Detection of the hard X-ray non-thermal emission from Kepler’s supernova remnant

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Abstract

We report the first robust detection of the hard X-ray emission in the 15–30 keV band from Kepler’s supernova remnant with the silicon PIN-type semiconductor detector of the hard X-ray detector (HXD-PIN) onboard Suzaku. The detection significance is 7.17 σ for the emission from Kepler’s entire X-ray emitting region. The energy spectrum is found to be well reproduced by a single power-law function with a photon index of \(3.13^{+0.85+0.69}_{-1.52-0.36}\), where the first and second errors represent 90%-statistical and systematic errors, respectively. The X-ray flux is determined to be \(2.75^{+0.78+0.81}_{-0.77-0.82} \times 10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\) in the 15–30 keV band. The wider-band X-ray spectrum in the 3–30 keV band, where the soft X-ray Suzaku/XIS spectrum is combined, shows that the non-thermal component does not have a significant X-ray roll-off structure. We find that the broad-band energy spectrum from the radio band, X-ray data of this work, and TeV upper limits can be reproduced with the one-zone leptonic model with a roll-off energy of \(\nu_{\text{roll}} = 1.0 \times 10^{17}\) Hz and magnetic field strength of \(B > 40\) μG. Application of the diagnostic method using indices in the soft and hard X-ray band to the data indicates that the maximum energy of the accelerated electrons in Kepler’s SNR is limited by the age of the remnant. The indication is consistent with the results of the one-zone leptonic modeling.

Key words: supernova remnants — Kepler — electron acceleration

1 Introduction

Supernova remnants (SNRs) are widely considered to be the primary origin of the galactic cosmic rays (GCRs), which are highly accelerated particles with energies up to \(\sim 10^{15}\) eV. The most plausible acceleration mechanism at SNRs is diffusive shock acceleration (DSA) (e.g., Axford et al. 1977; Bell 1978; Blandford & Ostriker 1978). The key feature of this process is that the acceleration is first order in the shock velocity and automatically results in a power-law spectrum with energy spectral index of \(\sim 2\). However Monte Carlo simulations show that steeper particle spectra > 2 is required to be consistent with the number of expected SNRs to be seen in TeV gamma-ray and the detected TeV SNRs (Cristofari et al. 2013). In addition, the basic DSA is not able to explain some of the observed characteristics, including the maximum energy of the particles, configuration of the magnetic field, and injection efficiency for the particle acceleration. More advanced, non-linear DSA models have been studied to address these issues (e.g., Berezhko et al. 2002; Berezhko et al. 2003; Ptuskin et al. 2010). The models predict that the magnetic field strength in the vicinity of the...
SNR shock is amplified to $\sim 100 \mu G$, with which particles can be accelerated up to $\sim 10^{15} \text{eV}$. The scenario is supported by the detection of a high magnetic field strength in X-ray observations (e.g., Uchiyama et al. 2007; Uchiyama & Aharonian 2008; Borkowski et al. 2018; Okuno et al. 2020; Matsuda et al. 2020).

Since Koyama et al. (1995) discovered the first observational evidence that electrons are accelerated up to multi-TeV energies in SN 1006, many astronomers have followed suit and made extensive study of the relations between GCRs and SNRs, both observationally and theoretically. In particular, observations in the X-ray energy band often provide invaluable information. In the X-ray band, young SNRs emit synchrotron radiation, typically with rather steep spectral indices of $\Gamma \approx 2-3.5$. This type of X-ray spectra suggest that they are emitted by high-energy electrons that have a rather steep energy distribution (Vink 2012). The highest energy of the electrons should be close to the maximum accelerated electron energy $E_{\text{max},e}$, which is determined from the magnetic field strength and shock speed (Reynolds & Keohane 1999). In addition, the curvature of an X-ray synchrotron spectrum provides information of the particle acceleration process, such as the so-called age-limited case and loss-limited case (Yamazaki et al. 2014). Thus, study of X-ray spectra of SNRs helps us gain insight about the particle acceleration and local environments.

Kepler’s SNR is the remnant of SN 1604 and one of the youngest SNRs in our Galaxy. It has a roughly spherical shell with a diameter of $\sim 200''$, accompanied with two protrusions in the north-west and south-east, and has been observed extensively in the radio and X-ray bands (e.g., Dickel et al. 1988; DeLaney et al. 2002; Reynolds et al. 2007). The center of the remnant is located at the Galactic coordinates $l = 4.5^\circ$ and $b = 6.8^\circ$. The distance to the remnant is still under discussion. Sankrit et al. (2005) reported a distance of $3.9 \pm 1.4 \text{kpc}$ from their proper motion measurement. Almost contradictorily, Reynoso & Goss (1999) estimated it to be $4.8-6.4 \text{kpc}$, using H I data obtained with the VLA. Their estimated distance has been supported by TeV gamma-ray observations. Based on the upper limit in the TeV gamma-ray range, the distance is estimated to be at least $6.4 \text{kpc}$, where the typical type Ia SN explosion model (Aharonian et al. 2008) was employed. To summarize conservatively, the distance to the remnant is $3-7 \text{kpc}$ (Kerzendorf et al. 2014). We adopt a distance of 4 kpc throughout this paper.

