HARD X-RAY EMISSION AND ⁴⁴Ti LINE FEATURES OF THE TYCHO SUPERNOVA REMNANT

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ABSTRACT

A deep hard X-ray survey of the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite has detected for the first time non-thermal emission up to 90 keV in the Tycho supernova (SN) remnant. Its 3–100 keV spectrum is fitted with a thermal bremsstrahlung of $kT \sim 0.81 \pm 0.45$ keV plus a power-law model of $\Gamma \sim 3.01 \pm 0.16$. Based on diffusive shock acceleration theory, this non-thermal emission, together with radio measurements, implies that the Tycho remnant may not accelerate protons up to >PeV but to hundreds TeV. Only heavier nuclei may be accelerated to the cosmic ray spectral “knee.” In addition, using INTEGRAL, we search for soft gamma-ray lines at 67.9 and 78.4 keV that come from the decay of radioactive ⁴⁴Ti in the Tycho remnant. A bump feature in the 60–90 keV energy band, potentially associated with the ⁴⁴Ti line emission, is found with a marginal significance level of $\sim 2.6\sigma$. The corresponding 3σ upper limit on the ⁴⁴Ti line flux amounts to $1.5 \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$. Implications on the progenitor of the Tycho SN, considered to be a Type Ia SN prototype, are discussed.

Key words: cosmic rays – gamma rays: ISM – ISM: supernova remnants – supernovae: individual (Tycho)

Online-only material: color figures

1. INTRODUCTION

The Tycho supernova (SN 1572) is a historical supernova (SN) occurring in early November of 1572 in the region of the constellation Cassiopeia. This SN explosion event was suggested to be a Type Ia SN, but no convincing evidence has been found (e.g., Ruiz-Lapuente 2004). Recent spectral analysis of the light echo from the explosion (Krause et al. 2008) has confirmed that the event was a Type Ia SN. Measurements of the distance to the Tycho remnant still have large uncertainties. The kinematic distance obtained by observing H I absorption toward the Tycho remnant gives a large distance range of 1.7–5.0 kpc (Albinson et al. 1986; Schwarz et al. 1995; Tian & Leahy 2011). Modeling of the observed γ-ray emission from Tycho suggests a distance greater than 3.3 kpc (Volk et al. 2008). A direct distance estimate is also given by X-ray ejecta proper-motion observations by Chandra and Suzaku, which give a distance of $4 \pm 1$ kpc (Hayato et al. 2010).

Supernova remnants (SNRs) are generally thought to be promising sites for the production of high energy cosmic rays (CRs) up to the energies of $>10^{15}$ eV. The accelerated electrons and protons can produce the non-thermal emissions observed from radio to gamma-ray bands. Non-thermal emission from the Tycho SNR has been detected in radio, X-rays, and gamma-rays. Radio images also show a shell-like morphology with enhanced emission along the northeastern edge of the remnant (Dickel et al. 1991; Stroman & Pohl 2009). Soft X-ray images by Chandra reveal non-thermal gamma-ray emission concentrated on the SNR rim (Hwang et al. 2002; Bamba et al. 2005; Warren et al. 2005), which has been interpreted as evidence of electron acceleration. The first evidence for hard X-ray emission from the Tycho SNR was reported by HEAO 1 (Pravdo & Smith 1979), which suggested a photon index of $\sim 2.72$ from 5–25 keV. RXTE also reported a hard X-ray continuum up to 20 keV with a photon index of $\sim 3$ (Petre et al. 1999). Recent detection by the Suzaku HXD-PIN detector up to 28 keV implies the possible presence of accelerated electrons up to energies of at least $\sim 10$ TeV (Tamagawa et al. 2009). The Suzaku spectrum of the Tycho SNR from 13–28 keV was described by a power-law model with a photon index of $\Gamma \sim 3.01 \pm 0.16$. Based on diffusive shock acceleration theory, this non-thermal emission, together with radio measurements, implies that the Tycho remnant may not accelerate protons up to >PeV but to hundreds TeV. Only heavier nuclei may be accelerated to the cosmic ray spectral “knee.” In addition, using INTEGRAL, we search for soft gamma-ray lines at 67.9 and 78.4 keV that come from the decay of radioactive ⁴⁴Ti in the Tycho remnant. A bump feature in the 60–90 keV energy band, potentially associated with the ⁴⁴Ti line emission, is found with a marginal significance level of $\sim 2.6\sigma$. The corresponding 3σ upper limit on the ⁴⁴Ti line flux amounts to $1.5 \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$. Implications on the progenitor of the Tycho SN, considered to be a Type Ia SN prototype, are discussed.

