The Transition from Young to Middle-aged Supernova Remnants: Thermal and Nonthermal Aspects of SNR N132D

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Abstract

Supernova remnants (SNRs) are the primary candidate of Galactic cosmic-ray accelerators. It is still an open issue when and how young SNRs, which typically exhibit strong synchrotron X-rays and GeV and TeV gamma rays, undergo the state transition to middle-aged SNRs dominated by thermal X-rays and GeV gamma rays. SNR N132D in the Large Magellanic Cloud is an ideal target to study such a transition, exhibiting bright X-rays and gamma rays, and with an expected age of ~2500 years. In this paper we present results of NuSTAR and Suzaku spectroscopy. We reveal that N132D has a nearly equilibrium plasma with a temperature of ~1.5 keV and a recombining timescale (n_e t_e) of 8.8 (7.0–10.0) × 10^{12} cm^{-3}s. Together with the center-filled morphology observed in the iron K line image, our results suggest that N132D is now at the transition stage from being a young SNR to being middle-aged. We have constrained the tight upper limit of nonthermal X-rays. Bright gamma rays compared to faint nonthermal X-rays suggest that the gamma rays are hadronic in origin. The spectral energy distribution from radio to gamma rays shows a proton cutoff energy of ~30 TeV. These facts confirm that N132D is undergoing the transition from a young to a middle-aged SNR. The large thermal energy of >10^{51} erg and accelerated proton energy of ~10^{50} erg suggest the supernova explosion might have been very energetic.

Key words: cosmic rays – gamma rays: ISM – ISM: individual objects (N132D) – ISM: supernova remnants – X-rays: ISM

1. Introduction

Supernova remnants (SNRs) play crucial roles in the physical processes of the universe, working as energy and heavy element suppliers, and accelerating cosmic rays at their shocks. They evolve on a rather short timescale in the interstellar medium. Young SNRs expand with high shock velocity and emit strong thermal and nonthermal X-rays from their shells. Synchrotron X-rays are excellent tools for detecting accelerated electrons (Koyama et al. 1995), in addition to distinguishing one of the key parameters, the magnetic field, from its small-scale and sometimes time-variable structures (Vink & Laming 2003; Bamba et al. 2005; Uchiyama et al. 2007), and thus resolving the origin of gamma rays (Aharonian et al. 2007, for example).

On the other hand, middle-aged SNRs are fainter in both thermal and nonthermal emission, and as a result their study has developed rather recently. Fermi/LAT has detected significant soft gamma rays from many old SNRs (The Fermi-LAT Collaboration 2015), implying that old SNRs still keep high-energy particles in space. However, detailed understanding of this nonthermal emission is still lacking, since no synchrotron X-rays have been detected from middle-aged SNRs to date. No synchrotron X-ray emission has been reported so far from middle-aged SNRs.

It is also noteworthy that most of the GeV-bright SNRs contain recombining plasma (e.g., Yamaguchi et al. 2009), implying that the plasma experienced rapid cooling during the SNR evolution. Such plasma emits a strong radiative recombination continuum and produces hard tails in the X-ray spectra. Resolving this component will help us to understand the environments of particle acceleration sites.

N132D is the X-ray/gamma-ray brightest SNR in the Large Magellanic Cloud (LMC; Sutherland & Dopita 1995). It has a ~14 pc ellipsoidal shell expanding at the average speed of 1650 km s^{-1} (Morse et al. 1995). The SNR has an age of about 2500 yr (Vogt & Dopita 2011). Chandra and XMM-Newton spectra have shown multi-temperature thermal emission with strong emission lines from O to Fe (Behar et al. 2001; Borkowski et al. 2007). Williams et al. (2006) reported a high dust density of ~15 cm^{-3}, a conclusion supported by the detection of a CO cloud with a mass of ~2 × 10^5 M⊙ in the south of the SNR (Banas et al. 1997; Sano et al. 2015). The southern part shows enhanced thermal X-ray emission with
a circular shape, which supports the presence of a dense ambient medium, whereas the northern part has a blown-out shape, implying a low-density interstellar medium in this direction. Recently, GeV and very-high-energy (VHE) gamma rays have been detected from N132D by Fermi and H.E.S.S. (H.E.S.S. Collaboration et al. 2015; The Fermi-LAT Collaboration 2015). The gamma-ray spectrum is very hard, like that of other young SNRs such as Cas A and RX J1713–3946 (Abdo et al. 2010a, 2011). Surprisingly, the measured luminosity in the 1–100 GeV band, \( \sim 10^{36} \text{erg s}^{-1} \) at 48 kpc (Macri et al. 2006), is two orders of magnitude higher than those of typical young SNRs. Actually, this is the highest luminosity among all known GeV SNRs (Acero et al. 2016).