In the soft X-ray band below 10 keV, non-thermal emission from Kepler’s SNR has been detected by past X-ray missions, which gave a roll-off frequency of $\nu_{\text{roll}} = 1.1-7.9 \times 10^{17} \text{Hz}$. This value suggests $E_{\text{max},e} \sim 50-130 \text{TeV}$ in the standard synchrotron radiation model emitted by accelerated electrons in a uniform magnetic field of $\sim 10 \mu G$ (Bamba et al. 2005; Cassam-Chenaï et al. 2004; Katsuda et al. 2008; Kinugasa & Tsunemi 1999). Given that the radial profile of the non-thermal X-rays from Kepler’s SNR follows the thin-filament structures at the shell, non-linear DSA may be playing a key role in electron acceleration. Bamba et al. (2005) extracted spatially-resolved X-ray energy spectra from the thin-filament structures of the shock front and estimated its roll-off frequency to be $\nu_{\text{roll}} = 3.6^{+3.3}_{-1.6} \times 10^{17} \text{Hz}$. Cassam-Chenaï et al. (2004) made image and radial profile analyses using XMM-Newton and found the X-ray emission in the south-east region to be largely non-thermal. Reynolds et al. (2007) also confirmed this feature with the deep Chandra observation and found that a few regions in Kepler’s SNR were dominated with a continuum component, which is possibly synchrotron emission. Indeed, the measured shock speeds $v_s$ from various regions of Kepler’s SNR have been consistently higher than the minimum value required to emit X-ray synchrotron emission $\sim 2,000 \text{km s}^{-1}$ (Aharonian & Atøyan 1999), the fact of which supports the synchrotron-origin hypothesis; $v_s$ from the X-ray brightest knots was estimated to be $9,100-10,400 \text{km s}^{-1}$ (Sato & Hughes 2017), that from the ejecta distributed widely over the inner of the rim was $2,000-3,000 \text{km s}^{-1}$ (Kasuga et al. 2018), and that from the overall rims of the remnant was $2,000-4,000 \text{km s}^{-1}$ (Katsuda et al. 2008). As such, several soft X-ray observations claimed to have found evidence that the non-thermal X-ray emission from Kepler’s SNR originates in accelerated electrons at the shell.

However, in the hard X-ray band above 10 keV, the flux and spectral shape of the synchrotron radiation have not been determined. In this paper, we report the first robust detection of the wide-band non-thermal spectrum of Kepler’s SNR taken with Suzaku (Mitsuda et al. 2007). The Suzaku observations and data reduction of Kepler’s SNR are described in section 2, our spectral analysis, in section 3, and discussion and summary, in section 4.

### 2 Observations and data reduction

The Suzaku satellite has two types of instruments, the X-ray imaging spectrometers (XISs: Koyama et al. 2007) and hard X-ray detector (HXD: Takahashi et al. 2007), covering the soft (0.2–10.0 keV) and hard (10–600 keV) X-ray energy bands, respectively. The HXD is a well-type-phoswitch scintillation counters, whose main photo-absorbers consist of silicon PIN-type semiconductor detectors (HXD-PIN) and Gd$_2$SiO$_5$ (hereafter GSO) crystal scintillators (HXD-GSO), covering energy bands of 10–70 keV and 40–600 keV, respectively. In this work, we analyzed the HXD-PIN data. No significant detection was made in the HXD-GSO data. Regarding the XIS data, we adopted the spectrum presented in Katsuda et al. (2015), which is taken from the observation with an observation ID of 505092040.

Suzaku made in total eight observations of Kepler’s SNR region in 2010 September, 2010 October, 2011 February, and
3 Spectral analysis

Spectral analysis was performed using XSPEC\textsuperscript{2} v12.10.1. We used Cash statistic C (Cash 1979; Kaastra 2017), which allows background subtraction in XSPEC by means of the W-statistic, for model-fitting of the spectral data.

