

## DISCOVERY OF A POSSIBLE ANOMALOUS X-RAY PULSAR IN THE SMALL MAGELLANIC CLOUD

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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 ( $\sim 1.5 \times 10^{35}$  ergs  $s^{-1}$ ), its near lack of variability for more than 20 yr, and its very 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 kyr. If this is a correct identification, it will be the first extragalactic AXP and the fastest yet discovered.

*Subject headings:* galaxies: individual (Small Magellanic Cloud) — pulsars: general — stars: neutron — X-rays: stars

### 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 6–12 s, X-ray luminosities in the range  $10^{34}$ – $10^{36}$  ergs  $s^{-1}$ , very soft X-ray spectra, little or no variability on timescales 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 ( $\sim 6$ ) 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 left over from a supernova explosion (Marsden et al. 2001; Francischelli & Wijers 2002).

In this Letter 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 ( $P = 5.44$  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 100 ks ACIS-I observation that began 2001 May 15 (observation ID 1881). The position of the source is  $01^{\text{h}}00^{\text{m}}43^{\text{s}}.14$ ,  $-72^{\circ}11'33''.8$  (J2000), approximately  $10'$  from the ACIS-I aim point. The density of the stellar field, and its location well out of the Galactic plane, mitigate against ready boresight correction of the *Chandra* data. Apart from applying the prescribed aspect

offset for this data set,<sup>3</sup> we have not further refined the provided aspect solution. Given the negligible uncertainty in the source centroid ( $\sim 0''.05$ ), we expect an absolute astrometric accuracy in line with the overall *Chandra* performance to date, which has provided a 90% confidence radial uncertainty of  $0''.6$ .<sup>4</sup>

In accordance with the *Chandra* source-naming convention, the source is designated CXOU J0110043.1–721134. A selection circle of 24 pixels ( $11''.8$ ) was chosen to encompass more than 90% of the source photons. A total 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 spacecraft were adjusted to the barycenter of the solar system and a fast Fourier transform (FFT) was performed.

Inasmuch as the ACIS-I CCD readout time is a fixed 3.241 s, the Nyquist limiting frequency for the FFT is  $1/6.482$  s = 0.154 Hz. In order to show clearly this limitation, the FFT was performed with a bin size of 0.1 s, 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 very soft. An acceptable spectral fit to the data is given by a blackbody model with an absorption column density  $1.4 \pm 0.2 \times 10^{21}$  H atoms  $\text{cm}^{-2}$  and a value of  $kT = 0.41 \pm 0.01$  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 that 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  $30'$  from the center of the field of view. This latter restriction

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<sup>3</sup> See the *Chandra* X-ray Center “Aspect caveat” page at [http://asc.harvard.edu/cal/ASPECT/aspect\\_caveats.html](http://asc.harvard.edu/cal/ASPECT/aspect_caveats.html).

<sup>4</sup> See <http://asc.harvard.edu/cal/ASPECT/celmon/index.html>.

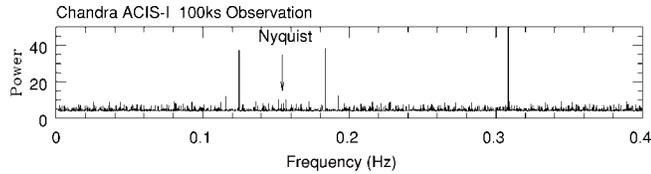


FIG. 1.—FFT of *Chandra* observation of CXOU J0110043.1–721134. The Nyquist frequency at 0.15427 Hz is indicated. The two power peaks of 0.124706(1) and 0.183828(1) Hz are aliases of each other. The remaining peak at  $1/3.241 = 0.3085$  Hz is due to the limited time resolution of the ACIS-I instrument.