Such a feature in the gamma-ray band implies that N132D is an energetic cosmic-ray supplier. Furthermore, it is difficult to create such bright gamma rays with leptonic models, suggesting that gamma rays are hadronic in origin. Interestingly, we have no report of a clear synchrotron X-ray detection from this source, probably because the soft X-ray spectrum is dominated by the luminous, high-temperature thermal X-rays up to the Fe K line band (Behar et al. 2001; Borkowski et al. 2007; Xiao and Chen 2008; Yamaguchi et al. 2014). We need sensitive observations in the hard X-ray band above 10 keV, where thermal emission becomes much fainter. NuSTAR is an ideal observatory for such a study because of its hard X-ray imaging system (Harrison et al. 2013). Suzaku also has a large effective area, and a low, stable background in the hard X-ray band, making it suitable for the nonthermal emission search (Mitsuda et al. 2007).

In this paper, we present the first results of the hard X-ray observation of N132D with NuSTAR and Suzaku. Sections 2 and 3 describe the observation details and the analysis results, respectively. In Section 4 we discuss the condition of particle acceleration on N132D, together with radio, infrared, GeV, and VHE gamma-ray results. In this work, the data reduction and analysis were performed with HEADAS version 6.20 and XSPEC version 12.9.1. For the spectral analysis, atomic database (ATOMDB) version 3.0.8 and the nei version (NEIEVERS) 3.0.7 were used. Throughout the paper, we use 90% error bars and confidence intervals.

2. Observations and Data Reduction

2.1. NuSTAR

N132D has been observed by the pixelated CdZnTe focal plane modules, FPMA and FPMB, on board NuSTAR with a single pointing on 2015 December 10–11. The data were reprocessed with the calibration database (ver 20151008). The cleaned events were extracted with the standard screening criteria, except for the criteria for the passage of the South Atlantic Anomaly (SAA). Since our target is faint in the hard band, and the background count rate slightly elevated around the SAA, we started the analysis with data filtered with the parameters SAAMODE = STRICT and TENTACLE = yes. The total exposure is 62.3 ks, which is 90% of the nominal screening case. The observation log is shown in Table 1.

2.2. Suzaku

N132D has been observed by Suzaku several times for calibration purposes. We selected all data except for those taken in Suzaku’s initial operation. The details of the observations are shown in Table 1. Suzaku has several kinds of detectors: four X-ray Imaging Spectrometers (XIS0–XIS3; Koyama et al. 2007a), each at the focus of an X-Ray Telescope (XRT; Serlemitsos et al. 2007), and a separate Hard X-ray Detector (HXD; Takahashi et al. 2007). We concentrate on the analysis of XIS, since NuSTAR has much better sensitivity than HXD. We have checked the HXD data and found no significant signal. Only three XISs operated in all of these observations. XIS1 is a back-illuminated (BI) CCD, whereas the others are front-illuminated (FI). The XISs were operated in normal full-frame clocking mode with spaced-row charge injection (Nakajima et al. 2008; Uchiyama et al. 2009). The data were reprocessed with the calibration database version 2016 February 14 for XIS and 2011 June 30 for XRT. We applied the standard screening criteria to create the cleaned event list. The total exposure is 240.3 ks. The observation log is shown in Table 1.
We also found stray light from LMC X-4 in both detectors and from LMC X-2 in FPMB (see Figure 1). Another nearby high-mass X-ray binary, XMMU J054134.7−682550, can produce stray light because it sometimes shows the flaring (Liu et al. 2005; Palmer et al. 2007). We have checked Swift/BAT observations (Krimm et al. 2013) and found that it was in the steady state with a flux of only ~1 mCrab, and it did not show any flare during our observation. We thus ignore the stray light effect from XMMU J054134.7−682550.

