X-ray emission from the young pulsar J1357-6429 and similar objects

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1. Introduction

Generally, X-ray radiation from an isolated neutron star (NS) can consist of two distinguished components: the nonthermal emission due to pulsar activity and radiation from the stellar surface. The former component is usually described by a power-law (PL) spectral model and attributed to radiative processes in the pulsar magnetosphere, whereas the thermal component can originate from either the entire surface of a cooling NS or small hot spots around the magnetic poles on the surface (polar caps), or both. Figure 1 represent an evolutionary picture of these two radiative components in X-ray emission of NSs. In the majority of very young pulsars (τ~1 kyr), the nonthermal component dominates, making it virtually impossible to accurately measure the thermal flux. As a pulsar becomes older, its nonthermal luminosity decreases faster than the thermal one does at NS ages of τ~100 kyr and, hence, the thermal radiation from the entire stellar can dominate at soft X-ray energies from middle-aged pulsars. For NSs older than 1 Myr, the surface temperature is too low to detect radiation from the whole surface in X-rays, only hot polar caps can be observable.

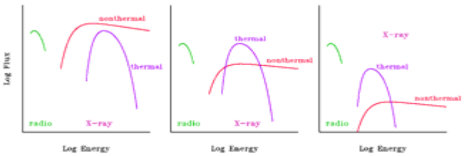

Fig. 1: see Zavlin 2007 for details —

Young active (~1 kyr): e.g., PSRs B1509-58, B0540-69, Crab

Middle-aged (~100 kyr): thermal component from the whole surface; Geminga, PSRs B1055-52, B0656+14

Old (>1 Myr): thermal emission from hot polar caps; e.g., millisecond pulsars, PSR B0950+08

2. PSR J1357-6127

Young pulsars are of a special interest for X-ray observations as they can emit both nonthermal and thermal components, but no prediction can be made as to which one would prevail. Observations with *Chandra* and *XMM*-Newton revealed that thermal radiation can be dominant in X-ray flux of a young object — the pulsars Vela (with the characteristic age τ_c=11.0 kyr) and J1119-6127 (τ_c=1.6 kyr) are examples of young NSs with the bulk of X-ray flux of a thermal origin (Pavlov et al. 2001; Gonzalez et al. 2005).

At a distance d=2.5 kpc derived from the pulsar's dispersion measure and the Galactic electron density model of Cordes & Lazio (2002), PSR J1357-6127 (J1357 for short), with spin period P=166 ms, spin-down energy dE/dt=3.1×10^{36} ergs/s and τ_c=7.3 kyr (Camilo et al. 2004), is one of the nearest objects in the group of about two dozen currently know pulsars with τ_c <15 kyr (according to the ATNF Pulsar Catalogue, see http://www.atnf.csiro.au/research/pulsar). The actual pulsar's age could be $\tau=2\tau_c/[n-1]$<15 kyr, for a typical magneto-dipole braking index n=2-3. Radio observations of J1357 revealed a strong glitch of its spin period (Camilo et al. 2004), $\Delta P/P$= -2.4 ×10^{-6}, similar to those experienced by some other young pulsars (e.g., Vela). All this supports the hypothesis that J1357 is indeed a young NS. It is located relatively close to the supernova remnant candidate G309.8-2.6, but a possible connection between these two objects has to be established yet, opposite to the case of the majority of young pulsars associated with supernova remnants.

3. X-ray observations of J1357

XMM-Newton observed J1357 on 2005 August 5 for 11.6 and 14.5 ks of effective exposures with the EPIC-pn and MOS instruments (respectively), operated in Full-Frame Window mode, with the highest achieved time resolution of 73.4 ms (not sufficient for a timing of J1357). Due to strong particle flares a background level during about 85% of the total observation span was higher by a factor of 3-20 than the ''quiescent'' rate. These data were reprocessed with the SAS v. 7.0.0 package.

J1357 was observed with the *Chandra* HRC-S instrument operated in Timing mode on 2005 November 18 and 19 for a 33.2 ks total effective exposure and with a 0.016 ms time resolution. The CIAO v. 3.4 software (CALDB v. 3.3.0.1) was used to reduce the HRC-S data from the two observations and combine them in a single dataset.

