THERMAL PROPERTIES OF THE MIDDLE-AGED PULSAR J1741−2054

A. Karpova1,2, A. Danilenko1, Yu. Shibanov1,2, P. Shternin1,2, and D. Zyuzin1

1 Ioffe Institute Politekhnicheskaya 26, St. Petersburg 194021, Russia; annakarpova1989@gmail.com
2 St. Petersburg State Polytechnical University, Politekhnicheskaya 29, St. Petersburg 195251, Russia.

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ABSTRACT

We present results of the spectral analysis of the X-ray emission from the middle-aged Fermi pulsar J1741−2054 using all Chandra archival data collected in 2010 and 2013. We confirm early findings by Romani et al. in 2010 that the pulsar spectrum contains a thermal emission component. The component is best described by the blackbody model with temperature \( \approx 60 \) eV and emitting area radius \( \approx 17 \ D_{\text{pc}} \) km. The thermal emission likely originates from the entire surface of the cooling neutron star if the distance to the pulsar is \( \approx 0.8 \) kpc. The latter is supported by a large absorbing column density inferred from the X-ray fit and empirical optical extinction–distance relations along the pulsar line of sight. The neutron star surface temperature and characteristic age make it similar to the well studied middle-aged pulsar B1055−52. Like this pulsar, PSR J1741−2054 is hotter than predicted by the standard cooling scenario.

Key words: pulsars: general − pulsars: individual (PSR J1741−2054) − stars: neutron

Online-only material: color figures

1. INTRODUCTION

One of the few ways to probe the physics of the dense matter in extreme conditions inside neutron stars (NSs) is to study the thermal emission from their surfaces (Haensel et al. 2007). Nearby middle-aged pulsars are natural targets for these aims. Many of them clearly show the thermal component in their soft X-ray spectra. In some cases it can be attributed to the emission from the entire NS surface and the surface temperature can be measured. So far it has been done only for a dozen middle-aged pulsars. Recent Fermi-LAT \( \gamma \)-ray discoveries open a new window for this type of study.

The middle-aged \( \gamma \)-ray pulsar J1741−2054, hereafter J1741, has a period \( P = 413 \) ms, a characteristic age \( \tau_c = 391 \) kyr, a spin-down luminosity \( E = 9.5 \times 10^{33} \) erg s\(^{-1}\), and a magnetic field \( B = 2.7 \times 10^{12} \) G (Abdo et al. 2013). After the discovery with Fermi (Abdo et al. 2009), it was studied in various bands. A dispersion measure (DM) of 4.7 pc cm\(^{-3}\) (Camilo et al. 2009) implies a distance of 380 pc for the Galactic electron density model of Cordes & Lazio (2002). A bow-shock nebula was detected around the pulsar in H\(\alpha\) (Romani et al. 2010). In X-rays, a point-like object identified with the pulsar and a compact pulsar wind nebula (PWN) structure and a PWN trail that extended 7\(\prime\) and 2\(\prime\) from the pulsar, respectively, were detected with Chandra (Romani et al. 2010).

Romani et al. (2010) pointed out the presence of a soft thermal component in the pulsar spectrum; however, no analysis of the thermal emission has been presented so far, save for a brief conference abstract by Sivakoff et al. (2011). Here we fill this gap and report results of analysis of the pulsar thermal emission.

2. ANALYSIS OF THE X-RAY SPECTRUM

Recently, the J1741 field has been extensively observed in X-rays with Chandra/ACIS as part of the large program\(^3\) which aimed at studying the spatial and temporal variability of PWNe. As a spin-off of the program, a substantial number of the pulsar photons was collected. We retrieved all the data obtained with Chandra (see Table 1). For all data sets, the data mode was VFAINT, the exposure mode was timed exposure (TE), and the pulsar was exposed on the S3 chip. The CIAO v. 4.6 chandra_repro tool with CALDB v. 4.5.9 was used to reprocess all data sets.

