The discovery of 12 min X–ray pulsations from 1WGA J1958.2+3232

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ABSTRACT
During a systematic search for periodic signals in a sample of ROSAT PSPC (0.1–2.4 keV) light curves, we discovered ∼ 12 min large amplitude X–ray pulsations in 1WGA J1958.2+3232, an X–ray source which lies close to the galactic plane. The energy spectrum is well fit by a power law with a photon index of 0.8, corresponding to an X–ray flux level of ∼ 10^{-12} erg cm^{-2} s^{-1}. The source is probably a long period, low luminosity X–ray pulsar, similar to X Per, or an intermediate polar.

Key words: cataclysmic variables — pulsar: general — stars: individual (1WGA J1958.2+3232) — stars: rotation — X–ray: stars.

1 INTRODUCTION
Recent ROSAT observations have substantially increased the number of known X–ray pulsators (XRPs; Hughes 1994; Dennerl, Haberl & Pietsch 1995; McGrath et al. 1994; Israel et al. 1997a, 1997b) and cataclysmic variables (CVs; Reinsch et al. 1994; Shafter et al. 1995; Buckley et al. 1995; Haberl & Motch 1995; Burwitz et al. 1996; Friedrich et al. 1996; Singh et al. 1996).

In this paper we report the discovery of highly significant pulsations at a period of 12 min in the X–ray flux of 1WGA J1958.2+3232, a serendipitous ROSAT PSPC source which lies in the galactic plane. We also discuss the possible nature of the compact object responsible for these pulsations.

2 X–RAY OBSERVATIONS AND DATA ANALYSIS
The field of 1WGA J1958.2+3232 was observed on 1993 May 4 12:48–13:49 UT (~ 3700 s exposure) and May 5 9:13–10:26 UT (exposure of ~ 4300 s) with the PSPC in the focal plane of the X–ray telescope on board ROSAT. About 10 point–like X–ray sources were detected within the field of view centered on the supernova remnant K4–41 (G 69.7+1.0). 1WGA J1958.2+3232 is located ~23 away from the image center. As a result of the periodic wobble in the ROSAT pointing direction (Briel et al. 1994) the source is at times partially obscured by the central ring and by one of the radial ribs of the PSPC window support structure. Therefore we determined the source position from an image accumulated by using only those time intervals in which the source was far from the window support structure. The source is located at RA = 19^h 58^m 13.8^s, DEC. = +32° 32’ 58”.7 (equinox 2000). The uncertainty radius of ~ 30” is dominated by the size of the Point Spread Function (PSF) ~ 23” away from the image centre, with partial obscuration due to the wobble playing a minor role (in the image obtained from the entire PSPC pointing the source position differed only by ~ 3’’ ). The ROSAT event list of 1WGA J1958.2+3232 were extracted from a circle of ~ 1.2’ radius (corresponding to an encircled energy of about 90%) around the X–ray position. Out of the 480 photons contained in the circle we estimated that ~ 120 photons derive from the local background.

The May 1993 light curve of 1WGA J1958.2+3232 was first analysed during a systematic study (Israel 1996) aimed at revealing periodicities in X–ray light curves of a sample of
Figure 1. Average power spectra of the original 0.1–2.4 keV ROSAT PSPC light curve of 1WGA J1958.2+3232 obtained as described in the text (lower thin line). The counting statistics noise corresponds to a power of two. The thick upper curve gives the average power spectrum of the light curve corrected for the effects of the wobble (see text). The latter powers have been shifted by 50. The highest peak in both power spectra (centered around 0.00135 Hz), corresponds to the 12 min modulation of 1WGA J1958.2+3232. The corrected light curve folded at the 721 s period is shown in the inner panel.

∼ 23000 X–ray sources selected from the White, Giommi & Angelini catalog (1994; WGA catalog). The photon arrival times were corrected to the barycenter of the solar system.

