**XMM–Newton discovery of transient X-ray pulsar in NGC 1313**

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Accepted 2008 March 31. Received 2008 March 20; in original form 2008 February 9

**ABSTRACT**

We report on the discovery and analysis of the transient X-ray pulsar XMMU J031747.5−663010 detected in the 2004 November 23 *XMM–Newton* observation of the spiral galaxy NGC 1313. The X-ray source exhibits pulsations with a period $P \sim 765.6$ s and a nearly sinusoidal pulse shape and pulsed fraction $\sim 38$ per cent in the 0.3–7 keV energy range. The X-ray spectrum of XMMU J031747.5−663010 is hard and well fitted with an absorbed simple power law of photon index $\Gamma \sim 1.5$ in the 0.3–7 keV energy band. The X-ray properties of the source and the absence of an optical/ultraviolet counterpart brighter than 20 mag allow us to identify XMMU J031747.5−663010 as an accreting X-ray pulsar located in NGC 1313. The estimated absorbed 0.3–7 keV luminosity of the source $L_X \sim 1.6 \times 10^{39}$ erg s$^{-1}$, makes it one of the brightest X-ray pulsars known. Based on the relatively long pulse period and transient behaviour of the source, we classify it as a Be binary X-ray pulsar candidate. XMMU J031747.5−663010 is the second X-ray pulsar detected outside the local group, after transient 18 s pulsating source CXOU J073709.1+653544 discovered in the nearby spiral galaxy NGC 2403.

**Key words:** galaxies: individual: NGC 1313 – X-rays: binaries.

**1 INTRODUCTION**

Since their discovery (Giacconi et al. 1971; Tananbaum et al. 1972), accreting X-ray pulsars have been major objects for both observational and theoretical study (White, Swank & Holt 1983; Nagase 1989; Bildsten et al. 1997). The majority of known X-ray pulsars are high-mass binary systems with supergiant or Be donors, clearly associated with younger stellar populations and regions of recent star formation (Charles & Coe 2006).

Traditionally, the study of X-ray pulsars was limited to our Galaxy and neighbouring Magellanic Clouds, because of the limited sensitivity and spatial resolution of previous X-ray missions. The advanced capabilities of a new generation of X-ray telescopes (*Chandra* and *XMM–Newton*) have not only caused a rush of new X-ray pulsar discoveries in the Galaxy and Magellanic Clouds (Edge et al. 2004; Haberl & Pietsch 2004; Chernyakova et al. 2005; Lutovinov et al. 2005; McGowan et al. 2007; Karasev et al. 2008), but also opened the possibility to extend X-ray pulsar search to more distant galaxies both inside (Osborne et al. 2001; Trudolyubov et al. 2005; Trudolyubov & Friedhorsky 2008) and beyond the local group (Trudolyubov, Friedhorsky & Córdova 2007). The nearby galaxies with recent star formation are especially suitable candidates for such studies, since they provide the environment in which X-ray pulsars are expected to be plentiful.

The nearby SBd spiral galaxy NGC 1313 at 4.1 Mpc (Méndez et al. 2002), provides an excellent opportunity to study X-ray source populations in a normal galaxy. The overall properties of NGC 1313 are similar to that of irregular Magellanic-type galaxies, and late-type spirals with vigorous recent and ongoing star formation. NGC 1313 was a target of X-ray observations with the *Einstein* (Fabbiano & Trinchieri 1987), *ROSAT* (Colbert et al. 1995; Miller et al. 1998; Schlegel et al. 2000), *ASCA* (Petre et al. 1994), *Chandra* (Schlegel et al. 2004; Zampieri et al. 2004), *XMM–Newton* (Miller et al. 2003; Schlegel et al. 2004; Smith et al. 2007) and *Suzaku* (Mizuno et al. 2007) observatories. These observations uncovered a substantial X-ray source population with three ultraluminous X-ray sources (two accreting binaries and the Type IIn supernova SN 1978K) among them.

In this Letter, we report on the discovery of the coherent 765.6 s pulsations in the flux of transient X-ray source XMMU J031747.5−663010 in NGC 1313, using archival data of *XMM–Newton* observations. We study X-ray spectral properties of the source, search for its optical/ultraviolet (optical/UV) counterparts and discuss its nature.