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 (distance 57 kpc; Feast & Walker 1987) and that the source spectrum has the same blackbody model 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 two *Einstein* observations are consistent. The HRI fluxes are consistent with a constant flux ( $\chi^2$  probability 6%). There is a single high PSPC observation (rp600455n00) that is nearly  $5\sigma$  above the mean. Without that observation the remaining PSPC count rates are consistent with a constant flux ( $\chi^2$  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  $s^{-1}$ . *ROSAT* observations that are not included in the table (e.g., PSPC observations with the source farther than 30' from the center of the field) show the source as well. Thus, the variability of this source on a timescale of months to years is relatively small. In addition, within the 100 ks *Chandra* observation there is no significant variation of the source count rate.

We can use the *Chandra* data as a guide to calculate what FFT power values are to be expected from the other obser-

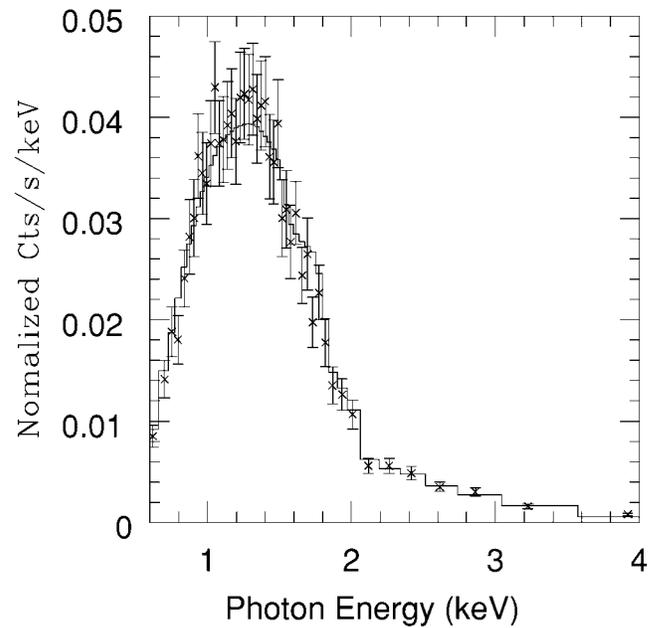


FIG. 2.—Spectral fit for CXOU J0110043.1–721134. The fit assumes a blackbody model with an absorption column density  $1.4 \pm 0.2 \times 10^{21}$  H atoms  $cm^{-2}$  and a value of  $kT = 0.41 \pm 0.01$  keV. The fit has a reduced  $\chi^2$  value of 1.4 for 45 degrees of freedom and thus is an acceptable fit.

varations. 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 CXOU

TABLE 1  
LIST OF OBSERVATIONS OF CXOU J0110043.1–721134

Satellite	Observation	Date	Exposure (ks)	Count Rate (counts $s^{-1}$ )	Mean Rate	$L$ (ergs $s^{-1}$ )
<i>Einstein</i> IPC	6297	1980 Apr	23	0.0122(13)	0.0133 (16)	$1.3 \times 10^{35}$
	3925	1979 Nov	20	0.0144(17)		
<i>ROSAT</i> PSPC	rp500250n00	1993 Oct	20.0	0.0275(16)	0.0280(8)	$1.6 \times 10^{35}$
	rp600195a00	1991 Oct	16.0	0.0273(14)		
	rp600195a01	1992 Apr	9.2	0.0300(21)		
	rp500142n00	1993 May	4.8	0.0263(29)		
	rp600455a02	1993 Oct	4.5	0.026(3)		
	rp600455a03	1994 May	4.0	0.012(7)		
	rp600455n00	1992 Dec	3.5	0.062(7)		
	rp600455a01	1993 Apr	1.7	0.034(9)		
<i>ROSAT</i> HRI	rh900445a01	1995 Apr	34	0.0095(6)	0.0090(8)	$1.5 \times 10^{35}$
	rh900445n00	1994 Apr	15	0.0105(9)		
	rh500137n00	1993 Apr	14	0.0073(10)		
	rh500418a03	1998 May	11	0.0071(10)		
	rh500418a01	1995 Oct	8.2	0.0089(12)		
	rh500418a02	1997 May	7.5	0.0098(13)		
<i>ASCA</i> GIS	55033000	1997 Nov	72	0.016(4)	$1.8 \times 10^{35}$	
<i>Chandra</i> ACIS-I	1881	2001 May	100	0.060(1)		$1.3 \times 10^{35}$

NOTE.—The luminosity is calculated for the interval 0.2–10 keV under the assumption that the spectrum is that given in Fig. 2.

