Discovery of a Possible Anomalous X-ray Pulsar in the Small Magellanic Cloud

R.C.Lamb\(^1\), D. W. Fox\(^1\), D.J. Macomb\(^2\), T.A. Prince\(^1\)

\(^1\) Space Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125
\(^2\) Physics Department, Boise State University, Boise, ID 83725-1570

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ABSTRACT

We report the serendipitous detection of a previously unreported pulsar from the direction of the Small Magellanic Cloud using data from the CHANDRA X-Ray Observatory. Because of its luminosity (~ 1.5 × 10^{35} ergs/s), its near lack of variability for more than 20 years, and its soft spectrum we propose that it is an anomalous X-ray pulsar (AXP). Data from the ROSAT PSPC in conjunction with the CHANDRA data give a period, \(P\), of 5.44 s and a spin down time, \(P/\dot{P}\), of 11 ky. If this is a correct identification it will be the first extragalactic AXP and the fastest yet discovered.

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) have a number of properties that distinguish them as a class from other pulsars. (See Mereghetti 2001 for a review.) They have periods in the range 6-12s, X-ray luminosities in the range 10^{34} – 10^{36} ergs/s, very soft X-ray spectra, little or no variability on time scales from hours to years, and they undergo relatively steady spin-down with no evidence for binary motion. The limited number of members of this class (~ 6) has inhibited development of a theoretical understanding of their properties. Models to account for their X-ray emission generally fall into two categories depending on the energy source, either loss of magnetic field energy (magnetar models) (Thompson & Duncan 1996; Heyl & Hernquist 1997) or accretion. Accretion models may be further subdivided according to the source of infalling material; binary companion models e.g. Mereghetti & Stella (1995), or accretion from a disk leftover from a supernova explosion (Marsden et al. 2001, Francischelli & Wijers 2002).

In this paper we present evidence for a possible addition to this class. In an examination of archival X-ray data from a number of X-ray satellites (ROSAT, Chandra, RXTE) we have discovered evidence for a previously unreported pulsar in the Small Magellanic Cloud. The properties of this pulsar are consistent with those of the AXPs. By virtue of the known distance to the SMC, 57 kpc (Feast & Walker 1987), the luminosity can be rather accurately established and it falls in the range of AXP luminosities. If this is a correct identification, then it will be the
fastest yet discovered ($P = 5.44 \text{ s}$) and the first extragalactic AXP if we discount the soft gamma repeater, 0526-66, in the LMC. This latter source exhibits all the characteristics of an AXP when it is not bursting (Marsden et al. 2001).

2. OBSERVATIONS

The discovery data were obtained from a 100ks ACIS-I observation which began 2001 May 15, obsid 1881. The position of the source is: $01^h 00^m 42.8^s$, $-72^\circ 11' 32.4''$ (J2000), approximately 10 arc minutes from the ACIS-I aim point. A selection circle of 24 pixels (11.8") was chosen to encompass $> 90\%$ of the source photons. 6099 photons were retrieved from the observation with a background estimated to be 111 photons. The times of arrivals of the source photons at the space craft were adjusted to the barycenter of the solar system and a fast Fourier transform (fft) was performed.

Inasmuch as the ACIS-I CCD read-out time is a fixed 3.241 seconds, the Nyquist limiting frequency for the fft is $1/6.482s = 0.154 \text{ Hz}$. In order to show clearly this limitation, the fft was performed with a bin size of 0.1 seconds, and a portion of the resulting power spectrum (normalized to unity power) is shown in figure 1. There are three peaks present, two of which are aliases of each other at $0.124706(1)$ and $0.183828(1)$ Hz, on opposite sides of the Nyquist frequency. These peaks have highly significant power values of 38.4. The chance probability of such a power is $\sim 3 \times 10^{-17}$. The peak at 0.308 Hz is due to the digitization limit (3.241 s) of the ACIS-I and has a power value approximately equal to the number of photons.

The spectrum of the source is soft. An acceptable spectral fit to the data is given by a thermal bremsstrahlung with an absorption column density $4.12 \pm 0.24 \times 10^{21}$ H-atoms/cm$^2$ and a value of $kT = 1.05 \pm 0.05 \text{ keV}$. The fit to the data is shown in Figure 2.

A search of imaging X-ray satellite archives for data for this source has produced many observations dating from 1979. These observations are listed in Table 1. The most extensive source coverage is from the ROSAT satellite. For ROSAT we have restricted the observations shown in the Table by excluding all observations which contain fewer than $\sim 50$ source photons. This means that for the ROSAT HRI exposures less than 7.5 ks are excluded. For the PSPC exposures less than 1.5 ks are excluded as are observations in which the source is more than 30 arc minutes from the center of the field of view. This latter restriction is designed to avoid large vignetting corrections to the counting rate.