The accelerated electrons emit synchrotron radiation observed from the radio to X-ray bands. However, the non-thermal emissions in the soft X-ray bands generally are difficult to discriminate from thermal components in SNRs. In the hard X-ray bands (> 10 keV), the observations are a direct way to probe the non-thermal emission properties, constraining the accelerating ability of SNRs. The hard X-ray properties of the Tycho SNR have never been studied in detail due to the poor sensitivity above 20 keV of past missions. Suzaku made a detection of the hard X-ray emission up to 28 keV (Tamagawa et al. 2009), but we do not know its spectral characteristics at higher energies. The instruments on board the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) have a better sensitivity above 20 keV up to several hundred keV and would provide new information on the non-thermal emission properties of the SNR.

In addition, hard X-ray studies on SNRs could search for the hard X-ray lines from radioactive ⁴⁴Ti at $\sim 68$ and 78 keV. ⁴⁴Ti is a short-lived radioactive isotope with a mean life of 85 years (Admad et al. 2006). In theory, the most plausible cosmic environment for the production of ⁴⁴Ti is the $\alpha$-rich freeze-out from high-temperature burning near the nuclear statistical equilibrium (Woosley et al. 1973; Timmes et al. 1996). This high required value for the entropy can be found in SNe. It is generally believed that core-collapse SNe dominate the production of radioactive ⁴⁴Ti (Timmes et al. 1996). The decay of ⁴⁴Ti can emit four lines at energies of 4.1, 67.9, 78.4, and 1157 keV, where the line flux at 4.1 keV is about 20% of the other lines, and the flux at 67.9 keV is about 93% the flux at 78.4 keV. Previously, the
67.9, 78.4, and 1157 keV lines from Cas A were reported (Iyudin et al. 1994, 1999; Vink et al. 2001; Renaud et al. 2006a, 2006b). Two hard X-ray lines at 67.9 and 78.4 keV from SN 1987A were recently discovered (Grebenev et al. 2012). These two SNe are known to be of core-collapse origin. Tentative detections of the 1157 keV line from Vela Junior (Iyudin et al. 1998) and the 4.1 keV line from G1.9+0.3 (Borkowski et al. 2010) were also reported.

Generally, a Type Ia SN like Tycho is not thought to produce a large amount of $^{44}$Ti. However, great uncertainty still surrounds the central driver of these Type Ia explosions: just what kind of star explodes? Is the white dwarf that blows up near the upper mass limit allowed by nature (the “Chandrasekhar mass”), or is it lighter (the Sub-Chandrasekhar mass), and does the explosion result from the slow accretion of matter from a companion star or the dynamic merger of two white dwarfs? An important diagnostic of the models is the nucleosynthesis that they produce. In the Chandrasekhar mass explosions, the fuel is a mixture of carbon and oxygen, and the burning produces a distinctive set of iron-group and intermediate-mass elements. Sub-Chandrasekhar mass models, on the other hand, have a component of explosive helium burning which produces a different set, titanium, which is rich in the isotopes of calcium. Depending on the kind of dwarfs that come together, merging white dwarfs can give both. Therefore, searching for the $^{44}$Ti lines in the Tycho remnant is an important tool to probe the nature of the progenitor in this Type Ia SN. The COMPTEL three-year search for the $^{44}$Ti signals of galactic sources gave an upper limit (2$\sigma$) of $2 \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$ (Dupraz et al. 1997; Iyudin et al. 1999). Early INTEGRAL/IBIS observations of the $^{44}$Ti hard X-ray lines also implied an upper limit (3$\sigma$) of $1.5 \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$ (Renaud et al. 2006b). In this work, we will report our detections of the hard X-ray emission up to 100 keV and search for $^{44}$Ti emission lines in the Tycho remnant with INTEGRAL observations.

