X-RAYS FROM THE NEARBY SOLITARY MILLISECOND PULSAR PSR J0030+0451 – THE FINAL ROSAT OBSERVATIONS

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ABSTRACT

We report on X-ray observations of the solitary 4.8 ms pulsar PSR J0030+0451. The pulsar was one of the last targets observed in DEC-98 by the ROSAT PSPC. X-ray pulses are detected on a 4.5σ level and make the source the 11^{th} millisecond pulsar detected in the X-ray domain. The pulsed fraction is found to be $69 \pm 18\%$. The X-ray pulse profile is characterized by two narrow peaks which match the gross pulse profile observed at 1.4 GHz. Assuming a Crab-like spectrum the X-ray flux is in the range $f_x = 2-3 \times 10^{-13}$ erg s^{-1} cm^{-2} (0.1–2.4 keV), implying an X-ray efficiency of $L_x/\dot{E} \sim 0.5-5 \times 10^{-3}\,(d/0.23\mathrm{kpc})^2$.

Subject headings: Pulsars: individual (PSR J0030+0451) — stars: neutron — X-rays: general — radiation mechanisms: non-thermal

1. INTRODUCTION

In the $P-\dot{P}$ parameter space, millisecond pulsars are separate from the majority of ordinary field pulsars. They are distinguished by their short spin periods and small period derivatives, giving them high spin-down ages of typically 10^9-10^{10} years and low magnetic field strengths of the order of 10^8-10^{10} G. More than $\sim 75\%$ of the known disk millisecond pulsars are in binaries with a compact companion star, compared with the $\cong 1\%$ of binary pulsars found in the general population. This gives support to the idea that their fast rotation has been recycled by angular momentum transfer during a past mass accretion phase (Bisnovatyi-Kogan & Komberg 1974; Alpar et al. 1982; Bhattacharya & Van den Heuvel 1991; Urpin et al. 1998). Today, 95 recycled pulsars are known of which 57 are located in the galactic plane (Camilo et al. 1999, Edwards et al. 2000, Lommen et al. 2000, Lyne et al. 2000, Manchester et al. 2000). The others are in globular clusters (Kulkarni & Anderson 1996, Camilo et al. 2000) which provide a favorable environment for the recycling scenario (Rasio et al. 2000). Only 10 of the 57 galactic millisecond pulsars are solitary (this includes PSR B1257+12 which is in a planetary system); the rest are in binaries usually with a low-mass white dwarf companion (Camilo et al. 1999). The formation of solitary recycled pulsars is not understood, but it is widely believed that after being 'spun-up' in a binary system the companion to the pulsar was either evaporated or the system was tidally disrupted.

Recycled pulsars were studied exclusively in the radio domain until the early 1990's, when ROSAT, ASCA and BeppoSAX, which had significantly higher sensitivities compared with previous observatories, were launched. The first millisecond pulsar discovered as pulsating X-ray source by ROSAT was PSR J0437–4715 (Becker & Trümper, 1993). Further detections which followed in recent years[3] sum up to almost $\sim 1/3$ of all X-ray detected rotation-powered pulsars.

The available data suggest that the observed emission is likely to be dominated by non-thermal processes. This is supported by observations of PSR B1821–24 (Kawai & Saito 1999), PSR B1937+21 (Takahashi et al. 1999) and PSR J0218+4232 (Mineo et al. 2000) for which power-law spectra and pulse profiles with narrow peaks have been measured by ASCA, RXTE or BSAX. For PSR J0437–4715 and PSR J2124–3358 the existing data do not allow us to unambiguously discriminate between the two likely scenarios: thermal emission from heated polar-caps or non-thermal emission from within the co-rotating magnetosphere. All other X-ray detected recycled pulsars (PSRs B1957+20, J1012+5307, B0751+18, J1744–1134 and J1024–0719) are identified only by their positional coincidence with the radio pulsar and, in view of the low number of detected counts, do not provide much more than a rough flux estimate. The power of XMM-Newton and Chandra is needed to explore their emission properties in more detail. However, the fact that all millisecond pulsars have roughly the same X-ray efficiency ($L_X/\dot{E} \sim 10^{-3}$) as ordinary pulsars supports the idea that the bulk of their X-ray emission has a common origin: magnetospheric, viz. non-thermal emission (Becker and Trümper 1997).

