 1976; McCray & Lamb 1976) or (2) the inner edge of an accretion disk (McCray et al. 1982). The latter scenario was motivated by detailed measurements of the pulse profile of Her X-1, which indicated strong modulation ($\sim$50%–100%) in the soft X-ray pulse waveform, shifted in phase relative to the hard X-rays.

Strong modulation is clearly not observed in the soft X-ray flux of RX J0059.2−7138, and in this respect, then, it is more similar to the several "pure" EUS sources seen in the Magellanic Clouds, such as CAL 83, CAL 87, RX J0527.8−6954, and the EUS source 1E 0056.8−7154 mentioned above. One of the models which may explain the soft X-ray emission from these sources is similar to the opaque partial shell model for Her X-1 mentioned above, in that it entails reprocessing of harder X-rays from the central accreting source. In this case, a compact object is shrouded by massive accretion, and the soft X-ray emission arises from the Compton scattering of harder X-rays from near the surface of the accreting object by a surrounding cocoon of ionized matter (Ross 1979). Furthermore, as shown by Kylafis & Xilouris (1993), models of this type for the EUS sources can be made consistent with unified models for low-mass X-ray binaries. For RX J0059.2−7138, any possible surrounding opaque shell surely must be partial, since I see the harder pulsed X-ray emission, which shows no evidence for intrinsic absorption, from near the neutron star's surface. Indeed, the challenge to understanding the X-ray emission from RX J0059.2−7138 in the context of this model rests on finding a geometry for the partial shell which would provide both the broad pulse seen in the hard X-rays but which would also produce little or no modulation in the EUS X-ray flux.

It is clear that the competing theory for the EUS sources in which the soft X-ray emission arises from steady thermonuclear burning of hydrogen on the surface of a white dwarf accreting from a main-sequence companion (van den Heuvel et al. 1992) cannot be an explanation for the soft emission from either Her X-1 or RX J0059.2−7138. One of the motivations for this attractive model arose from the concern that accreting neutron stars or black holes would be unable to reprocess the hard radiation from the central star into the soft X-ray band. The discovery of an EUS X-ray spectral component in an accretion-powered neutron star system, as presented here, indicates that such reprocessing is not only possible but evidently occurs in nature. It remains to be seen whether or not this discovery weakens support for the accreting white dwarf model as a description of the pure EUS sources.

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