In order to preserve the highest Fourier frequency resolution, a power spectrum was calculated over the entire observation time span (∼ 0.9 d). Four marginally significant peaks (≥ 3.5 σ over the entire spectrum) were detected around a frequency of 1.4 × 10^{-3} Hz. In order to minimise the windowing effects due to the 19.5 hr long gap between the May 4 and 5 observation intervals, we repeated the analysis by using two intervals (∼ 5000 s long), and calculated the average power spectrum from the power spectra obtained for each individual interval. Several peaks were clearly seen around a frequency of 1.37 × 10^{-3} Hz (period of ∼ 740 s); the highest of these peaks has a significance of ∼ 8.5 σ over the entire sample of ROSAT light curves analysed (see Fig. 1 lower thin line). The additional feature peaking at a frequency of 2.5 × 10^{-3} Hz is consistent with the (partial) obscuration of the source caused by 402 s wobble in the pointing direction. The 740 s modulation cannot represent the first sub–harmonics of the wobble period. Firstly, our systematic analysis of the power spectra of ∼ 23000 light curves from WGA sources (Israel 1996), shows that up to 10 higher harmonics of the wobble frequency are detected in a number of WGA sources. In no case, however, significant power at the first sub–harmonics of the wobble frequency is seen (neither it is clear how a modulation at 1/2 the wobble frequency could be introduced). Moreover the 1.37 × 10^{-3} Hz modulation of 1WGA J1958.2+3232 is inconsistent with half the wobble frequency. The latter was confirmed to be at its usual value of νw=2.49 × 10^{-3} Hz through the power spectrum analysis of the housekeeping data of the RA, DEC and roll angles of the pointing. The light curves of 1WGA J1954.6+3222 and 1WGA J1953.1+3251, two similarly bright X–ray sources in the field that were partially obscured by the central ring and the edge of the field itself, respectively, also showed significant peaks at 2.49 and 4.98 × 10^{-3} Hz.

Based on the above results we conclude that the ∼ 12 min modulation (νs = 1.37 × 10^{-3} Hz) is real and intrinsic to 1WGA J1958.2+3232. Due to the presence of the wobble signal (νw), sidelobes are expected in the power spectrum at frequencies νs ± νw (corresponding to ∼ 3.91 × 10^{-3} Hz and 1.15 × 10^{-3} Hz). A visual inspection of the power spectrum (lower thin line in Fig. 1) shows that these are small if present at all. To approximately correct the source light curve for the effects caused by the wobble, we adopted the following procedure (see Fig. 2): (a) we estimated the modulation introduced by the wobble by folding the light curve at the 402 s period over 10 phase intervals (the mean intensity was normalised to one). (b) We accumulated a light curve with a binning time of 40.2 s. (c) We devided each bin of the latter light curve by the corresponding bin of the light curve folded at the wobble period (see point a). The light curve obtained in this way is approximately corrected for the effects caused by the wobble (central panels of Fig. 2). By looking at the corrected light curve we note that the individual peaks of the source modulation at ∼ 12 min are more clearly seen and the scatter of their amplitude is decreased compared to the original light curve. The upper thick line in Fig. 1 shows the corresponding power spectrum of the corrected light curve. While the peak around a frequency of 1.37 × 10^{-3} Hz is still present (a power of 53 for the average of two power spectra corresponding to a significance of ∼ 7.4 σ
over the entire sample of ROSAT light curves analysed), the peaks originating from the wobble disappear as expected. The second harmonics of the \( \sim 12 \) min signal is now clearly discernable around a frequency of \( \sim 2.74 \times 10^{-3} \) Hz (peak power of 14).

Owing to poor statistics, a determination of the best period based on phase fitting proved unfeasible. Therefore we determined the best period in each of the two intervals by using a Rayleigh periodogram (cf. Leahy et al. 1983). The average of these periods gave 721.14 s (90% uncertainties are used throughout this letter) which is comparable to the Fourier resolution of the time span covered by the observation. The modulation was nearly sinusoidal, with a pulse fraction (semi-amplitude of modulation divided by the mean source count rate) of \( \sim 80\% \) in the 0.1–2.4 keV band (see the insert in Fig. 1). The arrival times of the pulse minima (that we adopted as phase 0) were determined to be JD 2449112.4838 \( \pm \) 0.0004.

The energy spectrum of 1WGA J1958.2+3232 was well fit (\( \chi^2/d.o.f. = 13.7/16 \)) by a simple power law (Fig. 3a), a model often used to describe the soft X-ray spectrum of an X-ray pulsar. The best fit was obtained for a photon index of \( \Gamma = 0.8 \pm 0.2 \) and a column density of \( N_H = (6 \pm 2) \times 10^{20} \) cm\(^{-2} \). The corresponding 0.1–2.4 keV unabsorbed X-ray flux is \( F_X \simeq 1.0 \times 10^{-12} \) erg cm\(^{-2} \) s\(^{-1} \). The spectral parameters are poorly constrained as shown in Fig. 3b where confidence contours are plotted in the \( N_H - \Gamma \) plane. Note that the galactic hydrogen column in the direction of the source is \( \sim 10^{22} \) cm\(^{-2} \), while the 3 \( \sigma \) upper limit derived from the PSPC spectrum is \( 4 \times 10^{21} \) cm\(^{-2} \), i.e. a factor of \( \sim 2.5 \) lower. Among single component models a thermal bremsstrahlung gave also an acceptable fit. In particular, we obtained a \( \chi^2/d.o.f. = 16.3/17 \) by fixing the plasma temperature \( k T_{\text{pl}} \) at 10 keV (an upper limit of 3 keV can be obtained from the data) in analogy with the spectrum inferred at higher energies for intermediate polars (IPs). In this case a column density of \( N_H = (1.2 \pm 0.8) \times 10^{21} \) cm\(^{-2} \) was derived.