3. Spatial analysis

Figure 2 presents a smoothed HRC-S image of the 8'' ×8'' region around the radio position of J1357. The image reveals a point-like source surrounded by a weak diffuse emission. The point-like source is centered at a position differing only by about a half of an arcsecond from the radio position of the pulsar (this difference is very close to the 1σ error in the HRC-S positional astrometry). The presence of the extended emission is also apparent in Fig. 3 showing two 1-D distributions of counts in rectangular apertures shifted along the main symmetry axis of the box plotted in Fig. 1: one histogram presents the distribution of detected counts, the other indicates the HRC-S point-spread function computed from a 2-D simulation performed with CIAO. The proximity of the X-ray and radio positions and the morphology of the extended emission suggest that the detected X-ray radiation is emitted by J1357 and its possible pulsar-wind nebula (PWN).

The 1''×1.6'' box shown in Fig. 2 contains 18 counts, of which only 14% belongs to background. Modeling of this emission with a PL spectrum of a photon index Γ=1.5 (typical for X-ray PWNe, see, e.g., Kargaltsev et al. 2007) yields the unabsorbed flux F=3.3×10^{-14} ergs/s/cm^2 in 0.5-10 keV, or luminosity L=2.5×10^{31} ergs/s =0.8×10^{-5} (for d=2.5 kpc).

No signatures of a large-scale diffuse emission, which could be associated with G309.8-2.6, were found in these HRC-S data.

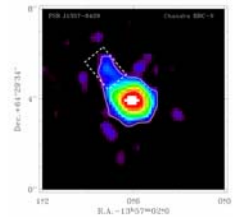

Fig. 2 *Chandra* HRC-S image (smoothed with a 0.4'' FWHM Gaussian) showing J1357 surrounded by an extended structure (indicated by the dashed box). White contours correspond to intensity levels of 0.17, 0.55 and 1.74 counts/arcsec^2/ks.

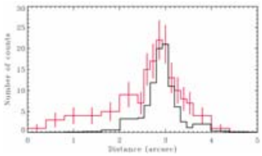

Fig. 3 Distribution of counts detected with the *Chandra* HRC-S instrument (red histogram) in rectangular apertures shifted along the main symmetry axis of the box plotted in Fig. 2. The black histogram shows the HRC-S point-spread function computed for the same apertures.

4. Timing and spectral analysis

For the timing analysis, 137 counts extracted from the 1''-radius circle centered at the pulsar's X-ray position (of them, 132 counts were estimated to belong to J1357) and an accurate radio ephemeris (Camilo 2007) obtained from observations at the Parkes radio telescope in an interval covering the *Chandra* HRC-S observations were used. The standard Rayleigh test resulted in a value of Z^2=12.0, or a signal detection at a 99.8% confidence level. Figure 4 presents the pulsed profile of J1357 extracted using the radio ephemeris, with the estimated pulsed fraction of p_f=63±15%. (defined as the fraction of counts above the minimum in the light curve). Because of the poor statistics, the shape of the pulsed profile is not well determined. The only certain result is that the pulsed fraction is rather large, implying special properties of the pulsar's X-ray emission.

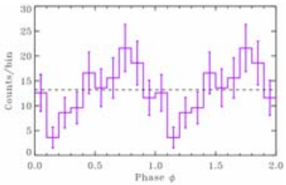

Fig. 4 Pulsed profile of J1357 extracted from the *Chandra* HRC-S data. The dashed line indicates the mean level.

5. Spectral analysis

The X-ray spectra of J1357 were extracted from the XMM-Newton EPIC-pn and MOS data, with the estimated source count rates of 56±8 (pn) and 17±4 (MOS) counts/ks in 0.3-10 keV. A single PL model fits the spectra rather well, with χ^2=1.2, yielding Γ=2.1±0.4. The derived nonthermal (isotropic) luminosity in 0.5-10 keV is L_X=2.0×10^{32} ergs/s =6.5×10^{-5} dE/dt (of this, about 10% belongs to the putative PWN).