An image of the pulsar neighborhood in 0.7–8.0 keV obtained by merging all data sets is shown in the left panel of Figure 1, where the pulsar is marked by an arrow. The compact PWN adjacent to the pulsar and the extended trail, enclosed in a dashed box, is clearly seen. Based on analysis of ObsID 11251, Romani et al. (2010) reported a tentative detection of a presumed torus of the PWN within 2\(\prime\) from the pulsar containing about 11% of the total data counts in this region. This conclusion followed from the appearance of the 2\(\times\)7.5 \(\times\)0.75 excess structure centered at the pulsar position after subtraction of the point-spread function (PSF) modeled by MARX. However, it is well known that the Chandra PSF does not fit well the point-source core and that there are some anisotropic irregularities in the fit residuals.\(^4\) The Chandra team advises treating features with small spatial dimensions and strengths like the presumed torus with caution.\(^5\)

To examine how the point-like pulsar is actually contaminated by the compact PWN, we modeled PSF event files for each data set using the ChaRT (Carter et al. 2003) and MARX tools. We estimated the number of residual counts with respect to that of the point-like source as follows.\(^6\) The data images were fitted with the sum of a symmetric two-dimensional (2D) Gaussian, which modeled a point-like source blurring due to pointing uncertainty (see, e.g., Weisskopf 2011), and a constant background, convolved with the modeled PSFs. The 2D residuals pattern is similar to those reported by the Chandra team for a number of point sources. The example for ObsID 11251 is shown in the right panel of Figure 1. We do not see

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\(^3\) “A Legacy Study of the Relativistic Shocks of PWNe,” PN 14500153; PI: Roger Romani.

\(^4\) http://cxc.harvard.edu/cal/Hrc/PSF/acis_psf_2010oct.html

\(^5\) http://cxc.harvard.edu/ciao/caveats/psf_artifact.html#advice

\(^6\) For details, see the corresponding ChaRT thread, http://cxc.harvard.edu/sherpa/threads/2dpsf/
evidence of any PWN structure in the central 2′. The most prominent southeast structure correlated with the Z+ detector axis and containing ≈3% of the total source counts is consistent with a “hook feature” described in the Chandra report. It is possibly related to imperfect modeling of the Chandra optics. The putative PWN torus claimed by Romani et al. (2010) could have been actually mixed up with this hook structure; in any case its detection is likely a result of an incorrect treatment of the systematic effects of the PSF subtraction.

In order to select the reliable aperture for extraction of the pulsar spectra we calculated brightness profiles from the PSFs and data event files using concentric annuli centered at the pulsar position with radii from 0′′ to 10′′ through 0′.29 and summed up the data and PSF profiles over all data sets. The resulting profiles are shown in Figure 2. It is seen that the data are dominated by the point source within the central 2′. We conservatively chose the 1′.5 radius aperture which contains ≥95% of the source counts. For the background, we used a region free of any sources in each data set. We extracted spectra with the CIAO v. 4.6 specextract tools. The spectra were grouped to ensure ≥25 counts per energy bin. Using the XSPEC v.12.8.1 we then fitted the spectra in the 0.3–10 keV range simultaneously with an absorbed composite model, a sum of a power law (PL), which models the pulsar magnetosphere emission, and a thermal component, which models emission from the NS surface. For the thermal component, we tried the magnetized NS atmosphere models NSA (Pavlov et al. 1995) and NSMAX (Ho et al. 2008), and a blackbody (BB) model.

The goodness-of-fit test shows that the hydrogen atmosphere models can be rejected for any reasonable model parameters. The reduced chi-squared value is \( \chi^2 \nu = 1.41 \) (dof = 557) for the NSA+PL and NSMAX+PL models. The single BB and PL, and BB+BB models give even worse fits: \( \chi^2 \nu = 8.09 \) (dof = 559), \( \chi^2 \nu = 1.91 \) (dof = 559), and \( \chi^2 \nu = 1.73 \) (dof = 557), respectively.

In contrast, the BB+PL model is statistically acceptable (\( \chi^2 \nu = 1.06 \), dof = 557). It is compared with the data in Figure 3 and its best-fit parameters are presented in Table 2. At the DM

### Table 1

| Obs ID | Instrument | Exp. (ks) | Start Date |
|-------|------------|----------|------------|
| 11251 | ACIS-S     | 48.78    | 2010 May 21|
| 14695 | ACIS-S     | 57.15    | 2013 Feb 6 |
| 14696 | ACIS-S     | 54.3     | 2013 Feb 19|
| 15542 | ACIS-S     | 28.29    | 2013 Apr 1 |
| 15543 | ACIS-S     | 57.22    | 2013 May 17|
| 15544 | ACIS-S     | 55.73    | 2013 Jul 12|
| 15638 | ACIS-S     | 29.36    | 2013 Apr 2 |

### Figure 1

*Left:* 2′6 × 2′6 fragment of the pulsar field in 0.7–8.0 keV as seen with Chandra/ACIS, smoothed with a 3 pixel Gaussian kernel. The 48′8 × 40′3 pulsar vicinity enclosed in the black box is enlarged in the inset, where the logarithmic brightness scale is used. The dashed polygon encloses the PWN trail. *Right:* PSF fit residuals for ObsID 11251. The cross marks the pulsar’s position. The Z+ detector axis direction and the “hook” structure are indicated.