3.1.2. Spectra

The source photons were extracted from a 1.4 arcmin radius region centered on N132D, whereas we selected the background region free from other sources and stray lights, as shown in Figure 1. The response files are produced with the nuproducts command under the point source assumption.

Figure 2 shows the background-subtracted spectra of NuSTAR FPMA and FPMB. One can see emission-like structures around 6.5 and 7.9 keV. The former is reported as a Kα emission line from He-like Fe (Borkowski et al. 2007; Yamaguchi et al. 2014), whereas there is no report on the latter. We fitted the spectra with a bremsstrahlung plus two Gaussian components. The c-statistic (Cash 1979) was used throughout this paper. The background spectra were fitted simultaneously in XSPEC, whereas background-subtracted spectra were used for the spectral plot.15 The best-fit models and parameters are shown in Figure 2 and Table 2. From the line center energies, we identified the 6.66 keV line as He-like Fe Kα, and 7.9 keV line as He-like Ni Kα or He-like Fe Kβ. One can also see the residuals above 10 keV, which can be nonthermal hard tail or higher-temperature components. The flux above 10 keV is 2.4 (2.0–2.8) × 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}.

3.2. Suzaku

3.2.1. Images

Figure 3 shows the Suzaku XIS3 5–10 keV image. We used only XIS3 since that part of XIS0 is not available and XIS1 has low efficiency and high background in this energy band. One can see a point-like source in the center of the field of view.

3.2.2. Spectra

We extracted source photons from a circular region with a radius of 2 arcmin, as shown in Figure 3. The background

15 See https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/manual/node293.html.
7 arcmin radius region (see Figure 3) and is adjusted with the 11–14 keV count rate, where we expect neither source nor CXB emission (Sekiya et al. 2016). We reproduced the CXB emission with the power-law model with a photon index of 1.4 and a surface brightness in the 2–10 keV band of $5.4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$ (Ueda et al. 1999). Since our target is point-like while the CXB is uniformly distributed, we simulated the CXB spectrum with the assumption of a uniform distribution within a 1.4 arcmin radius region, and fit it with the point sourcearf, and used the best-fit parameters in the N132D spectral fitting.

Figure 4 shows the NXB-subtracted XIS spectrum above 5 keV. One can see clear emission lines, similar to the NuSTAR results. We fit the spectrum with a bremsstrahlung plus two narrow Gaussian models. The fit returned cstat/dof of 167.5/111 with positive residuals around 6.9 keV, which could not be seen in the NuSTAR spectra, possibly due to the lack of statistics and energy resolution. We added one more narrow Gaussian to represent this structure, which improved the cstat/dof to 145.4/109. The line center energy agrees with the Fe Ly$\alpha$ emission line, and this is the first detection of this line from N132D. We still have small positive residuals on the high-energy end, which is consistent with the NuSTAR data. Table 3 shows the best-fit parameters.

### 3.3. Combined Spectral Analysis

In the previous subsection, we reported the first detection of Fe Ly$\alpha$ emission from N132D, indicating that a substantial fraction of Fe atoms in this SNR is highly ionized. Keeping this in mind, here we constrain thermal parameters with NuSTAR and Suzaku combined spectral analyses. We start the fitting with the 5–15 keV band. We first introduce a vpec model, a plasma in ionization equilibrium. We used the photoionization cross-section table by Balucinska-Church & McCammon (1992). The abundances of Fe and Ni were treated as a common free parameter, whereas those of the other elements were fixed to solar values (Anders & Grevesse 1989). The best fit was obtained with an electron temperature of 2.31 kT and cstat/dof of 145.4/109.

**Table 3**

| Parameters | Best-fit Parameters for the Suzaku Spectra$^a$ |
|------------|-----------------------------------------------|
| Bremss     | kT (keV)                                      |
|            | 2.25 (2.02–2.35)                              |
|            | Norm$^b$                                      |
|            | 3.4 (3.0–4.3)                                 |
| Gaussian 1 | $E_c$ (keV)                                   |
|            | 6.652 (6.648–6.660)                           |
| Gaussian 2 | $E_c$ (keV)                                   |
|            | 6.92 (6.88–6.98)                              |
| Gaussian 3 | $E_c$ (keV)                                   |
|            | 7.85 (7.77–7.93)                              |
| Flux$^c$   |                                              |
|            | 0.9 (0.5–1.4)                                 |
| cstat/dof  | 145.4/109                                     |

Notes.