The luminosity values given in the table are derived under the assumption that the source is associated with the SMC and that the source spectrum has the same power law form as determined by the fit to the CHANDRA data. The luminosity is calculated for the CHANDRA spectral range 0.2 to 10 keV.

From the Table, we notice a near constancy of flux values for a given instrument. The
Fig. 1.— FFT of CHANDRA Observation. The Nyquist frequency at 0.15427 Hz is indicated. The two power peaks of 0.124706(1) and 0.183828(1) Hz are aliases of each other. The remaining peak at $1/3.241 = 0.3085$ Hz is due to the limited time resolution of the ACIS-I instrument.

Fig. 2.— Spectral Fit to the CHANDRA data. The fit assumes the spectrum is a thermal bremsstrahlung with an absorption column density $4.12\pm0.24 \times 10^{21}$ H-atoms/cm$^2$ and a value of $kT = 1.05\pm0.05$ keV. The fit has a reduced chi-squared value of 0.83 for 45 degrees of freedom, and thus is an excellent fit.
Table 1. List of Observations of Source. The luminosity is calculated for the interval 0.2-10 keV under the assumption that the spectrum is that given in Figure 2

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Observ.</th>
<th>Date</th>
<th>Exp.(ks)</th>
<th>Ct Rate (cts/s)</th>
<th>Mean Rate</th>
<th>L (ergs/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Einstein IPC</td>
<td>6297</td>
<td>Apr 1980</td>
<td>23</td>
<td>0.0122(13)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3925</td>
<td>Nov 1979</td>
<td>20</td>
<td>0.0144(17)</td>
<td></td>
<td>0.0133 (16)</td>
</tr>
<tr>
<td>ROSAT PSPC</td>
<td>rp500250n00</td>
<td>Oct 1993</td>
<td>20.</td>
<td>0.0275(16)</td>
<td></td>
<td>1.4×10^{35}</td>
</tr>
<tr>
<td></td>
<td>rp600195a00</td>
<td>Oct 1991</td>
<td>16.</td>
<td>0.0273(14)</td>
<td>0.0280(8)</td>
<td>1.9×10^{35}</td>
</tr>
<tr>
<td></td>
<td>rp600195a01</td>
<td>Apr 1992</td>
<td>9.2</td>
<td>0.0300(21)</td>
<td>0.034(9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>rp500142n00</td>
<td>May 1993</td>
<td>4.8</td>
<td>0.0263(29)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rp600455a02</td>
<td>Oct 1993</td>
<td>4.5</td>
<td>0.0263(3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rp600455a03</td>
<td>May 1994</td>
<td>4.0</td>
<td>0.012(7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rp600455n00</td>
<td>Dec 1992</td>
<td>3.5</td>
<td>0.062(7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rp600455a01</td>
<td>Apr 1993</td>
<td>1.7</td>
<td>0.034(9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROSAT HRI</td>
<td>rh900445a01</td>
<td>Apr 1995</td>
<td>34</td>
<td>0.0095(6)</td>
<td>0.0090(8)</td>
<td>1.6×10^{35}</td>
</tr>
<tr>
<td></td>
<td>rh900445n00</td>
<td>Apr 1994</td>
<td>15</td>
<td>0.0105(9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rh500137n00</td>
<td>Apr 1993</td>
<td>14</td>
<td>0.0073(10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rh500418a03</td>
<td>Mar 1998</td>
<td>11</td>
<td>0.0071(10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rh500418a01</td>
<td>Oct 1995</td>
<td>8.2</td>
<td>0.0089(12)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>rh500418a02</td>
<td>May 1997</td>
<td>7.5</td>
<td>0.0098(13)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASCA GIS</td>
<td>55033000</td>
<td>Nov 1997</td>
<td>72</td>
<td>0.016(4)</td>
<td>0.0090(8)</td>
<td>1.6×10^{35}</td>
</tr>
<tr>
<td>CH. ACIS-I</td>
<td>1881</td>
<td>May 2001</td>
<td>100</td>
<td>0.060(1)</td>
<td>1.3×10^{35}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.3×10^{35}</td>
</tr>
</tbody>
</table>


two Einstein observations are consistent. The HRI fluxes are consistent with a constant flux (chi-squared probability 6%). There is a single high PSPC observation (rp600455n00) which is nearly 5σ above the mean. Without that observation the remaining PSPC count rates are consistent with a constant flux (chi-squared probability 26%)

The luminosity values from different detectors are also nearly consistent with one another, averaging to a value of $1.5 \times 10^{35}$ ergs/s. ROSAT observations which are not included in the table (e.g. PSPC observations with the source further than 30 arc minutes from the center of the field) show the source as well. Thus the variability of this source on a time scale of months to years is relatively small. In addition, within the 100ks CHANDRA observation there is no significant variation of the source count rate.