2. INTEGRAL OBSERVATIONS AND DATA ANALYSIS

INTEGRAL is ESA’s currently operational space-based hard X-ray/soft gamma-ray telescope covering a wide energy range of 3 keV–8 MeV (Winkler et al. 2003). In this work, we used two main instruments on board INTEGRAL, the imager IBIS (Ubertini et al. 2003) and X-ray monitors JEM-X (Lund et al. 2003). The hard X-ray data are mainly collected with the low-energy array called IBIS-ISGRI (INTEGRAL Soft Gamma-Ray Imager), which consists of a pixelated 128×128 CdTe solid-state detector that views the sky through a coded aperture mask (Lebrun et al. 2003). IBIS/ISGRI has a 12' (FWHM) angular resolution and arcmin source location accuracy in the energy band of 15–200 keV. JEM-X as the small X-ray detector collects the lower energy photons from 3–35 keV, which is used to constrain the lower hard X-ray band spectral properties of the Tycho SNR.

The Tycho SNR is frequently observed during the INTEGRAL surveys of the Cassiopeia region. We use the available archival data from the INTEGRAL Science Data Center (ISDC) where the Tycho SNR was within ~12 degrees of the pointing direction of INTEGRAL/IBIS observations. The total on-source time obtained in our analysis is about 4.9 Ms after excluding the bad data due to solar flares and the INTEGRAL orbital phase near the radiation belt of the Earth. The analysis was done with the standard INTEGRAL off-line scientific analysis (OSA; Goldwurm et al. 2003) software, version 10. Individual pointings in all collected IBIS data processed with OSA 10 were mosaiiced to create the sky images for the source detection in the energy ranges of 20–60 keV and 60–90 keV. The Tycho SNR was detected by IBIS with significance levels of $11.6\sigma$ and $5.0\sigma$ in two energy ranges, respectively (see middle and right panels in Figure 1). JEM-X imagers have a much smaller field of view (requiring an observing off-axis angle <5') and a relatively low sensitivity because of the small detector area; the total on-source time for the Tycho SNR is about 460 ks. The mosaic map around Tycho detected by JEM-X is also shown in Figure 1 (left panel). The detection significance level is about $9.8\sigma$ in the range of 3–10 keV.

The spectral extraction processes for IBIS and JEM-X are carried out individually. The Tycho remnant is about 8' in diameter in the sky. This size is smaller than the angular resolution of IBIS-ISGRI (12'), but larger than the angular resolution of JEM-X (3'). For IBIS, the spectral extraction was done using the software script ibis_science_analysis up to the SPE level with the input source catalog. Above ~90 keV, only upper limits can be given by the ISGRI detector. For the spectral analysis of the Tycho SNR using JEM-X, we made use of the mosaic_spec script to extract the spectrum from 3–35 keV by assuming a source size of ~8'. The spectral data points are directly derived from the mosaic images of JEM-X in four energy bands: 3–6 keV, 6–10 keV, 10–16 keV, and 16–35 keV.
3. HARD X-RAY SPECTRAL CHARACTERISTICS OF THE TYCHO SNR

We first derived the hard X-ray spectrum of the Tycho remnant obtained by IBIS, which has a very long exposure on the source. In Figure 2, we present the spectra of Tycho from 18 to 150 keV in two time intervals when IBIS carried out deep observations on the source, one in 2005 and the other from 2010 to 2011. Both spectra are fitted with a simple power-law model. There exists a feature around 60–90 keV in both spectra. These features may be attributed to the 44Ti line signal. To probe the bump feature near 60–90 keV in detail, we re-extracted the IBIS hard X-ray spectra from 18–200 keV using all available data with smaller energy bins from 30–90 keV. The lower energy band data points can be used to constrain the continuum better, so that the JEM-X spectrum of Tycho is extracted for analysis together in the following.

The extracted hard X-ray spectra from 3–35 keV from JEM-X and 18–200 keV from IBIS for the Tycho SNR are displayed together in Figure 3. The spectrum from 3–200 keV is initially fitted with a thermal bremsstrahlung of $kT \sim 0.92 \pm 0.48$ keV plus a power-law model of $\Gamma \sim 3.02 \pm 0.14$, reduced $\chi^2 = 1.251$ (22 d.o.f.). The derived hard X-ray non-thermal emission spectral property is still consistent with the Suzaku observations from 13–28 keV (Tamagawa et al. 2009). The derived continuum flux from 3 to 100 keV is about $8.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, corresponding to a hard X-ray luminosity of $\sim 2 \times 10^{35} d_{16}^2$ erg s$^{-1}$.