$^a$ Errors indicate single-parameter 90% confidence regions.

$^b$ Emission measure in units of $\frac{3.02 \times 10^{-15}}{4\pi D^2} \int n_e n_i dV$, where $D$ is the distance to the source (cm) and $n_e$, $n_i$ are the electron and ion densities (cm$^{-3}$).

$^c$ In units of $10^{-6}$ photons cm$^{-2}$ s$^{-1}$.

(2.23–2.39) keV and cstat/dof of 195.2/140, leaving positive residuals around 6.9 keV due to the Fe Ly$\alpha$ line detected in the Suzaku spectrum. This implies that the average charge balance is higher than the temperature predicted by the ionization equilibrium model. We thus added a second vpec component and found that the fit was improved significantly (cstat/dof = 134.6/140), with $kT$ of 1.1 (0.9–1.3) keV and 5.0 (4.5–6.3) keV. A higher charge balance is also achieved when the plasma is over-ionized. We thus replaced the second vpec model with a vremi model, including a higher initial temperature to represent a recombining plasma. This model also improved the fitting with cstat/dof of 173.4/140. We still have positive residuals in higher energy bands, which can be nonthermal emission from accelerated electrons. We thus added a power-law component. The photon index is fixed to 2.4, the same as that for the gamma-ray emission. The fitting was improved to cstat/dof of 155.8/139.
The next step of adding the power-law component was to extend the fitting range to the 2–15 keV band to check the plasma condition of these higher-temperature components. In the energy band below ~3 keV, we already know that there is at least one lower-temperature component (Borkowski et al. 2007), thus we added one more vapec component with lower temperature. Hereafter, we use “model (a)” for the three-vapec plasma model and “model (b)” for the two-vapec-plus-vrnei plasma model. We fixed the abundances of the low-temperature component to the LMC abundance (Russell & Dopita 1992), but the best-fit model has significant residuals on the Si and S lines. We thus left the abundances of Si and S for the low-temperature component free. The abundances of Si and S, and Fe and Ni of the middle-temperature component were treated as common free parameters, whereas the other elements were assumed to be solar abundance. We performed fine tuning on the XIS gain offset and treated the cross-normalizations of each detector as free parameters. We ignored the Galactic absorption column in the direction of N132D (1.6 $\times 10^{21}$ cm$^{-2}$; Kalberla et al. 2005), since it increases flux by only 3% in the 2–10 keV band, and 0.3% in the 6–7 keV band, which we are especially interested in for the Fe K line. Both models reproduce the observed spectrum. The gain offset obtained is 3–5 eV for FI and 9 eV for BI, which is roughly within the range of the XIS gain uncertainty. We find small residuals around 6.4 keV. We attribute this feature to fluorescence emission from neutral Fe, and thus added a narrow Gaussian with a fixed center energy of 6.4 keV. The fitting was improved, with a significance level for this emission component of 0.7σ for model (a) and 3.8σ for model (b). Finally, we estimate the flux (or its upper limit) of nonthermal X-rays by adding a power-law component. We fixed the photon index to be 2.4, the same value as that in the gamma-ray band. The fitting was improved with a 3.3σ detection power-law component for model (a) and a 30σ detection for model (b). The best-fit models and parameters are shown in Figure 5 and Table 4, respectively.

![Figure 5. Wide-band spectral fitting result for the model (a) (left) and model (b) (right) component models. The black, red, and blue crosses represent the NuSTAR, Suzaku FI, and BI data sets. The solid, dashed, and dotted lines represent thermal and power-law components, and the CXB for Suzaku.](image)

The X-ray spectrum from the statistical point of view. In order to determine the parameters of both the thermal and nonthermal components, we need further observations with excellent energy resolution; Hitomi, for example, could provide such observations (Hitomi Collaboration et al. 2017).

