X-ray Analysis of the Bright Source in the Supernova Remnant G350.0−2.0 Field

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Abstract. We present results of the analysis of the \textit{XMM-Newton} data on the bright source 1RXS J172653.4−382157 in the field of the supernova remnant G350.0−2.0. Its spectrum is well described by power law plus thermal component (blackbody or neutron star atmosphere) model. Therefore the source can be a rotation powered pulsar. Alternatively, it can be a cataclysmic variable star since its spectrum is equally well fitted by the two-temperature optically thin thermal plasma model. No periodic pulsations and flux time variability were found. The upper limit on the pulsed fraction of 27\% cannot help to state whether the source is a pulsar or a cataclysmic variable. A faint source was detected in the \textit{XMM-Newton} optical/UV monitor image and found in the GSC-II catalog and ESO H\(\alpha\) and optical/near infrared broadband sky survey images on the X-ray position of J172653.4−382157. Its spectral energy distribution favors the cataclysmic variable interpretation. Further optical and X-ray observations are needed to confirm this.

1. Introduction

The supernova remnant (SNR) G350.0−2.0 was discovered in the radio with Molonglo and Parkes telescopes at 408 MHz and 5 GHz, respectively [1]. The Very Large Array (VLA) observations [2] showed a complicated morphology of G350.0−2.0 that consists of three spatially distinct emission regions. In the optical, some H\(\alpha\) filaments and clumps spatially coincided with the radio structures were found [3]. G350.0−2.0 was observed in X-rays with \textit{ROSAT} and \textit{ASCA}. The multiwavelength data show that the SNR belongs to a mixed-morphology SNR type, which is characterized by a shell-like radio and center-filled X-ray morphology (see Fig. 1, left panel). The distance to G350.0−2.0 \(D \approx 3.7\) kpc was estimated basing on the radio surface brightness–to–diameter relationship \((\Sigma–D)\) [4]. A point-like X-ray source, 1RXS J172653.4−382157 (hereafter J1726), was detected inside the SNR with \textit{ROSAT} and \textit{ASCA}. Its nature is unclear. It may be an associated neutron star (NS) revealing itself either as a compact central object (CCO) or a rotation powered pulsar. However, no radio pulsar was detected within the SNR [5]. On the other hand, it may be an unrelated object, e.g. a cataclysmic variable (CV) star. X-ray spectral and timing analyses of the object using the \textit{ROSAT} and \textit{ASCA} data are problematic due to low count statistics. To understand J1726 nature and to better study the SNR properties we performed \textit{XMM-Newton}\(^1\) observations. Here we present some results of the observations focusing on the analysis of the J1726 emission.

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2. X-ray data
The XMM-Newton observations of G350.0−2.0 were carried out on 2013 September 21 with total exposure of 38 ks. All EPIC cameras were operated in the Full Frame Mode. The XMM-SAS v.13.5.0 software was used for data processing. Single and double pixel events (PATTERN ≤ 4) were selected for the EPIC-pn and single to quadruple-pixel events (PATTERN ≤ 12) – for the EPIC-MOS data. The periods of background flares were removed. The resulting effective exposures were 19.5, 21.3 and 15.8 ks for the MOS1, MOS2, and pn data, respectively. The XMM-Newton image of the G350.0−2.0 field is presented in the right panel of Fig. 1. The point-like source J1726 with coordinates RA = 261°7334 and Dec = −38°3595 obtained with edetect_chain tool, is clearly detected in the centre of the image. The extended emission is associated with the SNR.