However, there is still some excess around 60–90 keV in the residuals from this continuum’s best-fit model, which might be attributed to the 44Ti line emission. Thus we re-fit the spectra from 3 to 200 keV with a continuum model (a thermal bremsstrahlung and a power law) plus two Gaussian lines. The line positions in the fitting is fixed to be at 67.9 and 78.4 keV, and the line width is set to be zero due to the low spectral resolution of IBIS/ISGRI around 70 keV ($\sim 8\%$). In addition, to improve the statistical significance of hard X-ray line detection, we also fix the line flux ratio during the fitting: $F_{h} = 0.93 F_{78}$. Then we derive $kT \sim 0.81 \pm 0.45$ keV, and the photon index of $\Gamma \sim 3.01 \pm 0.16$ with the mean line flux of $F_{78} \sim (1.3 \pm 0.5) \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$ (reduced $\chi^2 = 0.422/21$ d.o.f.). The significance of the detection is still low ($\sim 2.6\sigma$) with the present measurements so that we also give a $3\sigma$ upper limit of $1.5 \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$ on the 44Ti line emission in Tycho. This marginal detection of the 44Ti signal in this Type Ia SNR is interesting and will help us to probe the progenitor of this remnant.

(A color version of this figure is available in the online journal.)
4. DISCUSSION

4.1. $^{44}$Ti Amount in Tycho Remnant

The creation of $^{44}$Ti in an SN requires the presence of a large mass fraction of helium heated briefly to temperatures in excess of about 2 billion K. These conditions exist either when material in nuclear statistical equilibrium is rapidly quenched at such a low density that the helium fails to fully reassemble into iron-group elements, the so-called alpha-rich freeze out (Woosley et al. 1973), or when a detonation wave passes through a helium-rich composition at typical white dwarf densities. The alpha-rich freeze out can happen either in a massive star, where it occurs in the deepest layers to be ejected (Timmes et al. 1996), or in the carbon-rich layers of a Type Ia SN (Iwamoto et al. 1999; Maeda et al. 2010; Seitenzahl et al. 2013). In the latter case, the synthesis of $^{44}$Ti is relatively small due to the high density during the freeze-out. Helium detonation occurs only in Type Ia SNe and there the production of $^{44}$Ti can sometimes be very substantial (Woosley & Weaver 1994; Timmes et al. 1996).

These general considerations translate into typical $^{44}$Ti yields for current models of Type Ia SNe. For Type Ia SNe resulting from carbon deflagration and detonation in white dwarfs near the Chandrasekhar mass, the yield is quite low, typically $(0.2-1.6) \times 10^{-5} M_\odot$ based on the multi-dimensional simulations (Maeda et al. 2010; Seitenzahl et al. 2013), with the lower values more typical of the most recent three-dimensional (3D) models. Sub-Chandrasekhar mass models for Type Ia SNe, on the other hand, are prolific sources of $^{44}$Ti and it has long been thought that the production of the nucleus $^{44}$Ca in nature occurs chiefly in this kind of explosion (Timmes et al. 1996). These models are characterized by a shell of helium of about 0.05–0.2 $M_\odot$ atop a carbon-oxygen dwarf of 0.7 to 1.0 $M_\odot$. The detonation of the helium induces a secondary detonation of the carbon and the entire white dwarf explodes, leaving no remnant. Recent calculations (Woosley & Kasen 2011) of this sort of model give $^{44}$Ti yields in the range $(5-500) \times 10^{-5} M_\odot$. While we can find no published nucleosynthesis studies, we also expect that merging white dwarfs in which one of the components is a helium white dwarf would give similarly high yields provided that some portion of the helium detonates (Dan et al. 2012).

Using the observed line flux, the $^{44}$Ti yield synthesized in the SN can be estimated:

$$M_{^{44}Ti} \approx 4\pi d^2 44m_p \tau \exp(t/\tau) F_{44Ti},$$

where $d$ is the distance of the Tycho remnant, $m_p$ the proton mass, $\tau$ the characteristic time of the $^{44}$Ti decay chain, $t$ the time since the explosion, and $F_{44Ti}$ the flux of the $^{44}$Ti emission line. As discussed in the introduction, we take the most likely distance distribution of the Tycho SN remnant to be 1.7–5.0 kpc in this work.