In this paper we report on soft X-ray observations of the solitary millisecond pulsar J0030+0451 using ROSAT. PSR J0030+0451 was discovered only recently with the Arecibo radio observatory during a drift scan search for pulsars (Lommen et al. 2000), and was detected independently during a search for sub-millisecond pulsars with the Bologna Northern Cross by D'Amico (2000). The pulsar has a rotation period of $P = 4.86$ ms and an apparent period derivative of $\dot{P} = 1.0(2) \times 10^{-20}$ s s^{-1} (Lommen et al. 2000). The intrinsic period derivative may be significantly smaller than this due to the Shklovskii effect (Shklovskii et al. 1970; Camilo et al. 1994). The pulsar spin-down age $P/2\dot{P} = 8 \times 10^9$ yrs is thus a lower-limit and $B_\perp = 2.2 \times 10^8$ G is an upper limit to the surface magnetic field. The inferred rotational energy loss rate is $\dot{E} \leq 3.4 \times 10^{33}$ erg s^{-1}cm^{-2}. Using the model of Taylor & Cordes (1993) for the galactic distribution of free electrons, the radio dispersion measure of $DM = 4.33$ pc cm^{-3} implies a pulsar distance of 230 pc and a column density of $N_H \sim 10^{20}$ cm^{-2}. In terms of the pulsars spin-parameters PSR J0030+0451 thus turns out to be a twin of the recent X-ray detected solitary millisecond pulsar J2124–3358 (Becker & Trümper 1999; Bailes et al. 1997), making it a very promising target for X-ray studies.

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[3]For a review on the X-ray emission properties and the observational status of recycled pulsars see Becker & Trümper 1999 and Becker 2000.

2. OBSERVATION AND DATA ANALYSIS

In the course of the ROSAT mission, PSR J0030+0451 was in the PSPC (Position Sensitive Proportional Counter) field of view on three different occasions. During the ROSAT All-Sky Survey (RASS) the pulsar was observed for 367 seconds between 1990 June 12-14, but the survey sensitivity of $\sim 3\times10^{-12}$ erg s^{-1}cm^{-2} was not sufficient to detect the pulsar. A search for serendipitous data in the ROSAT archive showed that the pulsar position was observed in 1992 July at about $\sim$ 43 arcmin off-axis. Unfortunately, the pulsar position turned out to be fully covered by a laceration in the PSPC entrance window support structure, reducing the detection sensitivity for the pulsar in that data to almost zero. When it became clear that the ROSAT mission would come to its ultimate end the PSPC detector was activated again after being out of the focus for more than two years. Among a few other sources, PSR J0030+0451 was scheduled to exhaust the remaining detector gas before the satellite was switched off. The observations took place on 1998 December 16-17 and provided us with 7743 sec of good data. The pulsar, together with the quasar GB1428+4217 (Boller et al. 2000), were the final targets observed by ROSAT.

The unstable behavior of the satellite during its last observations as well as the reduced gas flow and pressure in the PSPC caused several data anomalies. The reduced and non-uniform gas flow led to a variable and somewhat lower gain. Although the effect of this gain variation has been corrected during the standard processing, some soft events may have escaped detection due to their falling below the raw amplitude lower limit, i.e. event numbers in the channels below 15 (corresponding to about 0.15 keV) are incomplete. We have corrected for occasional master veto rates below 35 counts s^{-1} which indicate occasional breakdowns of the high voltage not recorded in the housekeeping data. In addition, we corrected for an occasional flickering of the high voltage which caused periods of frequent short accepted time intervals of less than 10s where the nominal voltage (and thus gain value) may not have been reached. Finally, a “sensitivity hole” appeared to develop in the north-western quadrant of the PSPC detector, which reached the on-axis position at the time of our observation. It is not possible to correct for this degradation in signal. Luckily, the millisecond pulsar position available at the time of scheduling was offset in right ascension and declination by a few arcmin in a direction opposite from the hole.