3. Spectral analysis
The J1726 spectra were extracted from MOS1, MOS2 and pn data within the 30″ radius aperture. For the background, we chose the 45″−75″ annulus region around J1726. The total number of the source counts was 410(MOS1)+625(MOS2)+1340(pn). Spectra were grouped to ensure > 15 counts per energy bin and fitted simultaneously in the 0.3–10 keV range using XSPEC package. We tried the absorbed (model phabs in XSPEC) power law (PL), power law plus blackbody (PL+BB) and power law plus the NS hydrogen atmosphere [6] (PL+NSA) models, assuming the NS origin of J1726. Another model we tried was the absorbed two-temperature optically thin thermal plasma (2MEKAL) model [7] which is frequently used to describe CVs spectra. Best-fit parameters are presented in Table 1. According to χ² values, all models are consistent with the data.

To check whether the thermal component is required if J1726 has a NS nature, we used F-test. The resulting null-hypothesis probability was ≈ 10⁻⁶, showing that the thermal component is needed to describe the source spectra. The fit for the PL+BB model is shown in Fig. 2. The derived photon index Γ and the BB temperature are typical for pulsar emission. At the same time, the thermal component can be equally well described by the hydrogen atmosphere.
model NSA with NS mass $M_{NS} = 1.4M_⊙$ and radius $R_{NS} = 13$ km. As always, the effective temperature, $T \approx 71$ eV, is smaller for the hydrogen atmosphere.

For the 2MEKAL model we obtained temperatures of 0.8 and 8.6 keV which are typical for cataclysmic variables. We also tried the single MEKAL model but it was rejected by the fit ($\chi^2 = 1.16$ for dof=135) and the F-test probability of $\approx 6 \times 10^{-7}$. A simple single-temperature model does not always describe CV spectra well (see, e.g., [8, 9]). The 2MEKAL fit reflect the fact that just above the white dwarf photosphere the accretion flow is shocked and the X-ray emission originates from plasma with a temperature distributed from the hotter shock to the cooler photosphere and unshocked flow.

### Table 1. J1726 best-fit spectral parameters for different models. All errors correspond to 90% confidence intervals. Unabsorbed fluxes $f_X$ refer to the 0.3–10 keV energy range. For the NSA+PL model, magnetic field $B = 10^{12}$ G and distance to the object $D$ was fixed at 3.7 kpc. Temperature $T_{NSA}$ is given as seen by a distant observer.

| Model/Parameters                  | PL    | PL+BB | PL+NSA | 2MEKAL |
|-----------------------------------|-------|-------|--------|--------|
| Column density $N_H$, 10$^{21}$ cm$^{-2}$ | 2.37$^{+0.35}_{-0.33}$ | 5.05$^{+2.03}_{-1.71}$ | 4.29$^{+0.40}_{-0.39}$ | 1.97$^{+0.37}_{-0.31}$ |
| Photon index $\Gamma$             | 1.81$^{+0.12}_{-0.11}$ | 1.71$^{+0.20}_{-0.20}$ | 1.60$^{+0.14}_{-0.14}$ |        |
| PL normalization $N_{PL}$, 10$^{-5}$ ph keV$^{-1}$ cm$^{-2}$ s$^{-1}$ | 7.82$^{+0.96}_{-0.85}$ | 7.26$^{+2.30}_{-1.79}$ | 6.08$^{+1.13}_{-1.03}$ |        |
| BB/NSA                               | 138$^{+42}_{-25}$ | 73$^{+3}_{3}$ |        |        |
| Emitting area radius $R$, km       | 1.29$^{+2.82}_{-0.89}$ $D_{\text{kpc}}$ | 13 (fixed) |        |        |
| Temperature $T_{1}$, keV           |        |        |        | $0.82^{+0.30}_{-0.13}$ |
| Temperature $T_{2}$, keV           |        |        |        | 8.56$^{+3.13}_{-2.13}$ |
| Unabsorbed flux $f_X$, 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ | 4.98 | 10.2 | 8.3 | 4.6 |
| $\chi^2$/dof                      | 146.44/135 | 119.38/133 | 122.30/134 | 126.42/133 |

We also extracted spectra of the whole SNR using the XMM-Newton Extended Source Analysis Software (XMM-ESAS) and fitted it with the collisionally-ionized plasma model VAPEC with solar abundances. The resulting absorption column density $N_H = (6.0 \pm 0.3) \times 10^{21}$ cm$^{-2}$. This value is compatible within uncertainties with $N_H$ obtained for J1726 with the PL+BB(NSA) model while it is considerably larger than $N_H$ obtained for the single PL and 2MEKAL models.

