**BeppoSAX and Chandra Observations of SAX J0103.2−7209 = 2E 0101.5−7225: A New Persistent 345 Second X-Ray Pulsar in the Small Magellanic Cloud**

G. L. Israel, S. Campana, S. Covino, D. Dal Fiume, T. J. Gaetz, S. Mereghetti, T. Oosterbroek, M. Orlandini, A. N. Parmar, D. Ricci, and L. Stella

Received 1999 December 6; accepted 2000 January 24; published 2000 February 15

**ABSTRACT**

We report the results of a 1998 July BeppoSAX observation of a field in the Small Magellanic Cloud which led to the discovery of ~345 s pulsations in the X-ray flux of SAX J0103.2−7209. The BeppoSAX X-ray spectrum is well fitted by an absorbed power law with a photon index of ~1.0 plus a blackbody component with $kT = 0.11$ keV. The unabsorbed luminosity in the 2–10 keV energy range is $\sim 1.2 \times 10^{36}$ ergs s$^{-1}$. In a very recent Chandra observation, the 345 s pulsations are also detected. The available period measurements provide a constant period derivative of $\dot{P} = 1.7$ s yr$^{-1}$ over the last 3 years, making SAX J0103.2−7209 one of the most rapidly spinning up X-ray pulsars known. The BeppoSAX position (30″ uncertainty radius) is consistent with that of the Einstein source 2E 0101.5−7225 and the ROSAT source RX J0103.2−7209. This source was detected at a luminosity level of a few times $10^{35}$−$10^{36}$ ergs s$^{-1}$ in all data sets of past X-ray missions since 1979. The ROSAT HRI and Chandra positions are consistent with that of a $m_v = 14.8$ Be spectral-type star already proposed as the very likely optical counterpart of 2E 0101.5−7225. We briefly report and discuss photometric and spectroscopic data carried out at the ESO telescopes 2 days before the BeppoSAX observation. We conclude that SAX J0103.2−7209 and 2E 0101.5−7225 are the same source: a relatively young and persistent X-ray pulsar in the SMC.

**Subject headings:** binaries: general — pulsars: individual (SAX J0103.2−7209, 2E 0101.5−7225)— stars: emission-line, Be — stars: rotation — X-rays: stars

1. INTRODUCTION

During 1997–1998, the number of X-ray pulsars found in the Small Magellanic Cloud (SMC) rapidly increased from three (SMC X-1, RX J0058.2−7226, and 2E 0050.1−7247; Lucke et al 1976; Hughes 1994; Israel et al. 1997) to 14 (for a review, see Yokogawa et al. 1998) thanks to sensitive observations using the large-area detectors on board the Rossi X-Ray Timing Explorer and ASCA satellites. The majority were found to be associated with massive Be spectral-type stars showing intense Hα emission lines. Only SMC X-1, which is associated with a supergiant B0 spectral-type star in a 3.9 day orbital period binary system, is a persistent (although moderately variable) X-ray pulsar. For all the remaining X-ray pulsars, pronounced variability (a factor $\geq 50$) or, more often, transient behavior has been definitively proven.

The source 2E 0101.5−7225 was detected at a nearly constant flux level in all the Einstein, ROSAT, and ASCA pointings that surveyed the relevant region of the SMC (see Hughes & Smith 1994), but pulsations were not found because of poor statistics. Based on the accurate position obtained with the ROSAT HRI, these authors found that 2E 0101.5−7225 is very likely associated with a Be spectral-type star (R.A. = $01^\circ 03^\prime 13^\prime\prime.86$, decl. = $−72^\circ 09^\prime 14^\prime\prime.1$; equinox J2000). The source 2E 0101.5−7225 is located near the optical limb of the supernova remnant SNR 0101−72.4. Hughes & Smith (1994) present several arguments that make the Be/X-ray binary—supernova remnant association unlikely.