2.1. *Spatial analysis*

We searched for the X-ray counterpart of PSR J0030+0451 by doing a maximum likelihood analysis of the source counts in combination with a spline fit to the background level and fitting the results. After applying the data corrections described above, 17 X-ray sources were detected in the PSPC field of view with a detection threshold of $\geq 5\sigma$ (cf. Fig.1). The sources are listed in Table 1. Because of the sensitivity in the north-western part of the detector the source list might not be complete for that sky region.

The loss of the last ROSAT star tracker in April 1998, which was substituted by the Wide-field camera star tracker, caused systematic position inaccuracies which were as large as 30 arcsec. Correlating the ROSAT sources with optical catalogues we find that RX J0030.1+0451 is within $\sim$ 17 arcsec with HD 2648, an F5-star with $m_v = 6.7$. This source is also detected in the ROSAT all-sky survey data and in the serendipitous archival data, although in the latter at an off-axis angle of $\sim$ 40 arcmin and close to the PSPC entrance window support structure. Its position accuracy given in the WGA catalog (White et al. 1994) is, for that reason, not very accurate. The position determined in the RASS data is about 1.5 arcmin off from the position obtained in the December 98 data. The X-ray emission is very soft with practically no emission beyond 0.5 keV.

Accepting the identification of RX J0030.1+0451 with HD 2648 we are able to use its optical position to improve the positional accuracy of all X-ray sources in the field. The differences in right ascension and declination for HD 2648 are found to be $\mathrm{RA}_{opt}-\mathrm{RA}_{Rosat}=0.45''$ and $\mathrm{DEC}_{opt}-\mathrm{DEC}_{Rosat} = -16.2''$. Applying these corrections to all X-ray sources resulted in the positions given in Table 1. Correlating the millisecond pulsar position with the corrected source locations, we find that RX J0030.4+0451 is within $\sim$ 11 arcsec to the radio position of PSR J0030+0451, making it a likely counterpart for the millisecond pulsar. Additionally, the USNO catalog lists an optical source with $m_V = 18.3$ and $m_B = 19.5$ at RA=00:30:27.84 and DEC=+04:51:34.74, which is only about 6 arcsec distant from the millisecond pulsar position. Although the USNO source may be the optical counterpart of the millisecond pulsar (which is expected to be much fainter at optical wavelength than $m_V \approx 19$), it is not a priori excluded that it is the counterpart of the ROSAT source RX J0030.4+0451 rather than the millisecond pulsar. With $B-V = 1.2$ the optical object could be a K5 star at $\sim$ 1.5 kpc, but an AGN is also possible. For $\log f_x/f_v$ we determine a value close to zero, which according to Maccacaro et al. (1988) would be in agreement with an AGN. The identification of a timing signature according to the millisecond pulsar rotation period is therefore necessary to unambiguously identify RX J0030.4+0451 as being the X-ray counterpart of PSR J0030+0451.

Two other X-ray detected sources in the PSPC field were identified with sources in the NRAO VLA Sky Survey at 1.4 GHz (NVSS, Condon et al. 1998) to within $10''$ and are shown in Table 1. This survey has a completeness limit of about 2.5 mJy. There are no NVSS sources within $3'$ of any other PSPC source in this field.

2.2. *Timing analysis*

In order to search for a 4.86 ms spin modulation from RX J0030.4+0451 we have selected all photons within an annulus of 70 arcsec centered on the source. The selection radius includes 103 events of which $\sim$ 10% belong to the background. The X-ray arrival times were corrected for the satellite's motion, and a barycenter correction was performed using the analysis software *eXsas* (Zimmermann et al. 1997). For the arrival time correction we fitted the clock calibration points, available for the days $334-340$ of 1998, with a first order polynomial[4].

Millisecond pulsars are stable clocks. Given the high precision of the pulsar's radio ephemeris (cf. Table 2), we related each X-ray photon arrival time directly to the pulsar's rotation phase ϕ. By applying the Z_n^2–test with $n = 1$ to 10 harmonics (Buccheri & De Jager 1989) in combination with the H-Test, to yield the optimal number of harmonics for a pulsed signal (De Jager 1987), we find a deviation from a flat pulse-phase distribution with a significance of 4.5σ for 4 harmonics. This establishes RX J0030.4+0451 as the X-ray counterpart of PSR J0030+0451 beyond any doubt, and makes it the 11^{th} millisecond pulsar detected in the soft X-ray domain.