3.1 Hard X-ray spectrum with the HXD-PIN

Before spectral analysis of the HXD-PIN, we evaluated the reproducibility of the NXB model (bgd-d) for the observation data. First, we calculated the reproducibility of the bgd-d model by comparing count rates in the 15–40 keV band between the spectra during the Earth occultations based on the criteria described in section 2 and NXB model. The reproducibility of the bgd-d model was derived to be in the range of 0.1–16% (the sixth column in table 1). Since the uncertainty in the NXB modeling is larger in shorter observations (Fukazawa et al. 2009), we excluded the two shorter-exposure observations of IDs of 505092010 and 505092060 in our analysis. In addition, since the HXD-PIN sensitivity is determined primarily by the systematic error below \(-30\) keV, we also excluded the observation ID 505092030, which has an uncertainty of 2.9%, to minimize the uncertainty of the obtained spectral shape.

Next, we evaluated the effect of poorly reproduced NXB models by inspecting the count-rate correlation between the “On Source” data and the NXB model in the same period in the 15–40 keV band. We split the total observation period of the “On Source” data in each observation into 1 ks and compared the NXB count-rate between the data and NXB model in 15–40 keV. The correlation plots were fitted with a function,

\begin{equation}
R_{\text{arc}} = a + bR_{\text{nxb}},
\end{equation}

where \(R_{\text{arc}}\) and \(R_{\text{nxb}}\) are the observed X-ray and predicted NXB count-rates, respectively, \(a\) is the X-ray emission such as the CXB and/or that from astronomical objects, and \(b\) is the slope of the relation between the observation data and the NXB model which should be unity in the ideal case. Figure 1 shows the data and fitting results, and the rightmost columns of table 1 lists the determined parameters \(a\) and \(b\).

The NXB was found to be relatively poorly reproduced in three of the correlation plots (observations IDs of 505092020, 505092050, and 505092070), in addition to those of the already excluded data, in the high-count rate range of each “On source” observation, where the parameter \(b\) of these observation IDs is not close to 1. Indeed, a hint of this tendency had been already reported by Bamba et al. (2008). Therefore, we excluded the observation IDs 505092020, 505092050, and 505092070 with a criterion of \(0.90 < b < 1.10\) from further analyses. Consequently, we analyzed the HXD-PIN data of the observation IDs 502078010 and 505092040 in this work and the total exposure of the data set is 143.76 ks. We adopted a systematic error of 1% for the following spectral analyses based on the NXB model uncertainties for observation IDs 502078010 and 505092040.

Since the emission region of Kepler’s SNR is slightly extended (the angular size of \(\sim 200''\)), we take into account the angular response of the HXD-PIN (the so-called “arf” in XSPEC) in estimating the effective area. Specifically, the effective area ratio of a point source to the spatial structure of Kepler’s SNR needs to be calculated. Note that the angular response of the PIN detectors has a pyramidal shape (Kokubun et al. 2007; Terada et al. 2005). For simplicity, we assumed that the area of the hard X-ray emission was the same as that of the soft X-ray emission, and that both had flat spatial distributions. Then, we calculated effective area ratio of the pyramidal shape...
Table 1. Suzaku observations used in this work. The observation IDs 502078010 and 505092040 are used for the analyses in this paper. The NXB uncertainties for those two observation IDs are consistent with Fukazawa et al. (2009) within 1σ of the statistical error.

| ID          | Date     | RA [deg] | Dec [deg] | Earth occultation | Observation | On Source observation | Exposure [ks] | Uncertainties [%] | Exposure [ks] | a [count sec⁻¹] | b     |
|-------------|----------|----------|-----------|-------------------|-------------|-----------------------|---------------|-------------------|---------------|---------------|-------|
| 502078010   | 2008-02-18 | 262.66   | -21.54    | 52.81             | 1.0±1.1     | 98.95                 | 0.04±0.01     | 0.94±0.05        |               |               |       |
| 505092010   | 2010-09-30 | 262.67   | -21.44    | 0.25              | 16.3±17.5   | 17.85                 | 0.06±0.03     | 0.88±0.11        |               |               |       |
| 505092020   | 2010-10-06 | 262.67   | -21.44    | 33.77             | 0.1±1.5     | 99.80                 | 0.07±0.01     | 0.86±0.06        |               |               |       |
| 505092030   | 2011-02-23 | 262.65   | -21.53    | 20.50             | 2.9±1.9     | 29.10                 | 0.04±0.02     | 0.97±0.08        |               |               |       |
| 505092040   | 2011-02-28 | 262.66   | -21.54    | 90.86             | 0.2±0.9     | 113.73                | 0.04±0.01     | 0.97±0.04        |               |               |       |
| 505092050   | 2011-03-08 | 262.66   | -21.54    | 70.29             | 0.8±0.9     | 122.47                | 0.21±0.01     | 0.35±0.04        |               |               |       |
| 505092060   | 2011-03-14 | 262.66   | -21.54    | 8.32              | 1.4±2.6     | 38.61                 | 0.01±0.03     | 1.04±0.10        |               |               |       |
| 505092070   | 2011-03-29 | 262.66   | -21.54    | 54.73             | 1.4±1.2     | 112.20                | 0.07±0.01     | 0.83±0.05        |               |               |       |

*: The exposure are the ones after processing of the HXD-PIN.