For a further check of the origin of hard X-rays, we compared an iron K line image and 10–15 keV band image of

| Figure 5 and Table 4 | Best-fit Parameters for the Combined Suzaku and NuSTAR Spectra$^{a}$ |
|----------------------|------------------------------------------------------------------|
| Parameters           | Model (a)$^{b}$ | Model (b)$^{b}$ |
| Low $kT$ comp.       | $kT$ (keV) | 0.54 (0.39–0.56) | 0.70 (0.65–0.71) |
| $Z_{\text{Fe}}$       | 1.9 (>1.4) | 0.63 (0.59–0.74) |
| $Z_{\text{Ni}}$       | 2.1 (>1.8) | 0.91 (0.86–1.10) |
| Norm$^{c}$            | 3.3 (0.1–4.1) | 5.6 (4.7–5.8) |
| Middle $kT$ comp.     | $kT$ (keV) | 1.2 (0.8–1.2) | 1.5 (1.3–1.6) |
| $kT_{\text{max}}$ (keV) | $\ldots$ | $\geq 8$ |
| $Z_{\text{Fe}} = Z_{\text{Ni}}$ | 0.45 (0.40–0.48) | 0.42 (0.36–0.49) |
| $n_e$ ($10^{11}$ cm$^{-3}$) | 0.74 (0.61–0.96) | 0.46 (0.40–0.57) |
| $n_{\gamma}$ ($10^{11}$ s cm$^{-3}$) | $\ldots$ | 8.8 (7.0–10.0) |
| Norm$^{c}$            | 2.8 (2.5–4.0) | 1.3 (1.2–1.7) |
| High $kT$ comp.       | $kT$ (keV) | 5.7 (4.0–6.8) | $\ldots$ |
| Norm$^{c}$            | 0.06 (0.05–0.10) | $\ldots$ |
| Neutral iron line     | Flux$^{d}$ | 1.5 (<5.7) | 6.7 (2.0–11.0) |
| Power-law             | $\Gamma$ | 2.4 (fixed) | 2.4 (fixed) |
| $F_{2-10keV}$ ($10^{-13}$ erg cm$^{-2}$ s$^{-1}$) | 1.9 (0.5–4.1) | 5.0 (4.2–7.3) |
| Gain fit for XIS FI (eV) | 3.9 | 5.4 |
| Gain fit for XIS BI (eV) | 11.7 | 9.8 |
| cstat/dof             | 419.5/323 | 431.3/323 |

Notes.

$^{a}$ Errors indicate single-parameter 90% confidence regions.

$^{b}$ Model (a) is three-vapec model, and model (b) is a two-vapec + vrnei + power-law model.

$^{c}$ Emission measure in units of $10^{-16}$ cm$^2$ s$^{-1}$, where $D$ is the distance to the source (cm) and $n_e$, $n_{\gamma}$ are the electron and ion densities (cm$^{-3}$).

$^{d}$ In units of $10^{-27}$ photons cm$^{-2}$ s$^{-1}$. 

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**3.4. Comments on the Pile-up Effect on Suzaku Spectra**

N132D is very bright in X-rays, so we should be careful about the pile-up effect, especially for the Suzaku data set, which can mimic the hard tail in the spectra. We thus investigated the pile-up effect in Suzaku spectra to judge whether or not the power-law component we detected is the result of pile-up. As the first step, we have checked the pile-up fraction with the ftool pileest, and found that the fraction is smaller than 4% for FI and 6% for BI. This is the average value for the all-energy band, whereas our special interest is in the harder energy band. Thus, as the next step we simulated the piled-up and non-piled-up spectra and compared them. We found that the upper limit of the ratio of flux coming from piled-up events to the total is ~10% in the 8–10 keV band. The flux ratio of the power-law component to the total in the 8–10 keV band is 10% for model (a) and 20% for model (b). The former is in the range of expected pile-up, whereas the latter is still larger than the expected pile-up ratio. Since we cannot judge which model is better, we thus treat the larger end of the error region of the power-law flux as the upper limit with systematic errors.

**4. Discussion**

**4.1. Thermal Emission**

Thanks to the large effective area of NuSTAR, and the low and stable background of Suzaku XIS above 5 keV, we detected significant Fe Lyα emission line for the first time. This suggests the existence of either a very high-temperature (model (a)) or over-ionized (recombining) component (model (b)). Although these models cannot be distinguished from the statistical point of view, the temperature required in model (a) is unusually high for a middle-aged SNR. Moreover, this model requires high abundances of Si and S in the low-temperature component, which is inconsistent with previous observations. We thus assume model (b) to be a reasonable interpretation for the high-temperature plasma in N132D and discuss its origin hereafter.