We may use the CHANDRA data as a guide to calculate what FFT power values are to be expected from the other observations. The limited time resolution of the ACIS-I data and the fact that the pulsed signal is near the Nyquist limiting frequency of 0.154 Hz prohibit any detection of harmonic content higher than the fundamental. We therefore make the assumption that the pulsations are purely sinusoid, in which case the power expected is $0.25 N_{\text{pulsed}}^2 / N_{\text{tot}}$, where $N_{\text{pulsed}}$ is the number of pulsed photons and $N_{\text{tot}}$ is the total number of photons. By setting the power to be the observed value of 38 and taking into account the 2% background, we find that the pulsed fraction is $16 \pm 3\%$.

As a further attempt to detect pulsations from this source we analyzed data from the observation (rp600195a00) which has the highest sensitivity to a pulsed signal. It has the second longest exposure (16 ks) of any of the PSPC observations and has by far the shortest duration (85 ks). Other comparable exposure PSPC and HRI observations have durations more than 15 times longer and their sensitivity to a periodic signal is diluted by the search range needed to cover potential frequency variation over this length of time. The duration of rp600195a00 is such that no phase slippage is expected for $\dot{P}$s in the range of the AXPs.

The source for this observation is within 12.7′ of the center of the PSPC field of view where the angular resolution is excellent, thus a selection circle of 80 pixels (40") could be used. With this selection 392 photons were retrieved, of which an estimated 37.6±1 are background. A comparison of the pulse height spectrum for the source and the background, showed that sensitivity to a pulsed signal could be enhanced by eliminating photons with energies less than 0.4 keV. With this restriction 358 photons remained. The times of arrival of these photons were adjusted to the barycenter of the solar system and an FFT was performed.

We restricted our search region to be near one of the two possible frequencies seen in the CHANDRA observation, either 0.1247 or 0.1838 (Hz). To account for a frequency change over the 9.6 years between the two observations we assume that the object has characteristics of the known AXPs. This implies that the pulsar is spinning down, and that the time scale for this, $P/\dot{P}$, is greater than 6.8 ky (see the table in Mereghetti 2001). In the search we have allowed for a possible time scale as short as 1 ky.
With these assumptions the range of frequencies to be searched is 1.20 mHz at the lower frequency and 1.76 mHz at the upper frequency. The ffts near these frequencies for both the CHANDRA observation (a) and (b) and the PSPC observation are shown in Figure 3. In the lower frequency search region there is no significant power peak, however in the upper region there is a peak power of 15.4 which may be significant.

To assess its significance we use a formula first derived by Fisher (1929). This formula gives the probability that a given Fourier power, P, taken from a range of n independent values of power, will be exceeded by chance. Equation (4) of Fisher gives that probability as a series, whose leading term, \( n(1 - g)^{n-1} \) is the only term which is significant for our values of P and n. The parameter “g” is the fraction of the power contained in the term in question. We have used normalized values of power, thus \( g = P/n \). However, since we have used a frequency digitization finer than the independent frequency spacing, 1/T, we must multiply Fisher’s expression by an oversampling factor. For the fft’s we have used a frequency spacing of \( \sim \frac{1}{5T} \) for which an appropriate value of the oversampling factor is 3 (Lewis, 1994).

Putting in the numbers we find a chance probability of \( 1.0 \times 10^{-4} \) of finding such a power of 15.4 or greater within either search range. We judge this to be sufficiently small to be a detection. Using the PSPC observation which occurred 3705 days prior to the CHANDRA observation, we derive a frequency derivative of \( -5.08 \pm 0.07 \times 10^{-13} \) Hz/s. This corresponds to a time scale, \( P/\dot{P} \), of 11 ky.

In addition to the peak at 0.183982(2) Hz there are two other peaks in its vicinity with powers greater than 8. They are separated from the main peak by 0.000173 Hz and 0.000519 Hz. These peaks are due to the on-time profile (window function) of the PSPC data. The 0.000173 Hz frequency is a beat frequency with the orbital period of the satellite (96 minutes); the 0.000519 Hz frequency is its third harmonic. In a simulation of the dataset we have reproduced this behavior.

The pulse profile of the PSPC observation is shown in Figure 4. There is no evidence in the fft for harmonics higher than the fundamental. The pulsed fraction is 36\( \pm \)5%. This disagrees with the 16% value derived from the CHANDRA detection. This discrepancy can be accounted for by the different spectral response of the two detectors and a difference between the unpulsed and pulsed spectrum. Relative to the ACIS-I detector the PSPC weights lower energy photons significantly more than higher energy photons. For example, the ratio of effective area for the PSPC at 0.8 keV to its effective area at 2.0 keV is \( \sim 3 \). The same ratio for the ACIS-I detector is \( \sim 0.8 \). Further we find that the pulsed source spectrum is somewhat softer than its unpulsed emission. Therefore because of the PSPC’s energy response it will detect the pulsed part of source emission more efficiently than the unpulsed part. This qualitatively accounts for the higher pulsed fraction as determined by the PSPC.