Fig. 1. Comparison of the NXB model count-rate (horizontal axis) and HXD-PIN data count-rate (vertical axis) in the 15–40 keV band. Light-blue shaded areas show the regions of 1σ errors.

The thermal emission that dominates the soft X-ray energy band may somewhat contaminate the hard X-ray emission in the HXD-PIN data. We use the soft X-ray spectrum obtained by Katsuda et al. (2015). Katsuda et al. (2015) showed that the soft X-ray spectrum was well reproduced with thermal models, with their analysis of the combined spatially-integrated spectra measured with the XMM-Newton Reflection Grating Spectrometer (RGS) (den Herder et al. 2001) and Chandra ACIS (Garmire et al. 2003) for the energy range below 2 keV and Suzaku XIS (using only the front-illuminated CCDs, XIS0 and XIS3) for above 2 keV. Katsuda et al. (2015) fitted these spectra in an energy range of 0.4–7.5 keV with a model consisting of an absorbed, vphock (shock plasma model) + three vneis (non-equilibrium ionization thermal plasma model) +
power-law + several Gaussian components with the XSPEC package (Arnaud 1996). The \texttt{vphabs}, three \texttt{vnei}, and power-law components in the model correspond to the emissions from the circumstellar medium (CSM), SN ejecta (Ejecta 1: the lower-temperature component, Ejecta 2: the higher-temperature component, Ejecta 3: the Fe-rich component), and synchrotron radiation, respectively. The several Gaussian components represent emission lines of Fe L and/or Ne K, Cr K, and Mn K (Katsuda et al. 2015).

In our fitting analyses, we applied the model presented in Katsuda et al. (2015) for thermal components but with the latest AtomDB ver 3.0.9\(^2\). The difference of the thermal parameters between those by Katsuda et al. (2015) and our work is summarized in appendix 1. Then we applied the obtained new best-fit model to the XIS spectrum in the 3–10 keV band, allowing only the normalization parameter of each thermal model. In this fitting, the normalization for the CSM and Ejecta 1 are fixed because the contributions of these components in the 3–10 keV band were relatively minor contribution. Figure 3 shows the XIS spectrum and best-fit models, whereas table 2 summarizes the best-fit parameters. We also fitted the XIS spectrum in the 0.5–10 keV band without fixing the plasma model, but the best-fit non-thermal parameters were consistent with each other within the statistical errors.

The cross-normalization factor on the effective areas between the XIS and HXD-PIN for a point-like source was estimated to be 1:1.10 (Kokubun et al. 2007). Using the correction factor of 0.96 for the effective areas for the XIS and HXD spectra estimated in the previous subsection, we carried out the model fitting for the 3–30 keV band with the fixed cross-normalization of 1.15×0.96~1.10. As for the non-thermal component in the model, we applied a single power-law function (top panel of figure 4). We also tested a broken power-law function. Our initial attempt yielded the best-fit broken energy of 2.78 keV, which is out of the energy band of the fitted spectra, with c-stat/dof=1.12. Thus, we fixed the broken energy at 10 keV and refitted the spectrum (bottom panel of figure 4). The best-fit parameters are tabulated in the third and forth columns of table 2.

Furthermore, we investigated the parameter spaces of a power-law model, applying it to each spectrum separately, to see whether the photon-indices of the non-thermal emission between the soft X-ray (3–10 keV) and hard X-ray (15–30 keV) bands differ. Figure 5 shows the confidence contour between the photon index and normalization at 1 keV from single power-law models applied individually to the HXD-PIN spectrum (15–30 keV), XIS spectrum (3–10 keV), and combined XIS and HXD-PIN spectra (3–30 keV) where the cross-normalization factor for HXD-PIN data is taken into account. We found the best-fit power-law parameters to be consistent in the 1-σ confidence level between one another.