In this Letter, we report the discovery of 345 s pulsations from the source SAX J0103.2−7209 during a BeppoSAX observation of the SMC. The comparison with the data of past X-ray missions allows us to conclude that SAX J0103.2−7209 and 2E 0101.5−7225 are the same object, a persistent source with moderate variability (within a factor of 5–10). We also report the results of the timing analysis of a recent public Chandra observation and discuss optical observations carried out at ESO.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. BeppoSAX Observation

The SMC field including the position of the 2E 0101.5−7225 was observed by the Narrow Field Instruments on board the BeppoSAX satellite (Boella et al. 1997a) on 1998 July 26–27 (effective exposure time of 40,320 s). We used data from the Medium-Energy (MECS; Boella et al. 1997b) and Low-Energy Concentrator Spectrometer (LECS; Parmar et al. 1997) instruments. A bright X-ray source (~$3.7 \times 10^{-2}$ counts s$^{-1}$, 1–10 keV) was detected on-axis in the MECS at R.A. = $01^\circ 03^\prime 13^\prime\prime$; decl. = $−72^\circ 09^\prime 16^\prime\prime$ (J2000: 90% confidence uncertainty radius of 30'). The MECS event list and spectrum were extracted from a circular region of 4′ radius (corresponding to an encircled energy of ~90%) around the X-ray position. A 4′ extraction radius (~85% encircled energy) was also used for the LECS in order to minimize the contamination of the soft X-ray emission from the bright nearby source 2E 0102.3−7217. The local background was measured in a region of the MECS and LECS images far from any detected field sources.
The arrival times of the ~1500 photons were corrected to the barycenter of the solar system, and background-subtracted light curves were accumulated in 0.5 s bins. A single power spectrum was calculated over the entire time span covered by the observation in order to maximize the sensitivity to coherent pulsations. Significant power spectrum peaks were searched for using the algorithm described in Israel & Stella (1996). A highly significant peak (~9.4σ based on the fundamental only; see upper left panel of Fig. 1) was found at a frequency of 0.002889 Hz, corresponding to a period of 345.2 s. An accurate determination of the period was obtained by fitting the phases of the modulation over four different intervals of ~16,000 s each. The scatter of the phase residuals was consistent with a strictly periodic modulation at the best period of 345.2 ± 0.3 s (90% confidence). A comparison of the 1–4 keV (Fig. 1, panel S) and 4–10 keV (panel H) folded light curves provides marginal evidence for an energy-dependent pulse profile: nearly sinusoidal at low energies but double-horned above 4 keV.

A spectral analysis was performed in the 0.7–6.5 and 1.6–10 keV energy ranges for the LECS and MECS, respectively. The spectra were rebinned to have at least 20 counts in each energy channel, such that χ² fitting techniques could be used. No single-component model was found to fit the data well (a power law gave a χ²/dof = 41/15, where dof is degrees of freedom). Among double-component models, an absorbed power law plus a blackbody gave the best fit (χ²/dof = 15/15) for a photon index of 1.0±0.2, N_H ≤ 3.8±2.5 × 10²¹ cm⁻², and a blackbody temperature of 0.11 ± 0.03 keV (uncertainties refer to 1σ).

The observed flux in the 2–10 keV energy band was 2.7 × 10⁻¹² ergs s⁻¹ cm⁻² (the soft component accounts for ~15% of the total), corresponding to an unabsorbed 2–10 keV X-ray luminosity of 1.2 × 10³⁶ ergs s⁻¹ assuming a distance of 62 kpc (Laney & Stobie 1994).

### Table 1

| Mission  | Instrument | Period (s) | Date      | Exposure (s) | 2–10 keV L_x (× 10^{36} ergs s⁻¹) | Reference                  |
|----------|------------|------------|-----------|--------------|----------------------------------|----------------------------|
| ASCA     | GIS        | 348.9 ± 0.3| 1996 May 21–23 | 32,912    | 5                                 | Yokogawa & Koyama 1998    |
| BeppoSAX | MECS       | 345.2 ± 0.2| 1998 Jul 26–27 | 40,320    | 11                                | Israel et al. 1998; this work |
| Chandra  | ACIS       | 343.5 ± 0.5| 1999 Aug 23   | 19,551     | ...                               | This work                  |