[4]Our fit is included in the ROSAT clock calibration table which is distributed as part of *eXsas* version APR-2000.

The X-ray pulse profile of PSR J0030+0451 is shown in Figure 2. It is characterized by two narrow peaks that are separated in phase by $\sim 180°$. The fraction of pulsed photons, which was determined by the bootstrap method described in Becker & Trümper (1999), is $69 \pm 18\%$. Fig.2 includes the radio pulse profile at 1.4 GHz for comparison with arbitrary phase alignment owing to the lack of absolute timing on ROSAT. The gross pulse morphology is the same in the two observing bands. The fine structure seen in the radio profile is not resolved in the X-ray profile owing to the limited photon statistics.

2.3. *Spectral analysis*

The low number of detected source counts together with the unstable behavior of the PSPC detector during the DEC-98 observations does not support a detailed spectral analysis of the pulsar data. We estimated the pulsar's energy output in the ROSAT band by converting the PSPC source count rate into an energy flux assuming a power-law spectrum $dN/dE \propto E^{-\alpha}$ with photon-index $\alpha = 2$ (c.f. Becker & Trümper 1997). The column density along the pulsar's line of sight is $N_H(galaxy) = 3 \times 10^{20}\,\mathrm{cm}^{-2}$ through the Galaxy (Dickey & Lockman 1990). Assuming an electron density of $n_e = 0.03\ \mathrm{cm}^{-3}$ the radio dispersion measure converts to $N_H(pulsar) = 1.3 \times 10^{20}\,\mathrm{cm}^{-2}$. Both numbers are of the same order and yield fluxes in the range $f_x = (2-3) \times 10^{-13}$ erg s^{-1} cm^{-2} (0.1 – 2.4 keV). The corresponding (isotropic) X-ray luminosity is $L_x \sim (1-2) \times 10^{30}\ (d/0.23\mathrm{kpc})^2$ erg s^{-1}. As mentioned already, the Shklovskii contribution to the pulsar's period derivative is unknown. Assuming a typical pulsar space velocity of 65 km s^{-1}, the intrinsic $\dot{P}$ of PSR J0030+0451 would be an order of magnitude smaller than what is measured. Each parameter derived from $\dot{P}$ also inherits the same possibility for correction. In particular, the rotational energy loss rate of $\dot{E} = 3.4 \times 10^{33}$ erg s^{-1} is an upper limit and could be a factor of 10 smaller when the proper motion is measured. Taking this uncertainty into account the pulsar's X-ray efficiency is in the range $\eta = L_x/\dot{E} \sim (0.5-5) \times 10^{-3}\,(d/0.23\mathrm{kpc})^2$.

3. SUMMARY AND CONCLUSION

PSR J0030+0451 is the 11^{th} millisecond pulsar detected in the soft X-ray band. In terms of its spin-parameters, it is almost a "twin" of the solitary millisecond pulsar J2124–3358 from which pulsed X-ray emission was discovered in a recent HRI observation (Becker & Trümper 1999). Although the present data do not support a detailed spectral analysis, the temporal emission characteristic of a high pulsed fraction ($\sim 69 \pm 18\%$), the phase separation of $\sim 180°$ between the two narrow peaks, and the gross similarity between the radio and X-ray pulse profile suggest that the mechanisms which create the pulsed X-rays are closely related to the radio emission process. The bulk of the observed X-rays is then likely to be of non-thermal origin.

