NON THERMAL X-RAYS FROM SUPERNOVA REMNANT G330.2+1.0 AND THE CHARACTERISTICS OF ITS CENTRAL COMPACT OBJECT

SANGWOOK PARK, OLEG KARGALTSEV, GEORGE G. PAVLOV, KOJI MOTO, PATRICK O. SLANE, JOHN P. HUGHES, DAVID N. BURROWS, AND GORDON P. GARMIRE

1 Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802, USA; park@astro.psu.edu
2 Department of Astronomy, University of Florida, Gainesville, FL 32611-2055, USA
3 Department of Applied Physics, University of Miyazaki, 1-1 Gakuen Kibana-dai Nishi, Miyazaki, 889-2192, Japan
4 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
5 Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854-8019, USA

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ABSTRACT

We present results from our X-ray data analysis of the supernova remnant (SNR) G330.2+1.0 and its central compact object (CCO), CXOU J160103.1–513353 (J1601 hereafter). Using our XMM-Newton and Chandra observations, we find that the X-ray spectrum of J1601 can be described by neutron star atmosphere models (T \sim 2.5–5.5 MK). Assuming the distance of d \sim 5 kpc for J1601 as estimated for SNR G330.2+1.0, a small emission region of R \sim 0.4–2.0 km is implied. X-ray pulsations previously suggested by Chandra are not confirmed by the XMM-Newton data, and are likely not real. However, our timing analysis of the XMM-Newton data is limited by poor photon statistics, and thus pulsations with a relatively low amplitude (i.e., an intrinsic pulsed fraction less than 40%) cannot be ruled out. Our results indicate that J1601 is a CCO similar to that in the Cassiopeia A SNR. X-ray emission from SNR G330.2+1.0 is dominated by power-law continuum (Γ \sim 2.1–2.5) which primarily originates from thin filaments along the boundary shell. This X-ray spectrum implies synchrotron radiation from shock-accelerated electrons with an exponential rolloff frequency ν_{rolloff} \sim 2–3 \times 10^{17} Hz. For the measured widths of the X-ray filaments (D \sim 0.3 pc) and the estimated shock velocity (v_s \sim a few \times 10^3 km s^{-1}), a downstream magnetic field B \sim 10–50 μG is derived. The estimated maximum electron energy E_{max} \sim 27–38 TeV suggests that G330.2+1.0 is a candidate TeV γ-ray source. We detect faint thermal X-ray emission in G330.2+1.0. We estimate a low preshock density n_0 \sim 0.1 cm^{-3}, which suggests a dominant contribution from an inverse Compton mechanism (than the proton–proton collision) to the prospective γ-ray emission. Follow-up deep radio, X-ray, and γ-ray observations will be essential to reveal the details of the shock parameters and the nature of particle accelerations in this SNR.

Key words: ISM: individual (SNR G330.2+1.0) – stars: neutron – supernova remnants – X-rays: stars

1. INTRODUCTION

Since nonthermal X-ray synchrotron emission was discovered in portions of SN 1006’s blast wave shock (Koyama et al. 1995), several young supernova remnants (SNRs) now show such strong particle acceleration sites in the shock front. The detection of nonthermal X-ray emission in SNRs thus provides an excellent opportunity to study the generation of high-energy cosmic rays. Based on the archival ASCA data, Torii et al. (2006) discovered that the overall X-ray emission from the Galactic shell-type radio SNR G330.2+1.0 shows a featureless spectrum primarily from a power-law (PL) continuum (Γ \sim 2.8). G330.2+1.0 is thus one of the rare members of Galactic SNRs in which X-ray emission is dominated by nonthermal continuum from synchrotron radiation of shock-accelerated relativistic electrons: there are only three other Galactic SNRs showing such characteristics, G347.3–0.5 (aka RX J1713.7–3946, Slane et al. 1999), G266.2–1.2 (aka RX J0852.0–4622 or “Vela Jr.”; Slane et al. 2001), and G1.9+0.3 (Reynolds et al. 2008). Torii et al. (2006) noted the general anticorrelation between the X-ray and radio intensities in G330.2+1.0, which may suggest multiple populations and/or acceleration processes to produce spatially separated X-ray and radio emission. The ASCA study of G330.2+1.0 was, however, limited by the low photon statistics (∼2000 counts for the entire SNR) and poor angular resolution (∼3' FWHM).