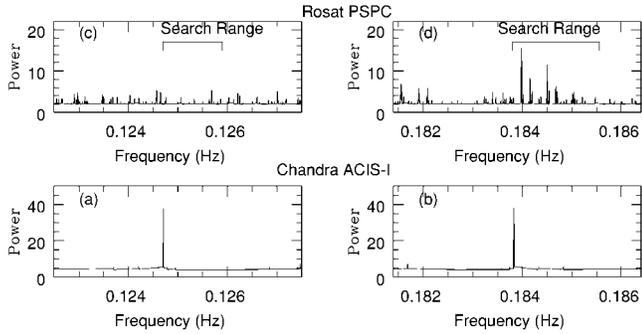


FIG. 3.—FFT of *Chandra* (a and b) and *ROSAT* PSPC observations (c and d) in the vicinity of 0.125 and 0.184 Hz. In (c) and (d) the search ranges are indicated. The peak in (d) is significant with a chance probability of  $1.0 \times 10^{-4}$  (see text for details), indicating that this is the right frequency for CXOU J011004.3–721134. 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 data set.

J011004.3–721134 we analyzed data from the observation (rp600195a00) that 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  $\dot{P}$ -values 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  $37.6 \pm 1$  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 yr 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 timescale for this,  $P/\dot{P}$ , is greater than 6.8 kyr (see the table in Mereghetti 2001). In the search we have allowed for a possible timescale as short as 1 kyr.

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 (Figs. 3a and 3b) 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 that 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

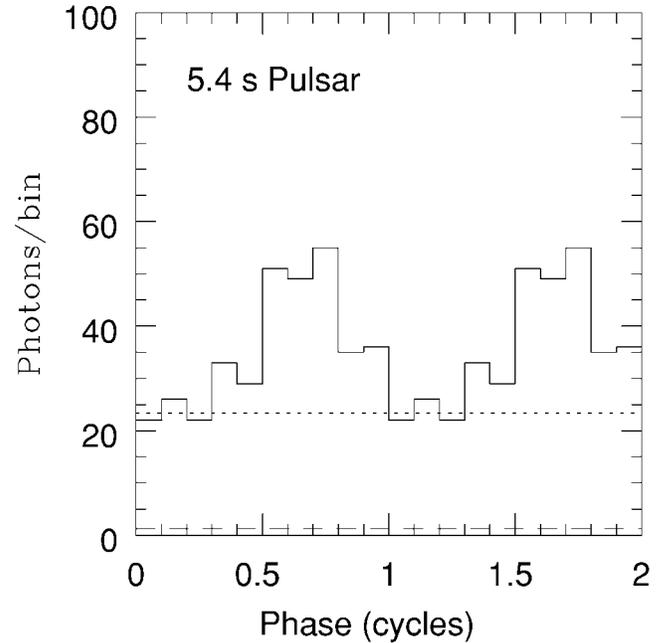


FIG. 4.—Pulse profile of PSPC observation (rp600195a00; see Table 1). The lower dashed line indicates the instrumental background levels. The upper dashed line gives the level of the unpulsed source emission.

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 FFTs we have used a frequency spacing of  $\sim 1/5T$  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 that occurred 3705 days prior to the *Chandra* observation, we derive a frequency derivative of  $-(5.08 \pm 0.07) \times 10^{-13} \text{ Hz s}^{-1}$ . This corresponds to a timescale,  $P/\dot{P}$ , of 11 kyr.

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 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 0.00519 Hz frequency is its third harmonic. In a simulation of the data set 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.