We have calculated the sensitivity of the remaining non-CHANDRA observations using this value of the pulsed fraction. We find that none of the other non-CHANDRA observations listed in Table 1 would be sensitive to this pulsation.
Fig. 3.— FFT of CHANDRA (a) and (b) and ROSAT PSPC Observations (c) and (d) in the vicinity of 0.125 and 0.184 Hz. In (c) and (d) the search ranges are indicated. The peak is (d) is significant with a chance probability of $1.0 \times 10^{-4}$ (see text for details). The two other nearby peaks in (d) at power values of 8 and 11 are due to the on-time profile (window function) of the dataset.
We have searched for a possible radio/optical counterpart to this source and find no radio counterpart, however there is an 18th magnitude star which is within 1 arc second of the source. It is star S01020208968 in the Guide Star Catalogue-II available on-line through http://vizier.u-strasbg.fr/viz-bin/cat?I/271#sRM99.3.

3. DISCUSSION

The properties exhibited by this source are fully consistent with the AXP class of X-ray pulsar (Mereghetti 2001 and references therein). Its spectrum is soft, is luminosity, $\sim 1.5 \times 10^{35}$ ergs/s/cm$^2$, is in the range of AXP luminosities ($10^{34} - 10^{36}$ ergs/s/cm$^2$), there is little variation in its long-term and short-term intensity, and it is spinning down with a characteristic age, $P/\dot{P}$, of 11 ky, typical of 3 of the 6 AXPs.

One of the central issues for AXPs is their energy source. If accretion then there may be a companion from which the accretion occurs and which will cause a modulation in the pulsation unless the orbit is observed face on. (Some models of accretion powered AXPs derive their accretion from a remnant disk leftover from a supernova explosion (Marsden et al. 2001, Francischelli & Wijers 2002).) The 100ks continuous CHANDRA observation provides an opportunity for a search for binary induced modulation.

We have subdivided the observation into four 25 ks segments, and separately performed an fft on each. The power peak in the 0.184 Hz region shows no significant frequency variation. In addition, we have explored what would happen to the time series of photons from the source if a hypothetical binary modulation were superimposed. For binary orbits with periods less than one day we find that a projected semi-major axis of more than 0.5 light seconds will reduce the power of the signal by more than one standard deviation in the power. We take this to be an effective limit on the size of any orbit. For orbital periods longer than the 1.2 day observation this size limit is weakened.

This absence of any apparent binary modulation on a time scale $\leq 1$ day is consistent with evidence for other of the AXPs (Mereghetti 2001) for the lack of a binary companion.

Three of the AXPs appear to be associated with relatively young ($< 20$ ky) supernova remnants. In each of these cases: (1E 2259+586: Rho & Petre 1997, Parmar et al. 1998); 1E 1841-045, Helfand et al. 1994; and J1844-0288, Vasisht et al. 2000) there is evidence for extended X-ray emission. We have examined the CHANDRA data for evidence of emission beyond that which is consistent with a point source. We find none. However, a better limit on any possible extension to the source may be derived from ROSAT HRI observations (the first two in the Table) in which the source was approximately 6 arc minutes from the center of the field where the angular resolution of the HRI is better than in CHANDRA data 10 arc minutes off-axis. One-dimensional profiles though the image in the right ascension and declination directions of the combined HRI dataset are consistent with a point source with a width ($\sigma$) of 2.0 arc seconds. There is no evidence
for emission at a level > 5% the counting rate at the peak of the profiles at a distance of 10 to 20 arc seconds from the source. Any extension to the source must be a distance from the source less than the width of the point spread function of the HRI, 10 arc seconds. This corresponds to a limit to the size of any extended X-ray emission of 2.8 pc at the distance of the SMC.

This limit is comparable to the X-ray extension observed for the two SNR/AXP associations with known distances (Kes 73/1E 1841-045 and CT109/1E 2259.1+586). A deep CHANDRA exposure with the source centered in the field of the HRC is needed to constrain strongly the possibility of a supernova remnant association for this pulsar.

This work made use of software and data provided by the High-Energy Astrophysics Archival Research Center (HEASARC) located at Goddard Space Flight Center.

REFERENCES


This preprint was prepared with the AAS L\LaTeX{} macros v4.0.
Fig. 4.— Pulse Profile of PSPC Observation (rp600195a00 see table 1). The lower dashed line indicates the instrumental background levels. The upper dashed line gives the level of the unpulsed source emission.