The position of 1WGA J1958.2+3232 was included in two EXOSAT channel multiplier array (CMA; 0.05–2 keV) fields observed on 1983 October 6 (25012 s effective exposure time) and 22 (10863 s). In both cases the source was not detected. The 0.1–2.4 keV flux upper limits (assuming a power law spectrum consistent with that derived from the ROSAT PSPC) are \( 1.2 \times 10^{-11} \) erg s\(^{-1} \) cm\(^{-2} \) and \( 1.3 \times 10^{-11} \) erg s\(^{-1} \) cm\(^{-2} \) for the October 6 and 22 observations, respectively.

1WGA J1958.2+3232 lies in a very crowded region close to the Galactic equator (\( \alpha = 69^\circ.1, \delta = 1^\circ.7 \)). About 15 stars with \( V > 12 \) mag are included in the current X-ray error circle (\( 30'' \) radius; see Fig. 4). The brightest star inside the error circle is 12.25 mag (RA = 19\(^{\text{h}}\) 58\(^{\text{m}}\) 11\(^{\text{s}}\) 4, DEC = 32\(^{\circ}\) 32\(^{\prime}\) 58\(^{\prime\prime}\) 7, equinox 2000), while a 12.28 mag star is few arcseconds outside (see Fig. 4) A visual inspection on the Palomar plates showed that the former star is bluer. The other bright stars included in the error circle have \( V \approx 14 \).

3 DISCUSSION

Based on available X-ray observations, it is not possible to unambiguously assess the nature of the compact object responsible for the X-ray pulsations observed in 1WGA J1958.2+3232. The column density inferred from the ROSAT PSPC spectrum is substantially lower than the galactic value, suggesting a far shorter distance than the edge of the galaxy in the direction of the source (\( \sim 15 \) kpc). Taking \( d = 1 \) kpc as an indicative value, the unabsorbed X-ray luminosity of the source is \( L_X = 1.2 \times 10^{32} \left( \frac{d}{1\,\text{kpc}} \right)^2 \) erg cm\(^{-2} \) s\(^{-1} \) in the 0.1–2.4 keV band and \( L_X = 6 \times 10^{32} \left( \frac{d}{1\,\text{kpc}} \right)^2 \) erg cm\(^{-2} \) s\(^{-1} \) in the 2–10 keV band (assuming a power law spectrum with \( \Gamma = 0.8 \)).

If 1WGA J1958.2+3232 contained an accreting magnetic neutron star, it would be one of a few XRPs known with rotation periods > 500 s. XRPs are mainly found in massive binary systems containing an O or B donor star. Their energy spectra are usually well modelled by relatively hard power law (\( \Gamma \approx 0 - 2 \)), with a cut-off at energies higher

Figure 2. ROSAT 0.1–2.4 keV PSPC X-ray light curve of 1WGA J1958.2+3232 obtained on 1993 May 4 (upper three panels) and May 5 (lower three panels). The first panel of each interval corresponds to the original light curve, while the central panel gives the corrected light curve (see text). In both cases the binning time is 80.4 s. The third panel shows the light curve folded at the wobble period.
than 10 keV (White, Swank & Holt 1983). Even though X-ray transient activity is common among systems with a Be-star primary, most long period ($\geq 100$ s) X-ray pulsars are persistent.

Among these is X Per, a low luminosity ($L_X \sim 10^{33} - 10^{34}$ erg s$^{-1}$; 2–10 keV) 835 s XRP with a peculiar 6.2 mag Be star companion (Braes & Miley 1972; White, Mason & Sanford 1977; see Table 1). If 1WGA J1958.2+3232 held a close resemblance to this system, then its distance would be in the 3–5 kpc range, making one of the brightest stars (in particular the V=12.25 blue star) in the X-ray error circle the most likely candidate optical counterpart.

Another system with similar properties is the 1455 s XRP RX J0146+6121, a low galactic latitude X-ray binary with a 11.3 mag Be star primary (White et al. 1987; Mereghetti, Stella & De Nile, 1993; Israel, Mereghetti & Stella 1994; Hellier 1994; Haberl et al. 1997). However, the low state X-ray luminosity of this system is likely much higher than that of 1WGA J1958.2+3232 ($\sim 2 \times 10^{35}$ erg s$^{-1}$ in the 2–20 keV energy band, for a distance of 2.5 kpc; Hellier 1994; $\sim (0.2-4.0) \times 10^{35}$ erg s$^{-1}$ in the 0.5–10 keV energy band; Haberl et al. 1997).

