X-ray Analysis of the Pulsar Wind Nebula DA 495 and its Central Object

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Abstract. We report the results of a simultaneous analysis of the Chandra and XMM-Newton data on the pulsar wind nebula DA 495 and its central object, J1952.2+2925, which is presumably a pulsar. The J1952.2+2925 pure thermal spectrum can be equally well described either by the blackbody model with a temperature of 215 eV and an emitting area radius of 0.6 km or magnetized neutron star atmosphere models with temperatures of 80–90 eV. We also used the high temporal resolution XMM-Newton/EPIC-pn data to search for pulsations from J1952.2+2925. No pulsations were found so we set an upper limit for the pulsed fraction which is 40%. Using of the interstellar absorption-distance relation allowed us to estimate the distance to DA 495, which lies between 1 and 5 kpc.

1. Introduction
The pulsar wind nebula (PWN) DA 495 (G65.7+1.2) was discovered in the radio band [1]. The distance to DA 495 $D$ was estimated as $\approx 2.1$ kpc under the assumption of association with the open cluster NGC 6834 [2]. Another estimations of 1–1.5 kpc are based on H I absorption measurements [3, 4]. DA 495 age is suggested to be about 20 kyr [4]. A spectral break was found at 1.3 GHz [4], spectral indices $\alpha_\nu = 0.45 \pm 0.20$ and $\alpha_\nu = 0.87 \pm 0.10$ below and above the break, respectively.¹ A compact source, 1WGA J1952.2+2925 (hereafter J1952), surrounded by diffuse emission was discovered in X-rays by ROSAT and ASCA and later observed by Chandra [5]. It was supposed to be a pulsar powering the PWN, although the analysis of the ASCA data allowed only to set an upper limit on the pulsed fraction of 50% for periods $> 30$ ms [6]. The nebula spectrum is described by a power law with $\Gamma = 1.6 \pm 0.3$. The J1952 spectrum is pure thermal and well fitted either with the blackbody model with a temperature $T \approx 2.5$ MK and an emitting area radius $R \approx 0.3$ km or with the neutron star atmosphere (NSA) model [7] with an effective temperature of $\approx 1$ MK and radius of 10 km [5]. Here we briefly report the results of Chandra and unpublished XMM-Newton X-ray data analysis clarifying the object parameters².

2. Timing analysis
We searched for pulsations from J1952 using the EPIC-pn data with the time resolution of 5.6 ms. J1952 light curve was extracted from a circular region of $20''$ around the source in the 0.5–1.4

¹ Assuming the spectral flux $F_\nu \propto \nu^{-\alpha_\nu}$, where $\nu$ is the frequency.
² See [8] for details.
keV energy band. A Fast Fourier Transform (FFT) analysis was used to search for pulsations. No pulsations were found, so we calculated an upper limit for the pulsed fraction (PF) of 40% (at the 99% confidence level) for periods $\geq 12$ ms using the method presented in [9].

3. Spectral analysis

The Chandra and XMM-Newton images of DA 495 are shown in Fig. 1. We extracted individual spectra of J1952 and the PWN from the Chandra data, and the spectrum of combined PWN+J1952 emission from the XMM-Newton data.

The J1952 spectrum was fitted with the NS atmosphere models NSMAX [10] with magnetic fields $B = 10^{12}$ and $10^{13}$ G and the blackbody (BB) model. The PWN emission was modelled by a power law (PL). We fitted the spectra simultaneously in 0.3–10 keV energy range. We utilize the absorption column density $N_H$–distance relation along its line of sight using the interstellar extinction distribution obtained in [11]. This allowed us to estimate the distance to DA 495 and the emitting area radius for J1952. The best-fit spectral parameters are presented in Table 1 and the example of the fit is shown in Fig. 2.

The values of the emitting area radius $R$ show that the emission originates from a hot spot on the pulsar surface for the BB model and from the entire NS surface for the NSMAX models. In the former case, a second BB component was added to derive a $3\sigma$ upper limit on the entire NS surface temperature of $\approx 60$ eV. $R$ was fixed at 13 km.

A PL component was added to the thermal model for J1952 to estimate an upper limit on the pulsar non-thermal luminosity $L_{\text{pl}}^{J1952}$. We assumed the photon index $\Gamma$ range of 0.5–2.0. The resulting $L_{\text{pl}}^{J1952} \approx 5 \times 10^{31}$ erg s$^{-1}$.