Note.—Luminosities refer to absorbed fluxes; 90% uncertainties are reported.
2E 0101.5
residuals.
in the high-resolution imaging mode for an effective exposure
time of 19,551 s. The source was detected at an off-axis angle
in the S4 (front-illuminated) CCD of the ACIS-S
detector with a count rate of about 9
counts s\(^{-1}\) in the 2–60 keV range; see Fig. 3,
bottom). The source shows two emission peaks separated by \(\approx 5\)°. However, the size of
the emission region is comparable with the 90% encircled energy
region of a source at 9° off-axis angle. We extracted a 3.24 s
binned light curve of the source from a region within 8° from
the center of the emission: R.A. = 01h03m 14s.06, decl. =
\(-72°09'15.25\) (equinox J2000). The statistical uncertainty ra-
dius is only \(\approx 0.5\)°, but at this stage the uncertainty in the absolute
positioning at such an off-axis angle might be as large as 90°.
However, the detection of the pulsations clearly associates the
Chandra source with that of BeppoSAX. We also note that the
Chandra coordinates are consistent with the ROSAT HRI un-
certainty circle and differ by less than 2° from those of the
proposed optical counterpart (see below), making the associ-
cation very likely. According to the Chandra source naming
convention, we designated it as CXO J010314.1–720915.

A single power spectrum was calculated over the entire ob-
servation. The search was performed over a period interval
around that detected by BeppoSAX and assuming a maximum
\([\dot{P}]\) of \(\approx 3\) s yr\(^{-1}\), which translates into a search over only two
Fourier frequencies (see Fig. 1, lower panels). A peak was
detected at a significance level of 7.5 \(\sigma\). A refined period was
determined by means of the phase-fitting technique; this gave
a value of 343.5 ± 0.5 s (see Table 1). We note that the Chandra
data were not corrected to the barycenter of the solar sys-
tem. However, for a relatively long-period pulsar in the direc-
tion of the SMC, the effect of the spacecraft and of the Earth’s
motion would cause a maximum correction of a factor of 10
smaller than the statistical uncertainty of the period given
above. The pulse profile is sinusoidal (over the whole Chandra
energy band), and the pulsed fraction is \(\approx 45\%\) (see Fig. 1).

In order to further address the issue of the double-peaked
Chandra image (see Fig. 3), we extracted two separate light
curves for each of the two peaks. We found that the signal
at 343.5 s was present with a similar pulsed fraction in both light
curves; this result is consistent with the hypothesis of a point-
like source. An independent confirmation was also obtained
through a raytracing simulation, encompassing a monochro-
matic source (1.49 keV) and models for the mirror assembly
and ACIS detector. The results indicate that the point-spread
function at an off-axis angle of 9° is artificially elongated in
the direction connecting the two peaks detected in the Chandra
image around the position of 2E 0101.5–7225; the two peaks
are probably artifacts resulting from the small number of X-
rays in the image. We conclude that the source is consistent with being pointlike.

3. OPTICAL OBSERVATIONS

Optical images (Hα and Hβ red continuum; 200 s each) of the BeppoSAX error circle of SAX J0103.2−7209 were obtained on 1998 July 24 at the Danish 1.5 m telescope with the Danish Faint Object Spectrometer Camera at La Silla (Chile) in order to search for emission-line stars. The data were reduced using standard ESO-MIDAS procedures for bias subtraction, flat-field correction, aperture photometry, and one-dimensional stellar and sky spectra extraction. Within the BeppoSAX position circle, we found only one Hα active object: this is the O9−B1 III−Ve $m_{{\text{V}}}=14.8$ star originally suggested as the optical counterpart of 2E 0101.5−7225 (Hughes & Smith 1994). A 10 Å resolution 3800−8500 Å spectrum (2″ slit) of this star was obtained with the same instrument on 1998 October 20. Strong Hα and Hβ emission lines were detected, with equivalent widths $-20 \pm 2$ and $-1.8 \pm 0.2$ Å, respectively. These results are in good agreement with those obtained by Hughes & Smith (1994) during observations carried out on 1992 December.