### Figure 2

Comparison of the observed radial brightness profile with the simulated PSF in the pulsar vicinity.
distance, the emitting area radius inferred from the fit is too large for a hot polar cap, which should be about 200 m for a 400 ms pulsar according to Sturrock (1971). At the same time, a rather large emitting area radius suggests that the thermal emission originates from a substantial part of the NS surface.

Fitting the PWN trail spectrum extracted from the dashed polygon in Figure 1 with the absorbed PL model, we get $N_H = (1.6^{+0.5}_{-0.5}) \times 10^{21}$ cm$^{-2}$ and photon index $\Gamma = 1.78 \pm 0.15$ (errors are at 90%), which are in agreement with the results of Romani et al. (2010) and with the $N_H$ inferred from the BB+PL fit (Table 2). An independent limit on the absorption column density, based on the H$\alpha$ nebula spectroscopy, is $N_H < 2.5 \times 10^{21}$ cm$^{-2}$ (Romani et al. 2010). To reconcile the large $N_H$ values from both the X-ray and the H$\alpha$ nebula spectroscopy with the electron column density $N_e \approx 1.4 \times 10^{19}$ cm$^{-2}$ deduced from the DM, one needs to assume a low ionization ratio of about 0.01 along the line of sight (Romani et al. 2010).

3. DISCUSSION

It is possible that the thermal component of the NS X-ray emission originates from the entire surface of the NS. The apparent radius of an NS with canonical parameters ($M_{NS} = 1.4 M_\odot$ and $R_{NS} = 10$ km) is approximately 13 km. In Figure 4, we show the confidence contours of the effective temperature $T$ and the absorbing column density $N_H$ versus the distance to the pulsar $D$ evaluated from the BB normalization. One sees that the pulsar should be at $0.8 \pm 0.2$ $R_{13}$ km, which is a factor of two larger than the DM distance.

We can estimate the distance independently as follows. The $N_H$ value derived from the X-ray fit is nearly half the entire Galactic $N_H$ in the pulsar direction, $3 \times 10^{21}$ cm$^{-2}$, according to the H$\text{i}$ survey by Dickey & Lockman (1990). Assuming a Galactic gaseous disk half-thickness of $\sim 0.1$ kpc and taking the pulsar latitude $b = 4^\circ 9$ the maximum distance inside the Galactic disk in the pulsar direction is about 1.4 kpc. Making the rough assumption that $N_H$ is proportional to the distance, we conclude that the pulsar must be approximately at half the maximum distance, which is 0.7 kpc. One precaution that should be taken with this estimate is that $N_H$ values from H$\text{i}$ surveys may underestimate the column density responsible for

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**Table 2**

| Parameter | Value |
|-----------|-------|
| Absorption column density, $N_H$ | $1.38^{+0.19}_{-0.19} \times 10^{21}$ cm$^{-2}$ |
| Photon index, $\Gamma$ | $2.66^{+0.06}_{-0.06}$ |
| PL normalization | $1.2^{+0.06}_{-0.06} \times 10^{-4}$ ph keV$^{-1}$ cm$^{-2}$ s$^{-1}$ |
| Emitting area radius, $R$ | $17^{+3}_{-2} D_{13}$ km |
| Temperature, $T$ | $60.0^{+0.2}_{-0.0}$ eV |
| $\chi^2$ (dof) | $1.06 (557)$ |

**Note.** All errors are at 90% confidence.
the X-ray absorption. However, the similar value of 0.7 kpc is obtained from the optical extinction ($A_V$–distance fit in the pulsar direction (Chen et al. 1998), where $A_V \approx 0.76$ is derived from the standard $A_V - N_H$ relation (Predehl & Schmitt 1995). Taking another $A_V$–distance fit from Drimmel et al. (2003) we get the distance of 0.9 kpc. While the use of extinction maps can underestimate the value along the specific line of sight due to the lack of high spatial resolution information, these distance estimates are in agreement with that obtained from the X-ray fit (see Figure 4). For completeness, the distance can also be estimated from an empirical correlation between the pulsar distances and $\gamma$-ray fluxes above 100 GeV. This “pseudo-distance” relation (e.g., Saz Parkinson et al. 2010) suggests a value $\sim 450$ pc. However, this is the most uncertain estimate (within a factor of 2–3) and thus is consistent with all others.