It has been recently argued that the group of X-ray detected ms-pulsars can be divided into two classes (see e.g. Kawai & Saito 1999). The first includes PSR B1821–24, B1937+21 and J0218+4232 ($P \sim 1.5-3$ ms, $\log \dot{E} \sim 35-36$ erg s^{-1}), for which the X-ray emission exhibits power-law spectra and the pulse profiles have narrow peaks, and therefore magnetospheric emission is invoked. The non-thermal, magnetospheric emission is expected to have a power-law energy spectrum. The second class comprises PSR J0437–4715 and J2124–3358 ($P \geq 5$ ms, $\log \dot{E} \sim 33-34$ erg s^{-1}) for which the X-ray emission is believed to be dominated by thermal polar-cap emission. Unfortunately the existing spectral data are not of sufficient quality to discriminate between the thermal polar-cap and non-thermal magnetospheric emission scenarios. Both models fit the data equally well. The argument for this second group being thermal emitters is that their pulse profiles are broad, and the pulsed fraction is small (pulsed fraction $\sim 20-30\%$) when compared to the non-thermal emitting sources (pulsed fraction $\geq 50-60\%$). The argument is not unreasonable – thermal polar-cap emission should result in broad sinusoidal soft modulated emission with a pulsed fraction $\leq 50\%$ (Pavlov & Zavlin 1998), whereas magnetospheric emission is reasonably expected to cause narrow pulse-peaks and large pulsed fractions.

Despite the apparent reasonableness of the previous arguments, the interpretation is not unique. Becker & Trümper (1997; 1999) have emphasized that the radiation cone produced by magnetospheric emission, which yields sharp peaks at one aspect angle, may well be less sharply modulated when viewed from other directions. Thus a broad, weakly modulated pulse profile is not unambiguous evidence for thermal emission. Indeed, one can argue on phenomenological grounds based on the L_x vs $\dot{E}$ relation (most of the X-ray pulsars lie close to the line $L_x \sim 10^{-3}\dot{E}$) that the X-ray emission from all ms-pulsars is dominated by magnetospheric emission. One could invoke a gross similarity between the X-ray and radio pulse profiles as part of this argument (see Fig. 8 and Fig. 13 from Becker & Trümper 1999). It would seem unlikely that the physical conditions involved change so dramatically with the parameters as to produce two distinct classes of sources. There are reasonable physical models that allow the radio and the X-ray emission to be produced by processes taking place in the pulsar magnetosphere from which the radio emission arises (cf. Crusius-Wätzel, Kunzel & Lesch 2000). There can still be thermal emission from the polar caps, e.g., heating by particle backflow from the magnetosphere and non-thermal magnetospheric emission from charged particles moving out along the curved open field lines, but the key question is how both emission mechanisms add together (e.g. Zhang & Harding 2000).

PSR J0030+0451 thus is found to be a hybrid. While its spin parameters suggest smoothly pulsed thermal emission, its observed X-ray pulse profile and pulsed fraction suggest a non-thermal origin of the X-ray emission. So have we fooled ourselves into creating two classes of millisecond pulsars? Is it possible that the emission from all recycled pulsars is simply due to a gradual variation of the parameters defining the magnetosphere, or will we need another interpretation entirely? Further X-ray observations by Chandra or XMM will surely shed some light on this topic providing detailed spectral and temporal information from this peculiar object.

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TABLE 1
X-RAY SOURCES DETECTED WITH A SIGNIFICANCE OF $\geq 5\sigma$ WITHIN THE ROSAT PSPC'S FIELD OF VIEW DURING THE DEC 1998 OBSERVATION OF PSR J0030+04551.

	PSPC source detected					NVSS source or Pulsar detected		
Nr.	Name RX	RA(2000) HMS	DEC(2000) DMS	Rate cts/s	Error cts/s	RA(2000) HMS	DEC(2000) DMS	Flux mJy
1	J0030.3+0527	00,30,23.86	+05,27,36.2	0.0095	0.002			
2	J0030.2+0521	00,30,16.90	+05,21,32.6	0.0077	0.002			
3	J0032.9+0518	00,32,59.39	+05,18,22.7	0.0175	0.003			
4	J0028.6+0516	00,28,36.60	+05,15,48.4	0.0127	0.002			
5	J0031.3+0513	00,31,20.93	+05,13,26.7	0.1189	0.005	00,31,20.87	+05,13,21.6	8.8
6	J0031.0+0511	00,31,01.65	+05,10,45.1	0.0125	0.002			
7	J0030.1+0504	00,30,08.11	+05,03,53.9	0.0084	0.001			
8	J0031.7+0503	00,31,47.85	+05,03,03.5	0.0097	0.002			
9	J0029.4+0454	00,29,25.63	+04,54,31.1	0.0034	0.001			
PSR	J0030.4+0451	00,30,28.14	+04,51,41.4	0.0156	0.002	00,30,27.43	+04,51,39.7	0.6
11	J0030.1+0451	00,30,08.74	+04,51,36.7	0.0338	0.009			
12	J0029.8+0445	00,29,53.87	+04,45,22.4	0.0076	0.001			
13	J0030.7+0440	00,30,47.38	+04,40,41.7	0.0039	0.001	00,30,47.71	+04,40,38.3	4.1
14	J0032.1+0438	00,32,10.80	+04,37,50.5	0.0090	0.002			
15	J0030.3+0433	00,30,22.83	+04,33,26.7	0.0058	0.001			
16	J0030.5+0421	00,30,35.26	+04,21,04.9	0.0297	0.003			
17	J0028.9+0417	00,28,57.01	+04,17,37.3	0.0839	0.005			