4. DISCUSSION

Although 2E 0101.5−7225 shares several characteristics with other X-ray pulsators in the Magellanic Clouds and in the Galactic plane (i.e., the spin period and pulsed fraction, the spectral shape at high energy and the presence of a soft thermal component, the association with a high-mass companion, etc.), it has also some peculiar differences which make it unusual.

The absence of long-term variability greater than a factor of $5−10$ over an interval of $\sim20$ years is strongly suggestive of a persistent X-ray pulsar, the second in the SMC since the discovery of pulsations from SMC X-1. Moreover, the association of the companion with a Be spectral-type star makes 2E 0101.5−7225 the first example of a persistent (main-sequence) Be/X-ray binary system in the SMC. The source 2E 0101.5−7225 is also a relatively low-luminosity ($10^{35}−10^{36}$ ergs s$^{-1}$) X-ray pulsar. Finally, the inferred period derivative of $-1.7$ s yr$^{-1}$ corresponds to a secular spin-up timescale of $\sim200$ yr, which is the shortest of any known X-ray pulsar in a high-mass X-ray binary.

By using the $P$ and $P^2$ measurements and an X-ray luminosity in the $(0.5−2) \times 10^{36}$ ergs s$^{-1}$ range, we infer a magnetic field of $(4−12) \times 10^{12}$ G and, correspondingly, a maximum magnetospheric radius of $r_m \sim 4 \times 10^9$ cm (see Lamb, Pethick, & Pines 1973). Since the derived corotation radius $r_c$ is $\sim8 \times 10^9$ cm, the $r_m$ is considerably smaller than $r_c$, and accretion on the surface of the neutron star proceeds unaffected by the magnetosphere’s centrifugal drag, as long as the luminosity of the source is larger than $\sim2 \times 10^{35}$ ergs s$^{-1}$. Such a luminosity is not unusual for a bright X-ray pulsar in a nearly circular orbit around a giant OB companion star where the intense stellar wind continuously supplies matter to the compact object.

Assuming a main-sequence star, an orbital period of $\sim300$ days is expected for 2E 0101.5−7225 based on the pulse period−orbital period correlation of Be star/X-ray pulsar binaries (Corbet 1984). A timing analysis of $I$-band photometric measurements from the Optical Gravitational Lensing Experiment revealed no evidence of any coherent signal in the 1−50 day period interval (see Coe & Orosz 2000), suggesting that 2E 0101.5−7225 is a long-period system.

The characteristics of 2E 0101.5−7225 have their closest analogy to those of the persistent low-luminosity ($10^{35}−10^{36}$ ergs s$^{-1}$; 2−10 keV band) X-ray pulsar RX J0146.9+6121, a 1455 s (spin-up timescale of $\sim250$ yr) spinning neutron star in a binary system with a B1 Ve companion star (see Reig, Fabbret, & Coe 1997; Haberl, Angelini, & Motch 1998; Merlègeni et al. 2000). Two other recently discovered long-period Be/X-ray pulsars in the SMC, namely AX J0051−735 (P = 323 s; Imanishi et al. 2000) and AX J0058−7203 (P = 280 s; Tsukamoto et al. 2000), although highly variable (a factor of 10−100), have a maximum luminosity level close to that of 2E 0101.5−7225.

In conclusion, we discovered a new X-ray pulsar with a period of $\sim345$ s in the SMC which is persistent, has a relatively low luminosity, is rapidly spinning up, and is associated with a O9−B1 III−Ve star. The relatively high value inferred for the magnetic field and period derivative point to a young object. All these findings make 2E 0101.5−7225 an unusual X-ray pulsar that deserves more detailed investigations with instrumentation ranging from the X-ray to the IR band.

This work was partially supported through ASI and CNAA grants. We thank the Chandra Data Archive (CDA) of the Chandra X-Ray Observatory Science Center (CXC) at CfA for a prompt release of the data. We thank R. Ragazzoni for obtaining the optical spectrum of the counterpart of 2E 0101.5−7225. We thank H. Tananbaum, R. J. Edgar, and L. Burderi for their helpful comments. This work has been supported in part by NASA contract NAS8-39073.

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