4. Distance to DA 495

The distance values for different models (see Table 1) within uncertainties are in agreement with one of the previous estimations, $D \approx 2.1$ kpc, which assumes association of DA 495 with the open cluster NGC 6834 [2]. Another distance estimation of $1.0 \pm 0.4$ kpc [4] is not compatible with the NSMAX models. It was based on H I absorption measurements indicating a systemic
Table 1. Best-fit spectral parameters. All errors correspond to 90% credible intervals. Emitting area radii $R$ and temperatures $T$ are given as seen by a distant observer. $N_{\text{pwn}}$ is the normalisation constant for the PL model of the PWN.

| Model/Parameters | BB          | NSMAX ($B = 10^{12}$ G) | NSMAX ($B = 10^{13}$ G) |
|------------------|-------------|--------------------------|--------------------------|
| $N_H$, $10^{21}$ cm$^{-2}$ | $2.6^{+0.5}_{-0.4}$ | $3.5^{+0.7}_{-0.6}$ | $3.4^{+0.7}_{-0.6}$ |
| $D$, kpc         | $2.4^{+1.3}_{-1.1}$ | $3.3^{+1.3}_{-1.3}$ | $3.2^{+1.3}_{-1.2}$ |
| $R$, km          | $0.6^{+0.6}_{-0.3}$ | $10^{+21}_{-7}$ | $6^{+3.5}_{-3.3}$ |
| $T$, eV          | $215^{+23}_{-23}$ | $76^{+19}_{-16}$ | $91^{+17}_{-15}$ |
| $\Gamma_{\text{pwn}}$ | $1.71^{+0.12}_{-0.12}$ | $1.85^{+0.14}_{-0.13}$ | $1.82^{+0.13}_{-0.13}$ |
| $N_{\text{pwn}}, 10^{-5}$ ph keV$^{-1}$ cm$^{-2}$ | $4.4^{+0.7}_{-0.6}$ | $5.1^{+0.9}_{-0.7}$ | $5.1^{+0.8}_{-0.6}$ |
| $\chi^2$/dof     | 455/461 | 455/461 | 454/461 |

Figure 2. Spectra of J1952+PWN system obtained with Chandra and XMM-Newton MOS1, MOS2 and pn detectors. Lines represent the best-fit model (NSMAX with $B = 10^{12}$ G for J1952 and PL for the PWN).

velocity for DA 495 of about +12 km s$^{-1}$, which is likely associated with the Local Arm [4]. In fact, another distance of 5 kpc also corresponds to this velocity. However, it was rejected for two reasons. First, the low absorbing column density was obtained from Chandra data for the BB model [5] meaning that the distance to DA 495 cannot be large. Second, the distance of 5 kpc was assumed to be beyond the Local Arm tangent point but the $\text{H}_1$ absorption from the tangent point was absent [4]. We note, that the radio data have a low signal-to-noise ratio so the latter absorption cannot be completely excluded. Moreover, it was shown [12] that the Local Arm extends between $l \approx 72^{\circ}$ and $52^{\circ}$ toward the Perseus Arm and may be a separate branch.
of the Perseus. Thus, the gas within this arm can be a natural source of the larger absorption column density at the larger DA 495 distance suggested by the NSMAX models.

5. PWN emission
The PWN best-fit spectral indices $\alpha_{\nu} = \Gamma - 1$ (Table 1) are consistent within uncertainties with $\alpha_{\nu} = 0.87 \pm 0.10$ (68% confidence) obtained from the radio data for frequencies $>1.3$ GHz [4]. We investigated whether a second break between the radio and X-ray is needed to describe the PWN spectrum. We fitted the X-ray spectra and the radio data taken from [4] simultaneously using power law models with one and two spectral breaks. To compare models with single and double-knee breaks we used an F-test which showed that in the case of the NSMAX+BPL models the second break is not needed, but in the case of the BB+BPL the PWN spectrum in X-rays is flatter. The additional break position lies in a range of $10^{14} - 10^{17}$ Hz.

6. Summary
J1952 has a pure thermal spectrum. For the BB model, the emission originates from a hot spot and for the NSMAX models – from the entire NS surface. The upper limit for the pulsed fraction of J1952 is 40% (99% confidence) for periods $\geq 12$ ms. The distance to DA 495 can be larger, up to 5 kpc, than it was supposed previously. The BB model for J1952 suggests that a second spectral break between radio and X-ray bands is needed to describe the PWN data while the atmosphere models do not require the additional break.

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