One the other hand, it is reasonable to assume that J1357 emits observable thermal radiation. Adding a thermal component improves the fit, χ^2=0.8, indicating that it is required by the data at a 99.998% confidence level. The thermal component can be equally well described by a blackbody (BB) spectrum and a NS magnetized atmosphere model ('NSA' code in the XSPEC package; see Zavlin 2007 for a review on NS atmosphere models). However, as in many other cases, the estimates on the temperature and size of the emitting area derived from these two models are very different: T^{∞}_{bb}=1.7±0.2 MK and R^{∞}_{bb}=2.5±0.5 km (redshifted values) in the BB fit, and T_{eff}=1.0±0.1 MK (effective temperature) for R=10 km in the NS atmosphere fit. The corresponding bolometric luminosities are L^{∞}_{bb}=3.7×10^{32} ergs/s and L_{atm}=7.1×10^{32} ergs/s. The parameters of the nonthermal component are similar in the both fits, Γ=1.2±0.2 and L_X=1.4×10^{32} ergs/s =4.5×10^{-5} dE/dt. The hydrogen column density toward J1357 inferred in these fits, (2-5)×10^{21} cm^{-2}, is comparable with the standard estimate given by the pulsar's dispersion measure. The thermal component contributes 72% of the X-ray flux observed at photon energies below 2 keV, regardless of whichever model is used to describe the component. The best fit involving the NS atmosphere model is shown in Fig. 5.

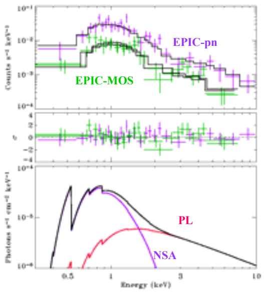

Fig. 5 Spectra of J1357 as detected with the XMM-Newton instruments and fitted with a two-component, NS atmosphere (NSA) and power-law (PL), model.

6. Summary on what the first X-ray observations have told us about J1357

- J1357 possibly powers a small-scale, tail-like PWN, with an efficiency, $L/[dE/dt]$, comparable to those measured for other pulsars
- The bulk of the pulsar's X-ray flux is most likely of a thermal origin. It makes J1357 the second known youngest pulsar, after PSR J1119-6127, with a thermal component dominating at softer energies.
- The spectral data alone cannot unambiguously reveal the origin of the thermal radiation. The results from the BB fit could be interpreted as emission from a heated small area (polar caps?) on the NS surface (although the estimated radius R^{∞}_{bb} exceeds by a factor of 10 the canonical polar cap estimate). Opposite to that, the fit the NS atmosphere models indicate that the thermal radiation originates from the entire NS surface.
- The detected pulsations of the pulsar's X-ray flux with p_f>50% suggest that the thermal radiation is intrinsically anisotropic, as predicted by the NS atmosphere models — otherwise the effect of the gravitational bending of photon trajectories near the NS surface would strongly suppress the pulsations. This obviously contradicts the simplistic (isotropic) BB interpretation. Such a large pulsed fraction also indicates that J1357 has an essential nonuniformity of the surface magnetic field and, hence, temperature. Then, the temperature T_{eff} inferred in the NS atmosphere fit assuming the uniform surface should be considered as an estimate on the ''mean'' surface temperature. The same conclusion stays for several other objects with large and/or energy-dependent pulsed fractions (e.g., PSRs J0538+2817 and J1119-6127 and; Zavlin & Pavlov 2004, Gonzalez et al. 2005).

7. Properties of thermal radiation of young pulsars

Table 1

PSR	τ_c/τ_{true} kyr	T_{eff} (NSA; R=10-12 km) MK	T^{∞}_{bb} MK	R^{∞}_{bb} km
1. J1119-6127	1.6	1.6	2.4	3.4
2. J1357-6429	7.3	1.0	1.7	2.5
3. Vela	11.0	0.9	1.6	2.8
4. B1706-44	17.5	1.0	2.0	1.8
5. J0538+2817	620/30	1.1	2.1	1.7
6. B2334+61	40.9	0.9	1.5	2.8

(see Zavlin 2007 for details)

Figure 6 presents NS cooling models with and without proton superfluidity (Yakovlev & Pethick 2004), as well as the measured (effective) surface temperatures for the six pulsar listed in Table 1. The superfluidity reduces the neutrino emission by suppressing the Urca processes and, hence, decelerates the NS cooling. This effect depends on NS mass, being stronger for higher masses. The comparison shown in Fig. 6 suggests that the interiors of these pulsars are superfluid, and their masses may be in the range M=(1.5-1.6) M_{solar}.

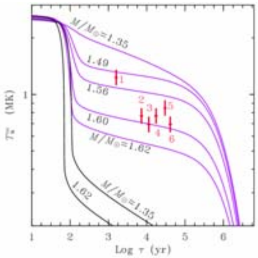

Fig. 6 NS cooling models with (purple) and without (black) proton superfluidity, for different NS masses. The crosses indicate the pulsars listed in Table 1. The surface temperatures estimated from NS atmosphere model fits.

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