### 4. Timing analysis

Detection of periodic pulsations in the J1726 X-ray emission would help to establish that it is indeed the NS or CV. For the timing analysis we used EPIC-pn data with time resolution of 73.4 ms. The event times were extracted from the 30" radius aperture in 0.3–10 keV range and corrected to the solar system barycentre using the SAS task barycen and J1726 coordinates. We searched for pulsations in the 0.15–4000 s range using $Z_n^2$ test [10]. The number of harmonics $n$ was varied from 1 to 5. No pulsations were found. We estimated an upper limit for the pulsed fraction (PF) of 27% (at the 99% confidence level) assuming $n = 1$ (i.e. sinusoidal signal) and following the method described in [11].

### 5. Optical/UV data

At the X-ray position of J1726 we found a faint optical source in the XMM-Newton Optical/UV Monitor (OM) image in the $U$ ($\lambda_{\text{eff}} = 344$ nm) filter. The SAS task omdetect resulted in the
background subtracted count rate of $0.15 \pm 0.03$ cts s$^{-1}$ that corresponds to the instrumental magnitude $U = 20.35 \pm 0.19$ ($U_{AB} = 21.28 \pm 0.19$)$^2$.

We also found this source in the Guide Star Catalog II (GSC-II)$^3$, in the SuperCOSMOS H$\alpha$ survey (SHS) [12] and in archived images obtained during two ESO surveys: the VISTA Variables in the Via Lactea Survey (VVV) and the VST Photometric H$\alpha$ Survey of the Southern Galactic Plane and Bulge (VPHAS+)$.^4$ Visual magnitudes and observed fluxes measured in different bands are presented in Table 2. The SHS H$\alpha$ and OM $U$-band images where the putative counterpart is marked by an arrow are shown in Fig. 3. The source coordinates are $RA = 17^{h}26^{m}55^{s}9$, Dec = $-38^{\circ}21^{\prime}34^{\prime\prime}4$ with the uncertainty of $0.3$ for both coordinates, and fully consistent with the X-ray position of J1726 obtained with the nominal XMM-Newton pointing accuracy of 2$''$(90% confidence)$^5$.

6. Discussion

The X-ray spectrum of the point source J1726 can be described by BB(NSA)+PL or by 2MEKAL models. In former case, parameters obtained from spectral fits are typical for a rotation powered pulsar. The corresponding column density for J1726 is consistent with that of the SNR supporting the NS origin of the source.

However, we found a faint optical source at the X-ray position of J1726. This source has a non-stellar spectral energy distribution with a strong excess in the narrow-band H$\alpha$ filter (Table 2). These spectral properties are common for CVs (see, e.g., [14]). If we assume that the optical source is the J1726 counterpart, then J1726 is a CV. This is supported by the X-ray spectrum of J1726, which can be described by the two-temperature thermal plasma model typical for CVs [8, 9]. Assuming that the optical source is the counterpart of J1726, we calculated the X-ray-to-optical flux ratio $f_X/f_B$. The magnitude $B_J$ was corrected for interstellar extinction

\[ f_X/f_B = \frac{B_J}{B_J + C} \]

This value should be considered with caution due to the source was on top of a straylight artefact, so it was difficult to measure its count rate accurately.$^2$

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$^3$ http://gsss.stsci.edu/Catalogs/GSC/GSC2/GSC2.htm

$^4$ https://www.eso.org/sci/observing/PublicSurveys/sciencePublicSurveys.html

$^5$ See http://xmm2.esac.esa.int/docs/documents/CAL-TN-0018.pdf
Figure 3. $1.5' \times 1.5'$ Hα (left) and OM $U$-band (right) images of J1726 field. The J1726 possible counterpart is marked by an arrow.