SNRs with recombining plasma have several characteristics. They are usually associated with GeV gamma-ray emission coming from molecular clouds. They also exhibit a mixed-morphology (MM) shape (a radio shell, plus center-filled thermal X-rays; Rho & Petre 1998) (c.f., Yamaguchi et al. 2009). However, N132D does not have a typical MM shape but rather a shell-like morphology in the soft X-ray band (Borkowski et al. 2007). The iron K line image, on the other hand, shows a center-filled morphology (Behar et al. 2001; Plucinsky et al. 2015). These facts imply that the low-temperature component mainly studied in previous works creates the shell-like structure, whereas the recombining component remains in the center of the remnant. These results may indicate again that N132D is in the transition stage from shell-like young SNRs to old ones with MM morphology; during the transition, the center-filled emission appears first, and after that the low-temperature emission from the shell disappears to create the MM morphology. In summary, it is expected that N132D is in a transition phase.

In order to derive the density and thermal energy, a uniform density sphere with a radius of 30 arcsec and 7 pc at 48 kpc was assumed (Macri et al. 2006). We derived the density from the emission measure ~3 cm⁻². The thermal electron energy of the recombining component, 3n_e kT times volume, is estimated to be ~9 × 10⁵⁰ erg. Combining the energies of lower-temperature components (Behar et al. 2001; Borkowski et al. 2007), the total thermal energy exceeds ~10⁵¹ erg. Moreover, the kinetic energy should be dominant when SNRs are young, thus the total energy...
2.6. Nonthermal Emission

N132D is the brightest SNR in the gamma-ray band (H.E.S.S. Collaboration et al. 2015; The Fermi-LAT Collaboration 2015). We estimated an upper limit on the nonthermal X-ray flux of $7.3 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ or $2.0 \times 10^{35}$ erg s$^{-1}$ in the 2–10 keV band. The photon index is flatter than the younger samples, Cas A (Helder & Vink 2008), Nakamura et al. (2012) suggested that the nonthermal X-ray luminosity becomes fainter when SNRs get older, thus our faint nonthermal X-rays in N132D are consistent with the older age. The primary nonthermal emission mechanism in the X-ray band is synchrotron from accelerated electrons, whereas GeV and VHE gamma rays have a leptonic origin via inverse Compton and/or a hadronic origin via π0 decay, respectively. The ratio between TeV gamma-ray flux in 1–10 TeV ($F_{\gamma,10}$) and synchrotron X-ray flux in 2–10 keV ($F_X$), $F_{\gamma,10}/F_X$, is useful to resolve these two possibilities (Yamazaki et al. 2006; Bamba et al. 2007; Matsumoto et al. 2007). In our case, $F_{\gamma,10}/F_X$ is larger than 7, which is much larger than young SNRs with strong synchrotron X-ray filaments (Yamazaki et al. 2006). This result implies that gamma rays from N132D have a hadronic origin. This agrees with the observational fact that the GeV gamma-ray luminosity is $\sim 10^{36}$ erg s$^{-1}$, which is very difficult to reproduce with the inverse Compton scattering of the cosmic microwave background ($10^{35}$ erg s$^{-1}$; Acero et al. 2016; Bamba et al. 2016). A more detailed discussion will be found in the following.

Figure 7 shows the broadband spectral energy distribution (SED) of N132D for a more quantitative study. 3.5 and 6 cm data were taken from Dickel & Milne (1995), whereas we used PLANCK data points at 100 GHz (Planck Collaboration et al. 2014). Planck Collaboration et al. (2014) used 2.6 arcmin radius region for the source spectra, which includes surrounding molecular clouds. We thus used this data point as an upper limit. Our analysis concentrates on the hard X-rays, whereas ASCA shows the upper limit of nonthermal emission in the 0.5–5 keV band with the assumption of $\Gamma = 2$ (Hughes et al. 1998). Fermi and H.E.S.S. data points were also used (H.E.S.S. Collaboration et al. 2015; The Fermi-LAT Collaboration 2015).