We have searched for a possible radio/optical counterpart to CXOU J0110043.1–721134 and find no radio counterpart. There is an 18th magnitude star<sup>5</sup> that is located 1'2 from the source. The position of CXOU J0110043.1–721134 has an uncertainty of 0'6, therefore it is unlikely to be associated with this star. Nevertheless, it remains a possibility pending refinement of the X-ray source position. From the density of stars in the Guide Star Catalogue within 30' of this position, there is a 4% probability of a chance association within 1'2. Multiband optical photometry has been performed on this star by Y. Nazé et al. (2002, in preparation). The authors believe this star may be an early B star. If this star is a binary companion of CXOU J0110043.1–721134, then it would be the first seen for an AXP and would raise the possibility of accretion as the source of its luminosity.

### 3. DISCUSSION

The properties exhibited by CXOU J0110042.8–721132 are fully consistent with the AXP class of X-ray pulsar (Mereghetti 2001 and references therein). Its spectrum is very soft, consistent with other AXPs, its luminosity,  $\sim 1.5 \times 10^{35}$  ergs s<sup>-1</sup> cm<sup>-2</sup>, is in the range of AXP luminosities ( $10^{34}$ – $10^{36}$  ergs s<sup>-1</sup> cm<sup>-2</sup>), 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 kyr, typical of three of the six 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 left over from a supernova explosion; Marsden et al. 2001, Francischelli & Wijers 2002.) The 100 ks continuous *Chandra* observation provides an opportunity for a search for binary-induced modulation.

We have subdivided the observation into four 25 ks segments

<sup>5</sup> S01020208968 in the Guide Star Catalogue II available on-line through <http://vizier.u-strasbg.fr/viz-bin/Cat?I/271#sRM99.3>.

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 1 day we find that a projected semimajor axis of more than 0.5 lt-s 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 (less than 20 kyr) 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' from the center of the field where the angular resolution of the HRI is better than in *Chandra* data 10' off-axis. One-dimensional profiles though the image in the right ascension and declination directions of the combined HRI data set are consistent with a point source with a width ( $\sigma$ ) of 2'0. There is no evidence for emission at a level of greater than 5% the counting rate at the peak of the profiles at a distance of 10'–20' 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'. 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.

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### REFERENCES

- Feast, M. W., & Walker, A. R. 1987, *ARA&A*, 25, 345  
 Fisher, R. A. 1929, *Proc. R. Soc. London A*, 125, 54  
 Francischelli, G. J., & Wijers, R. A. M. J. 2002, preprint (astro-ph/0205212)  
 Helfand, D. J., Becker, R. H., Hawkins, G., & White, R. L. 1994, *ApJ*, 434, 627  
 Heyl, J. S., & Hernquist, L. 1997, *ApJ*, 489, L67  
 Lewis, D. A. 1994, in *Statistical Methods for Physical Science*, ed. J. L. Stanford & S. B. Vardeman (San Diego: Academic Press), 367  
 Marsden, D., Lingefelter, R. E., Rothschild, R. E., & Higdon, J. C. 2001, *ApJ*, 550, 397  
 Mereghetti, S. 2001, in *The Neutron Star–Black Hole Connection*, ed. C. Kouvelitou, J. van Paradijs & J. Ventura (NATO ASI Ser.; Dordrecht: Kluwer), 351  
 Mereghetti, S., & Stella, L. 1995, *ApJ*, 442, L17  
 Parmar, A. N., Oosterbroek, T., Favata, F., Pightling, S., Coe, M. J., Mereghetti, S., & Israel, G. L. 1998, *A&A*, 330, 175  
 Rho, J., & Petre, R. 1997, *ApJ*, 484, 828  
 Thompson, C., & Duncan, R. C. 1996, *ApJ*, 473, 322  
 Vasisht, G., Gotthelf, E. V., Toril, K., & Gaensler, B. M. 2000, *ApJ*, 542, L49