An increase in the distance also means an increase in the X-ray and $\gamma$-ray efficiencies, i.e., the ratios of the X-ray nonthermal and $\gamma$-ray luminosities to $\dot{E}$. The X-ray efficiency in the 2–10 keV range derived from the X-ray fit is $9.7 \times 10^{-5} D_{0.8}^{-2}$ kpc. The $\gamma$-ray efficiency is $0.97 D_{0.8}^{-2}$ (Abdo et al. 2013). Such a high $\gamma$-ray efficiency is not unusual. There are $\gamma$-ray pulsars, Geminga for instance, with efficiencies almost equal to or even greater than one (Abdo et al. 2013).

It is natural to compare J1741 with “The Three Musketeers,” Geminga, PSR B0656+14, and PSR B1055–52, well-studied middle-aged pulsars with observed thermal emission (Becker & Trümper 1997). Like the Three Musketeers, J1741 demonstrates a soft thermal emission in X-rays, which is well fitted by the BB model, while all hydrogen atmosphere models fail, giving too large normalizations. In contrast to the Three Musketeers, however, the J1741 spectrum does not show an additional hot BB component. The thermal component of J1741 is not as prominent, with respect to the nonthermal one, as the thermal components of the Three Musketeers. This can explain the lack of a hot spot component in the spectral fit—it is possibly hidden under the strong nonthermal component. It is worth noting that J1741 has a relatively large PL photon index ($\Gamma \sim 2.7$) in comparison with the Musketeers ($\Gamma \lesssim 2$).

Let us compare the thermal properties of J1741 with data on other isolated NSs. In Figure 5, we show the standard NS cooling theory predictions (filled region; e.g., Yakovlev & Pethick 2004), which includes effects of nucleon superfluidity. In this model, the modified Urca processes are suppressed by the strong proton superfluidity. However, the minimal cooling theory also assumes the presence of neutron superfluidity, which enhances the cooling with respect to the standard level (see, e.g., Gusakov et al. 2004; Page et al. 2004, for details). This enhancement is required to explain the coldest sources in Figure 5; however, it makes it impossible to fit the data for hot sources utilizing the usual models for neutron superfluidity (Page et al. 2004, 2009). The sources at the “knee,” such as PSR B1055–52 and now J1741, can be reconciled with the minimal cooling if one shifts the neutron superfluidity to high densities, so that it does not take place in low-mass stars (with low central density) and operates in high-mass stars (Gusakov et al. 2004). This assumption makes it possible to explain all current data on cooling isolated NSs in a unified way, including the possibly real-time cooling NS in supernova remnant Cassiopeia A (Shternin et al. 2011). In this model, J1741 should have a low mass while the cold NSs should be massive. These considerations remain true if J1741 is several times younger and/or colder. In this case J1741's position on the cooling plane will agree with the standard cooling scenario. Nevertheless, the presence of superfluidity inside the NSs is almost undoubtedly the question remains only about its quantitative characteristics.

It is indeed possible that further analysis will result in a lower age or surface temperature of J1741. The characteristic age of an NS can be several times larger than its true age (see, e.g., Brinken et al. 2003; Thorsett et al. 2003). The lower temperature of the stellar surface also cannot be ruled out. For instance, the UV observations of PSR B1055–52 show a Rayleigh–Jeans
component which exceeds the extrapolation of the X-ray thermal spectrum by a factor of four. This led Mignani et al. (2010) to suggest that the X-ray emission in fact comes from a smaller hot region on the stellar surface (this is possible if the pulsar is closer), while the entire surface is colder, that is invisible in X-rays but showing itself in UV. For illustration, we show with the open diamond and the label 3′ in Figure 5 the position of the PSR B1055−52 according to the UV observations by Mignani et al. (2010; for the distance 350 pc). This makes the positions of PSRs B1055−52 and J1741 similar with respect to standard cooling curves. Note that for the other two Musketeers an extrapolation of X-ray thermal spectra agrees with the UV data, while for RX J1856.5−3754 and the other NSs of the “magnificent seven” the situation is similar to that of PSR B1055−52 (Kaplan et al. 2011). It is therefore interesting to investigate which is the case for J1741 in the UV.

To conclude, the X-ray spectra of J1741 can be well described by a sum of a PL and a single BB with temperature of about 60 eV. If the BB component is interpreted as a thermal emission from the entire surface of the NS, the distance to the pulsar should be approximately 0.8 kpc. A similar value follows from the analysis of the extinction toward the pulsar, supporting this interpretation. J1741 is a rather hot middle-aged NS and further studies will be useful to constrain the physical input of modern cooling theories.

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