An upper limit of the $^{44}$Ti line flux in Tycho is derived to be $1.5 \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$ (3$\sigma$). Figure 4 shows the $^{44}$Ti yield upper limit (the solid line) we have observed in the Tycho remnant plotted against the uncertain distance to the remnant according to Equation (1). The region between the two red arrows is the estimated $^{44}$Ti yield limit for distances in the most probable range, 1.7–5.0 kpc, based on the measured $^{44}$Ti line flux upper limit at 68 and 78 keV in Tycho. The estimated $^{44}$Ti yield ranges according to the simulation results of both the standard Chandrasekhar mass models and sub-Chandrasekhar mass models are also plotted. The present observed upper limit of the $^{44}$Ti yield in Tycho is still consistent with both explosion models for the Type Ia SNe.

Based on the diffusive shock acceleration (DSA) theory we discuss the acceleration ability of the Tycho SNR shock using the hard X-ray observation up to 100 keV, which probes the cutoff of the electron spectrum. The acceleration of electrons suffers from radiative energy loss. The maximum synchrotron photon energy where the electron acceleration and synchrotron cooling times are equal is $h\nu_{cutoff} \sim 0.15(\xi(E_{\text{max}}))^{-1} v_8^2$ keV (e.g., Katz & Waxman 2008), where $\xi(E) \geq 1$ is the ratio of the diffusion coefficient to the Bohm diffusion coefficient and could be energy dependent, and $v_8$ is the SNR shock velocity in units of $10^8$ cm s$^{-1}$. The measurements of the proper motion of ejecta in the Tycho SNR usually give an expansion velocity of $v \sim 5000$ km s$^{-1}$ (Hayato et al. 2010; Katsuda et al. 2010), so the synchrotron cutoff is $\sim 4\xi^{-1}$ keV, while the detected 100 keV emission in Tycho is well above this. Recently Zirakashvili & Aharonian (2007, 2010) investigated the spectral shape of the shock-accelerated electrons subject to synchrotron cooling in the context of DSA theory. They provided useful approximations for the subsequent synchrotron spectral shape, which is a slow function rather than a sharp cutoff. Using their approximation (Equation (37) in Zirakashvili & Aharonian 2007), in order for the 3–100 keV emission to be statistically compatible with a power law with a photon index of $\sim 3$, the cutoff should be $\sim 3$ keV$^4$. Therefore, the highest energy electrons are accelerated close to the Bohm limit, $\xi(E_{\text{max}}) \sim 1.3(\nu/5000$ km s$^{-1}(h\nu_{cutoff}/3$ keV)$^{-1}$, consistent with the fact that the approximation used is derived for the Bohm diffusion regime.

The postshock magnetic field can be constrained with the multi-band synchrotron spectrum. If the accelerated electron distribution follows a single power law, the downstream electron distribution is a broken power law, with a cooling break in the

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4 The cutoff energy in Equation (37) of Zirakashvili & Aharonian (2007) is not exactly the same as $h\nu_{cutoff}$ here but different by about 20%. However, given the uncertainty in the DSA theory and for the purpose of order of magnitude estimate, we neglect the difference.

Figure 4. Derived $^{44}$Ti yield upper limit in Tycho as a function of distance. The red solid line represents the upper limit function $a\sigma$ upper limit of $1.5 \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$ of the $^{44}$Ti yield. The figure also displays the calculated $^{44}$Ti yield ranges from the 2D and 3D simulation results of standard Chandrasekhar mass models (about 1.4 $M_\odot$; Maeda et al. 2010; Seitenzahl et al. 2013) and sub-Chandrasekhar mass models (Woosley & Kasen 2011) of Type Ia supernovae. (A color version of this figure is available in the online journal.)