Alternatively the 12 min X-ray pulsations of 1WGA J1958.2+3232 might arise from polar cap accretion onto a magnetic rotating white dwarf. In this case 1WGA J1958.2+3232 would belong to the intermediate polar class of cataclysmic variables. The energy spectra of IPs are, in most cases, well described by a thermal bremsstrahlung with a temperature $kT_{br}$ of a few tens of keV. The white dwarf rotation periods are usually in the 5–30 min range, whereas the orbital periods have values of few hours.

Due to the relatively short distance ($< 500$ pc) of most known IPs, their distribution covers a fairly wide range of galactic latitudes. However a sample of six intermediate polars located at low galactic latitude ($|bI| < 20^\circ$) has been recently identified in the ROSAT all-sky survey (Haberl & Motch 1995). Among these, three (RX J1712.6–2414, RX J0153.3+7446 and RX J0028.8+5917) are characterised by hard spectra consistent with those seen from classical IPs. Only the $V \simeq 14$ and $V \simeq 14.4$ optical counterparts of RX J1712.6–2414 and RX J0028.8+5917, respectively, have been studied in some detail (Motch et al. 1996; Buckley et al. 1995). The X-ray flux of these IPs is an order of magnitude higher than that of 1WGA J1958.2+3232, hinting to a factor of $\sim 3$ shorter distance. This analogy suggests that, if 1WGA J1958.2+3232 is an IP, then its optical counterpart is likely in the 16–18 mag range. Moreover note that the larger distance to 1WGA J1958.2+3232 would make its height above the galactic plane comparable to that of RX J1712.6–2414 and RX J0028.8+5917 (see Table 1).

Though unlikely, another possibility that cannot be rejected at present is that the 12 min modulation of 1WGA J1958.2+3232 corresponds to the orbital period of a low mass X-ray binary system. This would be only slightly longer than the shortest orbital period known, namely that of 4U 1820–303 (685 s; Stella, Friedhorsky & White 1987) However the pulsed fraction, in the case of 4U 1820–303 is only a few percents, much smaller than that of 1WGA J1958.2+3232. A considerably higher X-ray orbital modulation might be expected if the accretion disk rim mod-
Table 1: Comparison of 1WGA J1958.2+3232 with some XRPs and IPs observed by ROSAT

<table>
<thead>
<tr>
<th>Source</th>
<th>Period (s)</th>
<th>Pulsed fr. (%)</th>
<th>8I (deg)</th>
<th>PSPC Rate (ct s⁻¹)</th>
<th>V-mag</th>
<th>0.1–2.4 keV F_X (erg s⁻¹ cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1WGA J1958.2+3232</td>
<td>721</td>
<td>80</td>
<td>1.7</td>
<td>0.045</td>
<td>&gt; 12</td>
<td>1.2 × 10⁻¹²</td>
</tr>
<tr>
<td>X Per</td>
<td>835</td>
<td>40</td>
<td>−17</td>
<td>0.1–3.0</td>
<td>6.2, Be</td>
<td>2–50 × 10⁻¹²</td>
</tr>
<tr>
<td>RX J0146+6121</td>
<td>1412</td>
<td>80</td>
<td>−0.8</td>
<td>0.2</td>
<td>11.3, Be</td>
<td>5.6 × 10⁻¹²</td>
</tr>
<tr>
<td>RX J1712.6–2414</td>
<td>1003</td>
<td>40</td>
<td>8.7</td>
<td>0.65</td>
<td>14.0</td>
<td>9.5 × 10⁻¹²</td>
</tr>
<tr>
<td>RX J0028.8+5917</td>
<td>313</td>
<td>40</td>
<td>−3.5</td>
<td>0.6</td>
<td>14.4</td>
<td>8.8 × 10⁻¹²</td>
</tr>
<tr>
<td>RX J0153.3+7446</td>
<td>1414</td>
<td>40</td>
<td>12.4</td>
<td>0.02</td>
<td>—</td>
<td>3.4 × 10⁻¹³</td>
</tr>
</tbody>
</table>

We discovered large amplitude 12 min pulsations in the X-ray flux of 1WGA J1958.2+3232. This periodicity likely originates from polar cap accretion onto a rotating magnetic compact star, either a white dwarf in an intermediate polar, or a neutron star in an X-ray binary system. In the latter case 1WGA J1958.2+3232 would be one of the very few XRPs known with a spin period of > 500 s and a low X-ray luminosity. If instead 1WGA J1958.2+3232 hosts an accreting magnetic white dwarf rotation, it would likely represent a distant member of the class of low galactic latitude intermediate polars, recently discovered in the ROSAT all-sky survey. The additional possibility that the X-ray modulation arises from the orbital motion of a high inclination low mass X-ray binary with an accretion disk corona cannot be excluded at present.

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