The solid lines in the left panel of Figure 7 represent a pure leptonic model to reproduce the data points. We assumed the photon field of inverse Compton emission following the method of H.E.S.S. Collaboration et al. (2015), the infrared emission from dust in and around the SNR. This model requires a magnetic field of $\lesssim 20 \mu$G, a cutoff energy for electrons of 7 TeV, and a total amount of energy of electrons ($U_e$) of $2.5 \times 10^{49}$ erg. The derived $U_e$ is very large and unrealistic in a typical SNR, since we should also consider the energy of accelerated protons, which should be comparable or larger than that of electrons (Slane et al. 2016). The total electron energy does not change even if we assume different spatial distributions for electrons and protons. These results suggest that the emission cannot have a pure leptonic origin, but instead must have a hadronic one. This result is mainly from bright GeV gamma rays and faint synchrotron X-rays, which require a small magnetic field and as a result large $U_e$.

The right panel of Figure 7 represents the leptonic + hadronic model fit to the gamma-ray data. We estimated the maximum energy of accelerated proton $E_{\text{max}}$ first from the GeV–VHE gamma-ray spectrum, and determined the magnetic field and the amount of electrons with the assumption that electrons and protons have the same maximum energy. We then estimated the inverse Compton emission from accelerated electrons and the same infrared photon field as that in our pure leptonic model analysis (H.E.S.S. Collaboration et al. 2015). When we fix the proton spectral index to be 2.0 and a total proton energy of $10^{50}$ erg, we estimated the number density of 80 cm$^{-3}$ for the pre-shock interstellar gas and $E_{\text{max}}$ of 30 TeV. Assuming that electron cutoff energy is the same for $E_{\text{max}}$, we derived a $U_e$ of $\lesssim 10^{48}$ erg and magnetic field of $\lesssim 13 \mu$G.

The presence of a molecular cloud around the SNR supports the large number density of ambient matter. The best-fit proton energy is $\sim 10\%$ of the typical explosion energy. Note that the derived energy is only for those emitting gamma rays, so more energy is required if there are accelerated protons that do not emit gamma rays. These facts suggest that N132D is a very energetic cosmic-ray accelerator. This result can be connected to our results

![Figure 7. SED of N132D with pure leptonic (left) and leptonic + hadronic models (right), respectively (Dickel & Milne 1995; Hughes et al. 1998; Planck Collaboration et al. 2014; H.E.S.S. Collaboration et al. 2015; The Fermi-LAT Collaboration 2015). The solid and dashed lines represent leptonic and hadronic components, respectively. In the left panel, solid lines are for $U_e$ of $2.5 \times 10^{49}$ erg, cutoff energy of electrons of 7 TeV, and the magnetic field of 20 $\mu$G, respectively. In the right panel, the solid lines are for $U_e$ of $10^{48}$ erg, the magnetic field of 13 $\mu$G, and the maximum electron energy of 30 TeV, whereas the dashed lines are for the maximum proton energy of 30 TeV, the total proton energy of $10^{50}$ erg, and the density of surrounding matter of 80 cm$^{-3}$. Although the pure leptonic model on the left shows good agreement with the data, it is physically unrealistic because it requires too much energy in the electrons.](image-url)
through thermal factors, namely that the progenitor explosion was more energetic than conventional supernovae.

Many old SNRs with gamma rays are now identified as emitting from accelerated protons, with a maximum energy of \(~10\text{ GeV}\) (for example, W44 (Abdo et al. 2010b), W28 (Abdo et al. 2010c). On the other hand, the gamma-ray spectrum of N132D is harder than the spectra from such old SNRs, extending up to the \(~\text{TeV}\) range. Figure 8 shows the SED of RX J1713–3946 as a typical young SNR case (H.E.S.S. Collaboration et al. 2016), W44 as a typical middle-aged case (Ackermann et al. 2013), and N132D. It is widely agreed that the gamma-ray emission from W44 is of hadronic origin, whereas in the case of RX J1713-3946, there is still debate about whether it is leptonic (Ellison et al. 2010; Ohira & Yamazaki 2017) or hadronic (Yamazaki et al. 2009; Inoue et al. 2012; Gabici & Aharonian 2014). One can see that the cutoff energy of the gamma-ray spectrum of N132D is between those of W44 and RX J1713–3946. Actually, the maximum energy of accelerated protons in N132D (30\text{ TeV}) is between that for RX J1713.7–3946 (>100\text{ TeV}; Aharonian et al. 2007) and W44 (7–9\text{ GeV}; Abdo et al. 2010b). Our comparison implies that N132D is in a transition phase from young to old, also in the context of particle acceleration.