4.2. Non-thermal Hard X-Ray Emission Up To 100 keV

4 The cutoff energy in Equation (37) of Zirakashvili & Aharonian (2007) is not exactly the same as $h\nu_{cutoff}$ here but different by about 20%. However, given the uncertainty in the DSA theory and for the purpose of order of magnitude estimate, we neglect the difference.
synchrotron spectrum corresponding to where the synchrotron cooling time is equal to the SNR age, $h v_{\text{cool}} \approx 3B^{-2}k_{\text{yr}}^{-2}$ eV (e.g., Katz & Waxman 2008). At this break the synchrotron spectral index steepens by half. Given the normalization and spectral index of radio emission from Tycho (Kothes et al. 2006), the cooling break occurs around $\sim$10 eV in order for the extrapolated flux to match the observed X-ray flux of Suzaku and INTEGRAL (see also Figure 10 in Morlino & Caprioli 2012). Given $h v_{\text{cool}} \sim 10$ eV and $t \approx 440$ yr, the postshock magnetic field is then derived to be $B \approx 120(h v_{\text{cool}}/10 \text{ eV})^{-1/3} \mu \text{G}$, insensitive to $v_{\text{cool}}$- and comparable to that derived from the observation of the X-ray rim (e.g., Warren et al. 2005)\(^5\).

The acceleration of nuclei suffers mainly from the limited SNR age, thus the maximum nuclear energy is $E_{\text{max}} \approx 60Z\xi(E_{\text{max}})^{-1}B^{-4}v_{\text{h}yr}^{-2}$ TeV (e.g., Katz & Waxman 2008), where $Z$ is the nuclear charge number. Using the above constraints of $B$ and $\xi(E_{\text{max}})$ from observations, the maximum CR energy can be expressed as

$$E_{\text{max}} \approx 640Z\frac{\xi(E_{\text{max}})}{\xi(E_{\text{max}})} \left(\frac{hv_{\text{cutoff}}}{3 \text{ keV}}\right) \left(\frac{hv_{\text{cool}}}{10 \text{ eV}}\right)^{-1/3} \text{ TeV}, \quad (2)$$

with the only unknown parameter $\xi(E_{\text{max}})/\xi(E_{\text{max}})$. With the constraint of $B$ the 100 keV emitting electrons have high energy of $E > 200$ TeV, not far from the above value. The fact that the 3–100 keV spectrum is compatible with the Bohm diffusion regime suggests $\xi(200 \text{ TeV}) \sim 1$. Since $\xi$ may not vary sensitively with particle energy, we have $\xi(E_{\text{max}}) \sim 1$ and $\xi(E_{\text{max}})/\xi(E_{\text{max}}) \sim 1$, although $\xi(E_{\text{max}})/\xi(E_{\text{max}}) \ll 1$ could not be ruled out. There are hints from measurements of the expansion rate that Tycho is currently transiting into the Sedov–Taylor phase (e.g., Katsuda et al. 2010). During the transition SNRs are expected to produce the highest energy CRs in their whole lives. In summary, Tycho may not accelerate protons up to the PeV scale; however, it is possible that light nuclei with $Z \gtrsim 1$ may be accelerated to the PeV scale, but impossible to be far above PeV. A similar conclusion has been reached by, e.g., Bell (2013) using a specific model.

5. CONCLUSION

This work studied the hard X-ray properties of the Tycho SNR using INTEGRAL deep observations from 2003–2011. We detected Tycho up to 90 keV for the first time. The X-ray spectrum from 3–100 keV can be described by a thermal bremsstrahlung of $kT \sim 0.8$ keV and a power-law model of $\Gamma \sim 3$. A bump feature around 60–90 keV is found in the spectrum which is possibly the signal of $^{44}\text{Ti}$ emission lines at 68 and 78 keV. The Gaussian line profile is used to fit the two lines, and we find the marginal detection of the $^{44}\text{Ti}$ lines at a significance level of $\sim 2.6\sigma$. Thus we find a 3$\sigma$ upper limit of $1.5 \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$ for the $^{44}\text{Ti}$ lines.

The detected non-thermal emission up to $\sim$90 keV in the Tycho SNR also suggests that the remnant could accelerate protons to at least $\sim$200 TeV, but not up to the PeV scale. The light nuclei with $Z \gtrsim 1$ may be accelerated to the PeV scale, around the CR spectral “knee” region. This implies that the composition of CRs at the “knee” is not dominated by protons but by light nuclei, if normal SNRs are the origins of CRs at the “knee.”

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5 Note that by a similar argument Morlino & Caprioli (2012) derived an even somewhat higher magnetic field of 200 $\mu$G, leading to higher cosmic ray energy $E_{\text{max}}$.