4 Discussion and Summary

Kepler’s SNR has steep spectral indices ($\Gamma > 2$) in both the soft and hard X-ray bands (Bamba et al. 2005, Katsuda et al. 2015; see also section 3). The power-law component should represent the non-thermal emission. Their origin can be explained by the synchrotron radiation or the non-thermal bremsstrahlung, as well known as non-thermal emissions from SNRs. However, since the latter emission could be detected with the harder spectral index $\Gamma \sim 1.4$ (Tanaka et al. 2018) than our result, the former is more feasible to represent the XIS and HXD-PIN spectra by synchrotron emission at the highest energy of the electron pop-

\(^2\)http://www.atomdb.org
The best-fit model

Table 2. Best-fit parameters for Kepler’s SNR. Statistical errors are for the 90% confidence.

| Parameter       | XIS   | HXD-PIN† | XIS+HXD-PIN† |
|-----------------|-------|----------|-------------|
| Fitting range   | 3-10 keV | 15-30 keV | 3-30 keV   |
| Thermal component |       |          |             |
| CSM $[10^{10} \text{cm}^{-3}]$ | 344.80±0.04 | 344.80±0.04 | 344.80±0.04 |
| Ejecta 1 $[10^{3} \text{cm}^{-3}]$ | 961.42±0.04 | 961.42±0.04 | 961.42±0.04 |
| Ejecta 2 $[10^{5} \text{cm}^{-3}]$ | 2270.78±15.12 | 2263.27±15.76 | 2260.44±15.85 |
| Ejecta 3 $[10^{6} \text{cm}^{-3}]$ | 2857.75±16.33 | 2831.10±16.72 | 2832.48±16.99 |
| Non-thermal component | Single PL | Single PL | Broken PL |
| $\Gamma$ (all or soft) | 2.63±0.04 | 3.13±0.08 | 2.57±0.08 |
| $\Gamma$ (hard) | - | - | 2.10±0.09 |
| Breaking energy [keV] | - | - | 10* |
| Flux $[10^{-12} \text{erg cm}^{-2} \text{s}^{-1}]$ | 0.93±0.15 | 2.75±0.81 | 10.53±0.03 |
| Normalization [ph keV$^{-1} \text{cm}^{-2} \text{s}^{-1}$] | 1515.03/1411 | 0.37/3 | 1519.07/1416 | 1516.62/1415 |

*: Fixed values.
†: The first and second errors are the statistical and systematic errors, respectively.
‡: The integration range is the same as the fitting range.

Fig. 4. Broad-band spectra of Kepler’s SNR fitted with a model consisting of the thermal components described in Katsuda et al. (2015) and a non-thermal component of (Top panel) single power-law and (Bottom panel) 10-keV broken power-law. The data points in the soft X-ray band (3–10 keV) are taken from Katsuda et al. (2015).

Fig. 5. Confidence contours between the photon index and normalization at 1 keV for a single power-law model. Solid, dashed, and dotted lines correspond to 1,$\sigma$, 2,$\sigma$, and 3,$\sigma$ contours for the HXD-PIN spectrum, respectively. The black star shows the best-fit value of HXD-PIN spectrum, whereas blue and red crosses show those of the XIS (3–10 keV) and XIS+HXD-PIN (3–30 keV), respectively.

ulation. In this section, we model the broad-band non-thermal emission from the radio to TeV (upper limit) data and investigate the current particle distribution and properties of the local magnetic field.

Most of young SNRs are known to emit TeV gamma-ray emission (e.g., Archambault et al. 2017; H. E. S. Collaboration et al. 2018; Naumann-Godó et al. 2008; H. E. S. Collaboration et al. 2018; Aharonian et al. 2008; Acciari et al. 2009; Ahnen et al. 2017). In the so-called leptonic model, which is based on the assumption that their TeV
gamma-ray emission is produced by the inverse Compton scattering of high-energy electrons, the magnetic-field strength at an acceleration site can be estimated with the equation \( F_{\text{TeV}} / F_X \propto u_{\text{rad}} / u_B \), where \( F_{\text{TeV}}, F_X, u_{\text{rad}}, \) and \( u_B \) are the TeV flux, X-ray flux, energy density in the radiation field, and energy density of the magnetic field, respectively. The H.E.S.S. telescopes observed Kepler’s SNR in 2004 and 2005 with a total live time of 13 h and found no evidence for gamma-ray emission (Aharonian et al. 2008) with an estimated upper limit of \( 8.6 \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1} \) in an energy range of 0.23–12.8 TeV. The upper limit gives a constraint on the high-energy particle distribution and magnetic field. We use the radiative code and Markov Chain Monte Carlo (MCMC) fitting routines of \textit{Naima} ver. 0.9.1 \(^4\) to estimate the present-age particle distribution (Zabalza 2015) as follows. First, we fit the radio and X-ray data with a simple model in which the radiating electrons are assumed to follow an exponential roll-off power-law distribution,