Protons are accelerated to high energies when SNRs are young, and start escaping when SNRs get older or interact with molecular clouds (Ptuskin & Zirakashvili 2005; Ohira et al. 2010, 2012) and emit gamma rays (Gabici et al. 2009; Ohira et al. 2011). Since N132D is in the transition phase, the remnant has already accelerated protons to very high energies, and still produces them at a rate higher than it loses them. This may explain the exceptionally bright gamma-ray emission from N132D.

4.3. Comments on the Neutral Iron K line

We detected a possible signal of a neutral iron K line from N132D. The luminosity of the line is \(\sim1.9 \times 10^{33}\text{ erg s}^{-1}\), assuming a distance of 48 kpc (Macri et al. 2006).

A neutral iron K line from SNRs is rather peculiar, since the SNR plasma is highly ionized. RCW 86 has strong neutral iron K emission (Bamba et al. 2000), which is from plasma with a very low ionization timescale (Yamaguchi et al. 2008). The line lummosity is \(3.2 \times 10^{32}\text{ erg s}^{-1}\) (Ueno et al. 2007), with a distance of 2.3 kpc (Sollerman et al. 2003), which is similar to that in our case. On the other hand, this low-ionization plasma in RCW 86 has been heated very recently via the interaction with the cavity wall (Broersen et al. 2014), which is not the case for N132D because the main plasma is over-ionized.

Other samples with a neutral iron K line are 3C391 (Sato et al. 2014) and Kes 79 (Sato et al. 2016). The former has a line luminosity of \(\sim1.5 \times 10^{32}\text{ erg s}^{-1}\) (Sato 2016) at 8 kpc (Reynolds & Moffitt 1993), and the latter has a line luminosity of \(2.8 \times 10^{32}\text{ erg s}^{-1}\) at 7.5 kpc (Giacani et al. 2009), which is slightly smaller but comparable within the large error region of our case. Sato et al. (2016) claimed the possibility that the line from Kes 79 is due to K-shell ionization of neutral iron by the interaction of low-energy cosmic-ray protons with the surrounding molecular cloud, since the peak position of the line emission coincides with the molecular cloud (Giacani et al. 2009), together with the detection of GeV gamma rays (Auchettl et al. 2014). A similar discussion can be had for 3C391, together with OH masers (Frali et al. 1996) and GeV emission (Castro & Shane 2010). W44 is also similar to this sample, with the possible detection of neutral iron K line (\(7.0 \pm 5.0\times 10^{-6}\text{ ph cm}^{-2}\text{ s}^{-1}\), Sato 2016) and GeV gamma-ray emission (Acero et al. 2016). If these lines are due to low-energy cosmic-ray protons, the luminosities of a neutral iron K line and GeV gamma-ray may have a positive correlation, since the former is roughly proportional to the number of low-energy cosmic-ray protons in the MeV range and target mass (e.g., Valinia et al. 2000; Dogiel et al. 2011; Nobukawa et al. 2015), whereas the latter is proportional to the number of GeV protons and target mass. Figure 9 shows the relation between the neutral iron K line and 0.1–100 GeV gamma-ray luminosities of these SNRs. Although the sample number is too small and the error is large, the tendency is consistent with our scenario. This might be for first clue regarding proton acceleration in the MeV range in SNRs. In order to study this issue further, we need more X-ray observations with good energy and spatial resolution and better statistics.

5. Conclusions

We have performed X-ray spectroscopy of the SNR N132D in the LMC, using NuSTAR and Suzaku deep observations.
Thanks to the large effective area and low, stable background, we discover a very-high-temperature plasma or recombining plasma with \( n_T \sim 8.8 \times 10^{11} \text{ cm}^{-3} \). Together with the morphology of the iron K emission, we conclude that N132D is in the transition phase from a young shell-like SNR with ionizing plasma to a middle-aged, mixed-morphology SNR with recombining plasma. The total thermal energy of \( >10^{51} \text{ erg} \) shows that the progenitor explosion of N132D can be very energetic. We have created a tight upper limit of nonthermal X-rays. The spectral energy distribution from radio to VHE gamma rays shows us that the total energy of accelerated protons is very energetic, implying that N132D is a very efficient proton accelerator. The cutoff energy in the gamma-ray band also shows that N132D is in a transition stage from being young to being middle-aged.

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