**2 OBSERVATIONS AND DATA REDUCTION**

To study timing and spectral characteristics of XMMU J031747.5−663010, we used the data of 2004 November 23 *XMM–Newton* observation of NGC 1313 field with three European Photon Imaging Camera (EPIC) instruments (MOS1, MOS2 and pn)
Table 1. XMM–Newton and Chandra observations of NGC 1313 used in the analysis of XMMU J031747.5—663010.

| Date, UT     | Observation ID | Instrument    | Mode/filter | RA (J2000)a  | Dec. (J2000)a | Exposureb | Source luminosityc |
|-------------|----------------|---------------|-------------|--------------|--------------|-----------|-------------------|
| 2000 October 17 | 0106860101     | EPIC          | Full/medium | 03:18:22.61  | –66:30:36.4  | 21.6 (MOS)/21.6 (pn) | <4.1 × 1036 |
| 2002 October 13 | 2950           | ACIS-S        | Very faint  | 03:18:32.00  | –66:31:10.0  | 19.9      | <2.9 × 1036 |
| 2002 November 09 | 3550           | ACIS-I        | Very faint  | 03:17:55.00  | –66:34:40.0  | 14.5      | <4.0 × 1036 |
| 2003 October 02 | 3551           | ACIS-I        | Very faint  | 03:17:55.00  | –66:34:40.0  | 14.8      | <3.2 × 1036 |
| 2003 December 21 | 0150280301     | EPIC          | Full/Thin   | 03:18:20.30  | –66:37:03.2  | 10.0 (MOS)/8.4 (pn) | <1.4 × 1037 |
| 2003 December 23 | 0150280401     | EPIC          | Full/Thin   | 03:18:19.69  | –66:37:02.0  | 7.5 (MOS)/6.2 (pn) | <1.8 × 1037 |
| 2003 December 25 | 0150280501     | EPIC          | Full/Thin   | 03:18:19.26  | –66:37:01.3  | 8.6 (MOS)/7.0 (pn) | <2.0 × 1037 |
| 2004 January 08  | 0150280601     | EPIC          | Full/Thin   | 03:18 16.60  | –66 36 56.1  | 10.9 (MOS)/9.5 (pn) | <1.4 × 1037 |
| 2004 January 16  | 0150281101     | EPIC          | Full/Thin   | 03:18:14.90  | –66:36:51.6  | 8.6 (MOS)/7.0 (pn) | <1.7 × 1037 |
| 2004 August 23  | 0205230401     | EPIC          | Full/Thin   | 03:18:31.90  | –66:55:33.1  | 12.1 (MOS)/11.2 (pn) | <1.7 × 1037 |
| 2004 November 23 | 0205230501     | EPIC          | Full/Thin   | 03:18:25.09  | –66:36:59.5  | 15.6 (MOS)/14.0 (pn) | 1.6 × 1039  |
| 2004 June 05     | 0205230301     | EPIC          | Full/Thin   | 03:18:19.98  | –66:34:48.8  | 11.6 (MOS)/10.0 (pn) | <1.1 × 1037 |
| 2005 February 07 | 0205230601     | EPIC          | Full/Thin   | 03:18:12.06  | –66:36:31.1  | 12.4 (MOS)/10.9 (pn) | <1.4 × 1037 |
| 2006 March 06    | 0301860101     | EPIC          | Full/medium | 03:17:27.38  | –66:33:08.0  | 21.5 (MOS)/19.9 (pn) | <7.1 × 1036 |
| 2006 October 15  | 0405090101     | EPIC          | Full/Thin   | 03:18:23.51  | –66:30:38.9  | 100.0 (MOS)/98.0 (pn) | <2.3 × 1036 |

Note: aPointing coordinates.
bInstrument exposure used in the analysis.
cEstimated luminosity of XMMU J031747.5—663010 in the 0.3–7 keV band.

(Streuder et al. 2001; Turner et al. 2001), and the Optical Monitor (OM) telescope (Mason et al. 2001)(Table 1). We also used several 2000–2006 XMM–Newton observations of the same field to obtain upper limits on the source flux when the source was not detected.

We reduced XMM data using XMM–Newton Science Analysis System (SAS v 7.0.0).1 Before generating X-ray images, and source spectra and light curves, we performed standard preparation of the original event files to exclude time intervals with high background levels, applying an upper count rate threshold of 20 per cent above average background level. The standard SAS tool barycen was used to perform barycentric correction on the original EPIC event files used for timing analysis.

We generated EPIC-pn and MOS images of NGC 1313 field in the 0.3–7 keV energy band, and used the SAS standard maximum likelihood (ML) source detection script EDETECT_CHAIN to detect and localize point sources. We used bright X-ray sources with known counterparts from the USNO-B catalogue (Monet et al. 2003) and Chandra source lists to correct EPIC image astrometry. The astrometric correction was also applied to the OM images, using cross-correlation with USNO-B catalogue. After correction, we estimate residual systematic error in the source positions to be of the order of ~1 arcsec for both EPIC and OM.