NOTE.—The count rate given for RX J0030.1+0451 (HD 2648) was taken from the ROSAT all-sky survey data as this source turned out to be strongly effected by the PSPCs sensitivity hole.

TABLE 2
PULSAR PARAMETERS FOR PSR J0030+0451

Right ascension (J2000)	$00^h\ 30^m\ 27^s.432$
Declination (J2000)	$+04^\circ\ 51'\ 39''.7$
Pulsar Period, P	0.00486545320737 ms
Period derivative	1.0×10^{-20}
Epoch of period, T_0	MJD 50984.4
Dispersion Measure	DM 4.33 pc cm^{-3}
Dispersion based distance	d = 230 pc

NOTE.—From Lommen et al. 2000

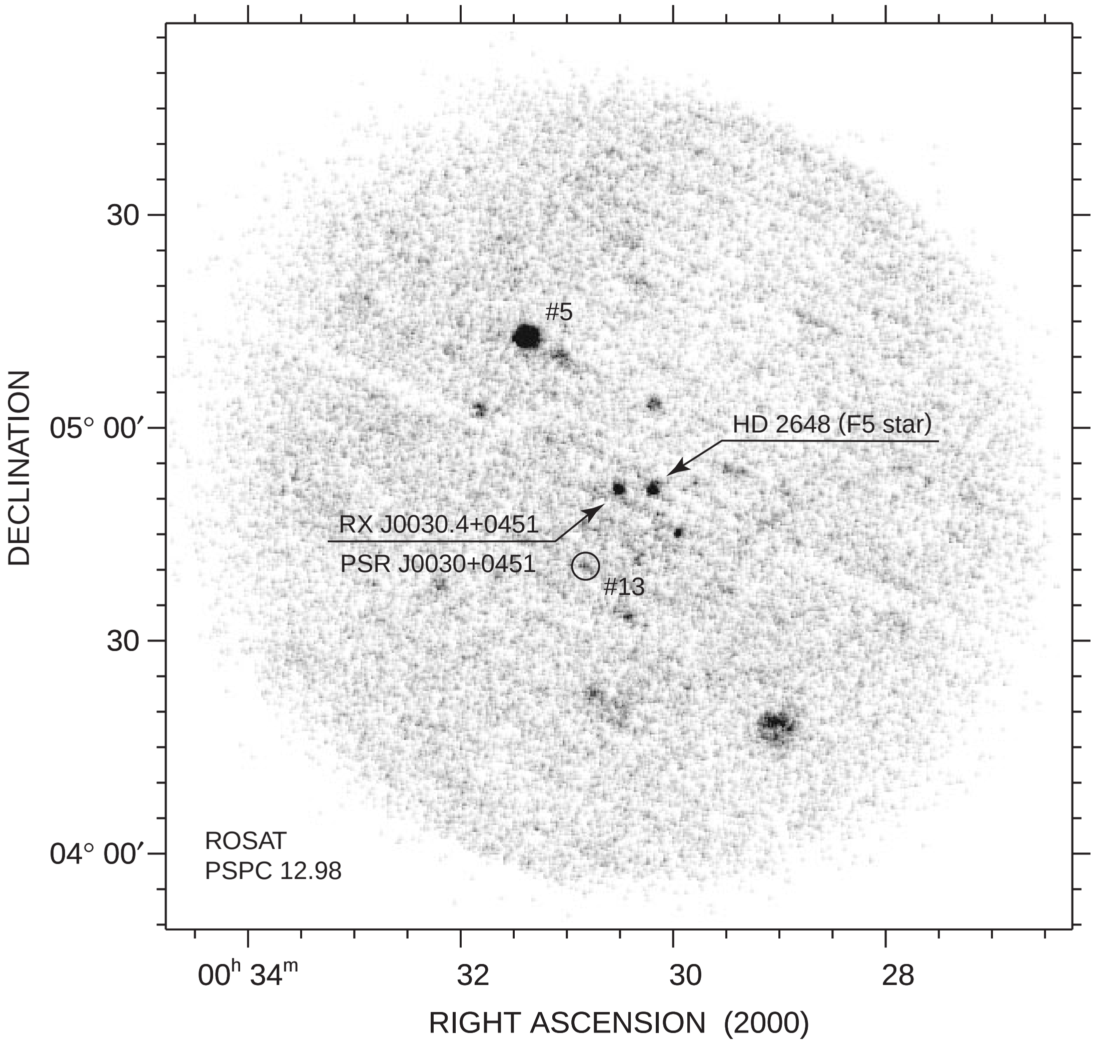