\[
N_e \propto E_e^{-\Gamma} \exp(-E_e / E_{\text{max},e}), \tag{2}
\]

and obtain the amplitude of the electron distribution. Then we calculate the flux of inverse Compton scattering (IC). The seed photon fields considered for the IC emission are the cosmic microwave background (CMB) radiation, a far-infrared (FIR) component with temperature \( T = 29.5 \) K and a density of \( 1.08 \) eV cm\(^{-3}\), and a near-infrared (NIR) component with temperature \( T = 1800 \) K and a density of \( 2.25 \) eV cm\(^{-3}\). The values for FIR and NIR are derived from GALPROP by Shibata et al. (2011) for a distance of 4 kpc. Table 3 lists the best-fit parameters, and figure 6 shows the obtained spectral energy distribution along with the radio and X-ray data and H.E.S.S. upper limits. Note that the non-thermal emission measured by HXD-PIN (the blue-shaded region) shows slightly a higher flux than the model curve in figure 6, though they are consistent within the systematic error. We confirmed that there is no hard X-ray sources in the field of view of the HXD-PIN (34’ × 34’) by looking over the \textit{INTEGRAL} catalog\(^5\). In order to further investigate a possible contamination of an additional emission, like non-thermal bremsstrahlung, we fitted the XIS + HXD-PIN spectra with the model constructed in section 3.2 plus a second power-law component with a fixed \( \Gamma \) of 1.4 which is expected for the non-thermal bremsstrahlung (e.g., Tanaka et al. 2018). Consequently, we obtained the \( c \)-value of 1519.08 which does not significantly improve from the original model. Thus, the contamination from the non-thermal bremsstrahlung is not statistically significant with the upper limit of the flux of \( 6.61 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1} \) (68% confidence range) in the 3–30 keV band, which is one order of magnitude lower than the flux of bremsstrahlung component of W49B (Tanaka et al. 2018).

### Table 3. The best-fit parameters of the radiating electron distribution from the radio and X-ray data.

| \( B \) [\( \mu \text{G} \)] | \( p_e \) * | \( E_{\text{max},e} \) [TeV] * | \( W_e \) [erg] * |
|---|---|---|---|
| 30 | 2.44 ± 0.01 | 25.5 ± 0.7 | 5.01 ± 0.04 \times 10^{47} |
| 40 | 2.44 ± 0.01 | 21.9 ± 0.6 | 3.04 ± 0.03 \times 10^{47} |

* : \( p_e \) and \( E_{\text{max},e} \) are the spectral index and maximum energy of the electron distribution defined in eq (2), respectively.

† : The total energy of the radiating electrons above 511 keV for an assumed distance of 4 kpc.
Fig. 6. Spectral energy distribution of the entire Kepler’s SNR from the radio to TeV gamma-ray bands. The inset panel shows zoomed-up data in the X-ray band (1–30 keV). The radio data points (magenta) are from DeLaney et al. (2002). The TeV gamma-ray upper limits are from Aharonian et al. (2008). Red- and blue-shaded regions are the non-thermal emission measured with the XIS and HXD-PIN, respectively (see table 2). The red-shaded region takes into account only the statistic error, whereas the blue-shaded region takes into account both the statistic and systematic errors.

\[ N(E_e) \propto E_e^{-p_e} \exp\left(-\frac{E_e}{E_{\text{max},e}}\right)^a, \]  

(4)

where \( E_e \), \( p_e \), and \( a \) are the electron energy, spectral index, and cutoff shape parameter, respectively (see Yamazaki et al. (2014)). The simple diagnostic method presented by Yamazaki et al. (2014) uses the relation between the soft and hard X-ray spectral indices.

Figure 7 shows the predicted relation between the soft and hard X-ray indices for 3 sets of \( p_e = 2.0, 3.0, \) and 2.3, which are taken from figures 1 and 5 in Yamazaki et al. (2014). We plot in the figure the observed soft and hard X-ray spectral indices of three young SNRs: RX J1713.7−3946 (Tanaka et al. 2008), Vela Jr (Takeda et al. 2016), and Kepler’s SNR (this work). Note that the data point of Kepler’s SNR from this work is taken from the fourth column in table 2 (section 3.2). We find that the data points of Vela Jr and Kepler’s SNR are off any of the predicted lines, even the most extreme case of \( p_e = 3 \) and \( a \approx 0.5 \) in our set of examples (figure 7). The discrepancy may suggest that the particle acceleration is limited not by synchrotron cooling but by their ages (Yamazaki et al. 2014).