Table 2. Visual magnitudes, observed and dereddened fluxes of the J1726 possible optical counterpart obtained from the VVV and VPHAS+ surveys. $u$, $g$, $r$, $H_\alpha$ and $i$ magnitudes obtained using point spread function (PSF) fitting are taken from the VPHAS+ catalogue. $Z$ magnitude was obtained from VVV catalogue and $B_J$ – from GSC-II. Dereddening was done with the interstellar absorption $A_V = 0.89$, which was obtained from $N_H$–$A_V$ relation [13] using $N_H=1.97 \times 10^{21}$ cm$^{-2}$ obtained from the 2MEKAL fit.

| Filter | MJD          | Magnitude | Flux (µJy) | Dereddened flux (µJy) |
|--------|--------------|-----------|------------|-----------------------|
| U(OM)  | 56556.83866  | 20.35 ± 0.19 | 11 ± 2     | 41.7 ± 7.6            |
| $B_J$  | 42270.43179  | 21.61 ± 0.49 | 9.6 ± 6    | 24.5±16.3 ± 2        |
| $u$    | 56566.01030  | 19.81 ± 0.07 | 17.8 ± 1.2 | 65.8 ± 4.4           |
|        | 56566.01254  | 19.74 ± 0.07 | 19.0 ± 1.2 | 70.3 ± 4.4           |
| $g$    | 56566.02029  | 21.04 ± 0.05 | 15.7 ± 0.7 | 42.1 ± 1.9           |
|        | 56566.02224  | 21.17 ± 0.05 | 13.8 ± 0.7 | 37.0 ± 1.9           |
| $r$    | 56566.02705  | 20.33 ± 0.06 | 23.7 ± 1.3 | 48.6 ± 2.7           |
|        | 56566.02785  | 20.51 ± 0.08 | 20.0 ± 1.5 | 41.0 ± 3.1           |
|        | 56149.08459  | 20.58 ± 0.06 | 18.8 ± 1.0 | 38.6 ± 2.1           |
|        | 56149.08535  | 20.66 ± 0.06 | 17.5 ± 1.0 | 35.9 ± 2.1           |
| $H_\alpha$ | 56149.07406  | 19.13 ± 0.04 | 55.4 ± 2.1 | 108.5 ± 4.3         |
| $i$    | 56149.09070  | 20.02 ± 0.06 | 25.4 ± 1.4 | 43.6 ± 2.4           |
|        | 56149.09146  | 19.76 ± 0.07 | 32.1 ± 2.0 | 55.2 ± 3.4           |
| $Z$    | 55725.26322  | 18.97 ± 0.09 | 58.2±5.2   | 87.6±7.9              |
of $A_V=0.89$, which was obtained from $N_H-A_V$ relation taken from [13] and using $N_H=1.97 \times 10^{21}$ cm$^{-2}$ obtained from the 2MEKAL fit, using the extinction law of [15] and then the optical flux was calculated as in [16]. The unabsorbed X-ray flux was obtained in the 0.3–10 keV energy band. $f_X/f_B \approx 10$, which less than the values obtained for isolated NSs ($\sim 10^3$) or low-mass X-ray binaries ($\sim 10^2 - 10^3$) [17], but is typical for CVs [16], supporting the CV interpretation of J1726. However, a situation when a CV visible in the optical and a NS visible in the X-rays spatially coincide can not be ruled out. However, this situation appears to be implausible.

We did not find any time variability typical for CVs in the X-ray data. The obtained upper limit on PF of periodic flux variations 27% is non-informative since PFs of many CVs are lower than this value.

To conclude, it is most likely that J1726 is a CV. Detailed optical and X-ray multi-epoch studies can help to confirm that.

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