FIG. 1.— The two degree ROSAT PSPC image of the field around PSR J0030+0451. RX J0030.4+0451 and the F5-star HD 2648 are located close to the optical axis, with a separation of ~ 4 arcmin. The sensitivity hole is only barely visible in the north-western quadrant of the image. The two sources which are coincident with NVSS radio sources are indicated.

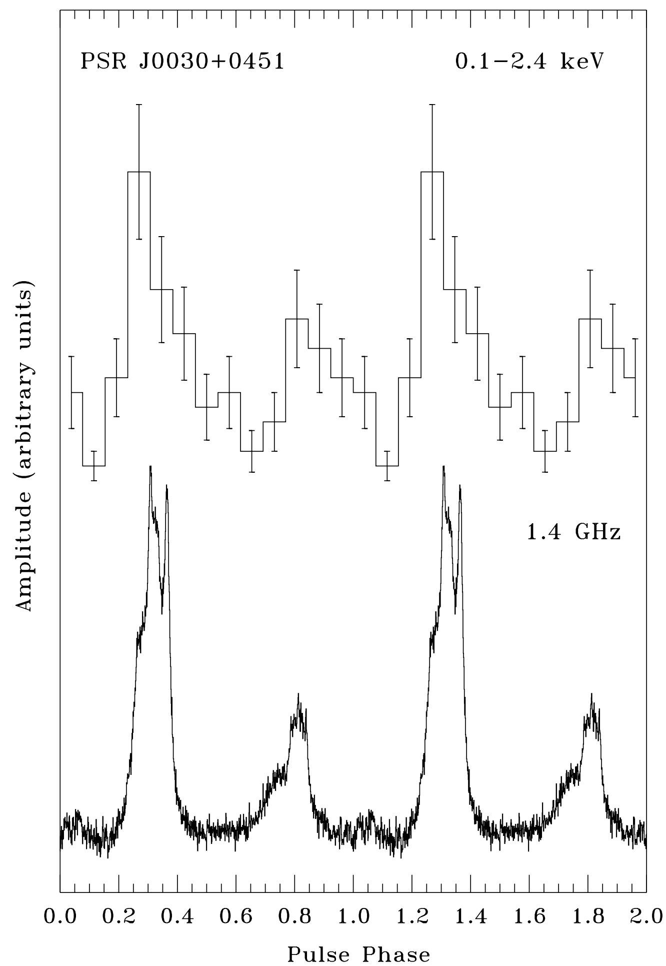

FIG. 2.— X-ray and radio pulse profile of PSR J0030+0451 as observed with the ROSAT PSPC in the 0.1–2.4 keV band (top) and the Arecibo radio telescope at 1.4 MHz (bottom). Two phase cycles are shown for clarity. The phase alignment is arbitrary.