The maximum electron energy in the age-limited case for Kepler’s SNR is calculated to be, from eq (A.2) in Yamazaki et al. (2014), under an assumption of the age of 400 yr,

\[ E_{\text{max},e} \simeq 120 \left(\frac{\eta}{1}\right)^{-1} \left(\frac{v_s}{4,000 \text{ km s}^{-1}}\right)^2 \left(\frac{B}{40 \mu G}\right) \text{TeV}, \]  

(5)

where \( v_s \) and \( \eta \) are the shock speed and gyro-factor, respectively. Combining eqs (5) and (3) yields the relation between \( v_s \) and \( B \),

\[ v_s \simeq 1,700 \left(\frac{\eta}{1}\right)^{\frac{1}{3}} \left(\frac{B}{40 \mu G}\right)^{-\frac{1}{2}} \left(\frac{\nu_{\text{roll}}}{1.0 \times 10^{17} \text{ Hz}}\right)^{\frac{1}{4}} \text{ km s}^{-1}. \]  

(6)

In Tsuji et al. (2020), \( \eta \) at the rims of Kepler’s SNR are estimated \( \eta = 0.3–3.2 \). Utilizing the values, \( v_s \) is estimated 930–3,000 km s\(^{-1}\). This value is plausible, considering the measured shock speed at the rim of the remnant of 2,000–4,000 km s\(^{-1}\) (Katsuda et al. 2008). At least, it does not exceed the highest speed of 10,400 km s\(^{-1}\) measured from the X-ray bright knots (Sato & Hughes 2017). We conclude that the particle acceleration at Kepler’s SNR is age-limited.

In the case of age-limited acceleration, the synchrotron loss time \( t_{\text{sync}} \) should be larger than the age of Kepler’s SNR \( t_{\text{age}} \approx 400 \text{ yr} \). From Vink (2012), we estimate the synchrotron loss time adopting our modeling result,

\[ t_{\text{sync}} \simeq 640 \left(\frac{\nu_{\text{roll}}}{1.0 \times 10^{17} \text{ Hz}}\right)^{-\frac{2}{3}} \left(\frac{B}{40 \mu G}\right)^{\frac{2}{3}} \text{ yr}. \]  

(7)

Thus, the estimated \( t_{\text{sync}} \) is longer than \( t_{\text{age}} \), and it indicates the
the magnetic field strength can be derived from γ-ray observations, and the remnant age under age-limited acceleration. It is important to note that the age-acceleration model is expected that Kepler’s SNR will produce more energetic electrons. In the GeV–TeV energy range, the maximum energy of accelerated protons up to the same energy as electrons. In order to study the detail of proton acceleration at SNR, GeV–TeV energy range is very helpful. Due to low flux from Kepler’s SNR in GeV–TeV range, it is difficult to extract physical parameters regarding proton acceleration with the current GeV–TeV instrument. This study could be performed by future CTA observatory.

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Appendix 1 Thermal emission from Kepler’s SNR

The vnei model employed in the model-fitting for Kepler’s SNR in this work uses AtomDB\(^6\). AtomDB is an atomic database designed for X-ray plasma spectral modeling. The current version of AtomDB is primarily used for modeling collisional plasma, where hot electrons collide with (astrophysically abundant) elements and ions and generate X-ray emission. AtomDB has been updated several times\(^7\). This work uses AtomDB 3.0.9, whereas Katsuda et al. (2015) used AtomDB 2.0.2. As a result, our fitting of an identical dataset to those of Katsuda et al. (2015) has yielded somewhat different results from theirs. Table 4 summarizes the fitting results in the 0.5–7.0 keV band by Katsuda et al. (2015) and us. Most of the best-fit parameters between the two works agree within \(\lesssim 30\%\).

\(^6\)http://www.atomdb.org

\(^7\)http://www.atomdb.org/download.php
Table 4. The best-fit parameters for the thermal models of Kepler’s SNR.