To extract EPIC-pn source light curves and spectra during the 2004 November 23 XMM–Newton observation, we used the elliptical region with semi-axes of 22 and 18 arcsec and position angle of 40°. Due to the source proximity to the edge of EPIC-MOS CCD, the source counts were extracted from the elliptical region with semi-axes of 20 and 16 arcsec, including ~70 per cent of the source energy flux. The adjacent source-free regions were used to extract background spectra and light curves. The source and background spectra were then re-normalized by the ratio of the detector areas.

For spectral analysis, we used data in the 0.3–7 keV energy band. In this analysis, we use valid pn events with pattern 0–4 (single and double) and pattern 0–12 (single quadruple) events for MOS cameras. To synchronize both source and background light curves from individual EPIC detectors, we used the identical time filtering criteria based on Mission Relative Time (MRT), following the procedure described in Barnard et al. (2007). The background light curves were not subtracted from the source light curves, but were used later to estimate the background contribution in the calculation of the source-pulsed fractions.

The EPIC spectra were grouped to contain a minimum of 20 counts per spectral bin in order to allow χ2 statistics, and fit to analytic models using the XSPEC v.12.2 fitting package (Arnaud 1996). EPIC-pn, MOS1 and MOS2 spectra were fitted simultaneously, but with normalizations varying independently. For timing analysis, we used standard XANADU/XRONOS v.5.3 tasks.

The data of Chandra observations were processed using the CIAO v3.4.4 threads. We performed standard screening of the Chandra data to exclude time intervals with high background levels. For each observation, we generated X-ray images in the 0.3–7 keV energy band, and used CIAO wavelet detection routine WAVDETECT to detect point sources.

To estimate upper limits on the quiescent source luminosities, the Chandra/ACIS and XMM/EPIC count rates were converted into energy fluxes in the 0.3–7 keV energy range using web PIMMS,1 assuming an absorbed power-law spectral shape with photon index Γ = 1.5 and Galactic foreground absorbing column N_H = 3.6 × 1020 cm−2.

In the following analysis, we assume a distance of 4.1 Mpc for NGC 1313 (Méndez et al. 2002). All parameter errors quoted are 68 per cent (1σ) confidence limits.

3 RESULTS

3.1 Source detection and optical counterparts

A new X-ray source XMMU J031747.5—663010 has been discovered in the data of the 2004 November 23 XMM–Newton observation.

1 See http://xmm.vilspa.esa.es/user.

1 http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html
2 http://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/xronos.html
3 http://asc.harvard.edu/ciao/
4 http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html
observation of the NGC 1313 field (Table 1). The estimated source luminosity was $\sim1.6 \times 10^{39}$ erg s$^{-1}$, assuming the distance of 4.1 Mpc. We measure the position of XMMU J031747.5$-$663010 to be $\alpha = 03^h17^m47.59^s, \delta = -66^\circ30'10.2''$ (J2000 equinox) with an uncertainty of $\sim1.0$ arcsec (Fig. 1). The projected galactocentric distance of XMMU J031747.5$-$663010 is $\sim3$ arcmin or $\sim3.6$ kpc at 4.1 Mpc. The analysis of other archival observations of the same field with XMM–Newton and Chandra did not yield source detection with an upper limit ($\sim2\sigma$) ranging from $\sim2 \times 10^{39}$ to $\sim2 \times 10^{37}$ erg s$^{-1}$ (or $\sim80$–$800$ times lower than outburst luminosity), depending on the duration of the observation and instrument used (Table 1).

The search for the optical counterparts using the deep images of NGC 1313 from Las Campanas Observatory 2.5-m du Pont telescope (Kuchinski et al. 2000) did not yield stellar-like objects brighter than $\sim21$ mag in V and $\sim20$ mag in B band within the $3\sigma$ error circle of XMMU J031747.5$-$663010. We also used the data of the 2004 November 23 XMM–Newton/OM observation to search for optical/UV counterparts to the source during its X-ray outburst (Fig. 1). We did not detect any stellar counterparts to XMMU J031747.5$-$663010 in the OM images down to the limit of $\sim20$ mag in the V and U bands.

### 3.2 X-ray pulsations

We performed timing analysis of XMMU J031747.5$-$663010 using the 2004 November 23 data from all three XMM–Newton/EPIC detectors in the 0.3–7 keV energy band. After a barycentric correction of the photon arrival times in the original event lists, we performed a Fast Fourier Transform (FFT) analysis using standard XRONOS task POWSPEC, in order to search for coherent periodicities. For the analysis of XMM–Newton data, we used combined synchronized EPIC-pn and MOS light curves with 2.6-s time bins to improve sensitivity. We found strong peak in the Fourier spectrum at the frequency of $\sim1.3 \times 10^{-3}$ Hz (Fig. 2, upper panel). The strength of the peak in the Fourier spectrum corresponds to the period detection confidence of $\sim3 \times 10^{-9}$ (Vaughan et al. 1994).

To estimate the pulsation period more precisely, we used an epoch folding technique, assuming no pulse period change during 2004 November 23 observation. The most likely value of the pulsation period, 765.6 s (Table 2) was obtained fitting the peak in the $\chi^2$ versus trial period distribution with a Gaussian. The period errors in Table 2 were computed following the procedure described in Leahy (1987). The source light curves were folded using the periods determined from epoch folding analysis. The resulting folded light curve in the 0.3–7 keV energy band is shown in Fig. 2 (upper panel) and Table 2.

The period error in Table 2 was computed following the procedure described in Leahy (1987). The source light curves were folded using the periods determined from epoch folding analysis. The resulting folded light curve in the 0.3–7 keV energy band is shown in Fig. 2 (upper panel). The source has sinusoidal light curve with a period of 765.6 s.

### Figure 1

Upper panel: combined 0.3–7 keV XMM/EPIC image covering a $10 \times 10$ arcmin$^2$ region of NGC 1313, taken on 2004 November 23. The position of new pulsar XMMU J031747.5$-$663010 is marked with an arrow, and the position of NGC 1313 nucleus (Ryder et al. 1995) is shown with a cross. Three other bright X-ray sources in the field are also marked for reference (Schlegel et al. 2000). Lower panel: optical V-band image of NGC 1313 disc taken with Las Campanas Observatory 2.5-m du Pont telescope (Kuchinski et al. 2000). The image is a $3 \times 3$ arcmin$^2$ centred on the XMMU J031747.5$-$663010 position, shown with black circle of 3 arcsec radius ($3\sigma$).

### Figure 2

Upper panel: power spectrum of XMMU J031747.5$-$663010 obtained using the data of 2004 November 23 XMM–Newton/EPIC (EPIC-pn, MOS1 and MOS2 detectors combined) observation in the 0.3–7 keV energy band. Lower panel: corresponding background-corrected source X-ray pulse profile folded with most likely pulsation period (765.6 s). The sinusoidal fit to the pulse profile is shown for comparison with the dotted line.

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Table 2. X-ray pulsation parameters and spectral-fit information for XMMU J031747.5−663010.

| Timing parameters | Power law*WABS spectral model parameters |
|-------------------|------------------------------------------|
| Period (s)        | Flux_{abs} \( b \) | Flux_{abs,corr} \( c \) | \( L_{abs} \) \( d \) | \( L_{abs,corr} \) \( e \) | \( \chi^2 \) (d.o.f.) | Instrument |
| 765.6 ± 4.0       | 38 ± 3 | 23 ± 4 | 1.48^{+0.10}_{-0.09} | 7.84 ± 0.35 | 9.98^{+0.55}_{-0.52} | 1.58 | 2.01 | 64.9(52) | pn+M1+M2 |

*Pulsed fraction in the 0.3–7 keV energy band.
\( b \) Absorbed model flux in the 0.3–7 keV energy range in units of \( 10^{-13} \) erg s\(^{-1}\) cm\(^{-2}\).
\( c \) Unabsorbed model flux in the 0.3–7 keV energy range in units of \( 10^{-13} \) erg s\(^{-1}\) cm\(^{-2}\).
\( d \) Absorbed luminosity in the 0.3–7 keV energy range in units of \( 10^{39} \) erg s\(^{-1}\), assuming the distance of 4.1 Mpc.
\( e \) Unabsorbed luminosity in the 0.3–7 keV energy range in units of \( 10^{39} \) erg s\(^{-1}\), assuming the distance of 4.1 Mpc.

Figure 3. Normalized X-ray light curves of XMMU J031747.5−663010 folded at the best pulsation period in the soft (0.3–2 keV, upper panel) and hard (2–7 keV, middle panel) energy bands along with hardness ratio (lower panel), computed taking background contribution into account.

To investigate energy dependence of the source pulse profile, we extracted light curves in the soft (0.3–2 keV) and hard (2–7 keV) bands for 2004 November 23 observation, and folded them at the corresponding best pulsation period (Fig. 3). Both bands show quasi-sinusoidal pulse profiles. Because of the relatively poor statistics, we could detect only marginal difference between source pulse profiles at low and high energies, which have background-corrected pulsed fractions of 34 ± 4 and 40 ± 4 per cent.