| Parameter                                                                 | Katsuda et al. (2015) | This work | Ratio*   |
|---------------------------------------------------------------------------|------------------------|-----------|----------|
| CSM component                                                             |                        |           |          |
| $kT_e$ (keV)                                                              | 1.06±0.03              | 0.97±0.01 | 0.92±0.03|
| log($n_e t_{cm^{-3} sec}$)                                                | 10.81±0.02             | 10.71±0.01| 0.99±0.00|
| Abundance$^{ab}$ (solar)N                                                  | 3.31±0.24              | 1.93±0.17 | 0.58±0.07|
| Redshift ($10^{-3}$)                                                      | 1.39±0.05              | 1.34±0.05 | 0.96±0.05|
| Line broadening (E/1 keV eV)                                             | 2.91±0.36              | 2.09±0.17 | 0.72±0.11|
| $\int n_e r_{H} dV/4\pi r^2 (10^5 cm^{-5})$                               | 193.15±0.43            | 344.80±3.98| 1.79±0.04|
| Ejecta components                                                          |                        |           |          |
| (1)$kT_e$ (keV)                                                           | 0.37±0.01              | 0.35±0.00 | 0.95±0.03|
| log($n_e t_{cm^{-3} sec}$)                                                | 10.52±0.01             | 10.75±0.02| 1.02±0.00|
| Abundance ($10^4$ solar)O                                                 | 0.25±0.02              | 0.05±0.02 | 0.20±0.08|
| Ne                                                                        | 0.67±0.06              | 0.21±0.03 | 0.31±0.08|
| Mg                                                                        | 0.73±0.07              | 0.48±0.05 | 0.62±0.09|
| S                                                                         | 15.53±0.22             | 11.20±0.09| 0.72±0.01|
| Ca                                                                        | 18.99±0.52             | 16.74±0.45| 0.88±0.03|
| Fe                                                                        | 36.40±1.69             | 31.43±1.16| 0.86±0.05|
| $\int n_e r_{H} dV/4\pi r^2 (10^5 cm^{-5})$                               | 961.42±114.02          | 1843.48±123.31| 1.92±0.02|
| Redshift ($10^{-3}$)                                                      | -2.94±0.01             | -0.81±0.01| 0.28±0.00|
| Line broadening (E/1 keV eV)                                             | 9.15±0.21              | 5.48±0.14 | 0.60±0.02|
| (2)$kT_e$ (keV)                                                           | 2.08±0.02              | 1.435±0.00| 0.69±0.01|
| log($n_e t_{cm^{-3} sec}$)                                                | 10.32±0.01             | 10.47±0.00| 1.01±0.00|
| Abundance$^{ab}$ ($10^4$ solar)Fe                                         | 3.58±0.04              | 2.57±0.02 | 0.72±0.02|
| $\int n_e r_{H} dV/4\pi r^2 (10^5 cm^{-5})$                               | 875.35±74.73           | 2228.54±99.52| 2.55±0.02|
| (3)$kT_e$ (keV)                                                           | 2.59±0.01              | 3.74±0.12 | 1.44±0.05|
| log($n_e t_{cm^{-3} sec}$)                                                | 9.21±0.10              | 9.34±0.02 | 1.01±0.00|
| Abundance$^{ab}$ ($10^4$ solar)Ar                                         | 0 (< 0.19)             | 2.47±0.59 | -        |
| Ca                                                                        | 1.43±0.31              | 4.24±0.73 | 2.97±0.82|
| Redshift ($10^{-3}$)                                                      | -5.73±0.14             | -4.46±0.10| 0.78±0.06|
| Line broadening (E/1 keV eV)                                             | 12.10±0.27             | 7.486±0.16| 0.62±0.02|
| $\int n_e r_{H} dV/4\pi r^2 (10^5 cm^{-5})$                               | 5808.47±71.17          | 2823.47±30.07| 1.64±0.01|

Additional lines

| Parameter                                                                 | Katsuda et al. (2015) | This work | Ratio*   |
|---------------------------------------------------------------------------|------------------------|-----------|----------|
| FeL-OKCenter (keV)                                                        | 0.708±0.004            | 0.72±0.001| 1.02±0.00|
| Norm ($10^{-2}$ ph keV$^{-1}$ cm$^{-2}$ s$^{-1}$)                         | 68.18±5.95             | 196.07±8.96| 2.88±0.26|
| FeL-NeKCenter (keV)                                                       | 1.272±0.004            | 1.272±0.001| 1.02±0.00|
| Norm ($10^{-2}$ ph keV$^{-1}$ cm$^{-2}$ s$^{-1}$)                         | 22.75±1.2              | 23.66±1.20 | 1.04±0.08|
| CrKCenter (keV)                                                           | 5.514±0.035            | 5.51±0.03 | 1.00±0.01|
| Norm ($10^{-2}$ ph keV$^{-1}$ cm$^{-2}$ s$^{-1}$)                         | 85.18±10.1             | 0.10±0.02 | (1.17±0.33)×10$^{-3}$|
| MnKCenter (keV)                                                           | 5.976±0.042            | 5.960±0.041| 1.00±0.01|
| Norm ($10^{-2}$ ph keV$^{-1}$ cm$^{-2}$ s$^{-1}$)                         | 60.18±16.3             | 0.07±0.02 | (1.16±0.46)×10$^{-3}$|

* The ratio is the values obtained in this work to those obtained by Katsuda et al. (2015).