3.3 X-ray spectra

The pulse phase-averaged XMM–Newton/EPIC spectra of XMMU J031747.5−663010 can be adequately fit with the absorbed simple power-law model with photon index, \( \Gamma \approx 1.5 \) and an equivalent hydrogen density \( N_H \approx 2.3 \times 10^{21} \) cm\(^{-2}\). The corresponding absorbed luminosity of the source in the 0.3–7 keV band is \( \sim 1.6 \times 10^{39} \) erg s\(^{-1}\), assuming the distance of 4.1 Mpc. The best-fitting spectral model parameters of the source are given in Table 2. The measured absorbing column \( N_H \) is \( \sim 6 \) times higher than the Galactic hydrogen column in the direction of NGC 1313, \( 3.6 \times 10^{20} \) cm\(^{-2}\) (Dickey & Lockman 1990), consistent with an additional intrinsic absorption within the system and inside the disc of NGC 1313.

Figure 4. EPIC count spectra and model ratios of XMMU J031747.5−663010 during the 2004 November 23 observation. The EPIC-pn data are plotted with filled circles, while EPIC-MOS1 and MOS2 data are shown with filled and open squares, respectively. The best fit absorbed power-law model approximation of EPIC-pn, MOS1 and MOS2 data is shown with solid, dotted and dashed histograms.

4 DISCUSSION

The absence of the bright optical counterpart to XMMU J031747.5−663010, its overall X-ray properties (spectrum, pulsations, transient behaviour) and positional coincidence with NGC 1313 disc, allow us to conclude that it should be located outside our Galaxy and probably belongs to NGC 1313. The X-ray pulsations and energy spectrum of XMMU J031747.5−663010 imply that it is almost certainly an accreting highly magnetized neutron star in a high-mass binary system (White et al. 1983; Nagase 1989). The association with NGC 1313 makes this source an extremely bright object with luminosity \( L_X \sim 1.6 \times 10^{39} \) erg s\(^{-1}\), greatly exceeding the isotropic Eddington luminosity limit for a 1.4 M\(_{\odot}\) neutron star accreting hydrogen-rich material.

The relatively long pulse period of XMMU J031747.5−663010 (765.6 s) places it among the systems with a companion that is either a supergiant or a Be star on a Corbet diagram (Corbet 1986). The transient behaviour of the source lends support to the interpretation of this source as yet another Be binary, since the majority of Be systems display recurrent/transient outbursts. An extremely high luminosity of the source still falls into the luminosity range...
observed in the Be X-ray pulsars, with one system, A0538-66 known to reach similar luminosity during its giant (type II) outburst (White & Carpenter 1978; Skinner et al. 1982). The high luminosity of XMMU J031747.5–663010 is also consistent with theoretical predictions for super-Eddington accretion on to highly magnetized ($B \gtrsim 10^{12}$ G) neutron star (Basko & Sunyaev 1976).

The high-mass nature of the system implies its relatively young age, consistent with its location within one of the spiral arms of NGC 1313 (Fig. 1). Since the Be interpretation still remains preliminary, optical identification is essential to determine the nature of the system. For optical identification, deeper optical observations are needed. The follow-up monitoring observations with Chandra and XMM–Newton are needed to test, if it shows recurrent outbursts. Future X-ray observations of XMMU J031747.5–663010, if it reappears, could improve source localization and study long-term evolution of its X-ray properties and X-ray pulsation.

XMMU J031747.5–663010 is the second X-ray pulsar detected outside the local group, after 18 s pulsating X-ray source CXOU J073709.1+653544 in the nearby spiral galaxy NGC 2403 (Trudolyubov et al. 2007). Both sources are extremely bright transient systems with total luminosities $\gtrsim 10^{39}$ erg s$^{-1}$, and probably belong to a rare class of most luminous Be binary X-ray pulsars. Similar systems can be detected and studied effectively with a series of moderately deep (10–50 ks) monitoring XMM–Newton and Chandra observations up to the distances of several Mpc. Therefore, the detailed analysis of the existing archival and new observations of nearby spiral and irregular galaxies have a potential to significantly increase statistics of these systems, and provide us with better understanding of their nature and connection to the underlying stellar population.

ACKNOWLEDGMENTS

The author would like to thank the referee for comments and suggestions that improved the Letter. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Centre Online Service, provided by the NASA/Goddard Space Flight Centre. XMM–Newton is an ESA Science Mission with instruments and contributions directly funded by ESA Member states and USA (NASA). Chandra X-ray Observatory is operated by the Smithsonian Astrophysical Observatory on behalf of NASA. This research also made use of NASA/IPAC Extragalactic Data base (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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