We observed G330.2+1.0 with Chandra to perform a detailed imaging and spectral study of the SNR, which could not be performed with the low angular resolution detectors on board ASCA (Park et al. 2006). In our initial work on the Chandra data, we discovered a candidate neutron star (CXOU J160103.1–513353, J1601 hereafter) at the center of the SNR (Park et al. 2006). The featureless X-ray spectrum of J1601 is well described by a blackbody (BB) model with T \sim 5.7 MK. The high foreground column (N_H \sim 2.5 \times 10^{22} cm^{-2}) is consistent with that for SNR G330.2+1.0, supporting their spatial association. Assuming the distance d \sim 5 kpc to G330.2+1.0 as estimated by the H I absorption (McClure-Griffiths et al. 2001), a small area (\sim 0.4 km) for the BB region is implied. The observed X-ray luminosity is L_X \sim 1 \times 10^{33} erg s^{-1} in the 1–10 keV band. No counterpart is found in the optical, IR, and radio bands, and a large X-ray-to-optical flux ratio (f_X/10 keV/f_V > 9) is estimated. There is no evidence for long-term time variability in the 1–7 keV band up to \sim 10 hr timescales in the light curve of J1601. All these characteristics are typical for the peculiar manifestation of neutron stars found at the center of several SNRs, dubbed “central compact objects (CCOs)” (Pavlov et al. 2002). A particularly intriguing aspect of J1601 is its possible pulsations (Park et al. 2006). Because of the low photon statistics (∼600 counts) and the long frame time (3.24 s) of the Chandra data, the detection of the periodicity (P \sim 7.48 s) was not conclusive (∼2σ significance).

We have recently performed a follow-up observation of G330.2+1.0 and J1601 with XMM-Newton to compensate the low photon statistics and poor time resolution of the Chandra data. When combined with the high angular resolution Chandra...
data, the good time resolution and large collecting area of XMM-Newton can help reveal the detailed nature of the SNR and the CCO. We report here the results from our analysis of G330.2+1.0 and J1601 using our XMM-Newton and Chandra data. Unfortunately, the XMM-Newton data are significantly contaminated by flaring background. Nonetheless, using the available data (Chandra + XMM-Newton), we derive some fundamental properties of J1601 and G330.2+1.0. In Section 2, we describe the observations and the data reduction. X-ray spectral and timing analyses of J1601 are presented in Sections 3 and 4, respectively. We present the spectral analysis of G330.2+1.0 in Section 5. In Section 6, we discuss implications on the results from data analysis of the CCO and SNR. Finally, a summary and conclusions are presented in Section 7.

2. OBSERVATIONS AND DATA REDUCTION

We observed G330.2+1.0/J1601 with the European Photon Imaging Camera (EPIC) on board XMM-Newton Observatory on 2008-03-20 (ObsID 0500300101). The pointing (R.A.[J2000] = 16°01′31.4, decl.[J2000] = −51°33′53.6′′) is to J1601 which is positioned at the center of the nearby circular X-ray shell of SNR G330.2+1.0. We chose the small-window mode (4′4 × 4′3 field of view (FOV) and 6 ms time resolution) for the EPIC pn to search for pulsations of J1601. We chose the full-window mode (∼30′′ diameter FOV) for the EPIC MOS detectors to study the entire SNR. The medium filter was used for all detectors. We reduced the data using the Science Analysis System (SAS) software package version 7.1.0.

Our XMM-Newton observations of G330.2+1.0/J1601 were significantly contaminated by flaring particle background. We removed time bins in which the overall count rate is 2σ (the pn) or 3σ (the MOS1 and MOS2) above the mean value for time intervals unaffected by flaring background. Time intervals including a considerable contamination by the flaring background (∼50% above the average quiescent rate) were eliminated by these time-filters. After the time filtering, 26, 31, and 33 ks exposures for the pn, MOS1, and MOS2, respectively, are available for further data analysis, which is ∼40%–45% of the total exposure. We then reduced the data following the standard screening of event pattern (PATTERN ≤ 12 for the MOS1/2 and PATTERN ≤ 4 for the pn) and hot pixels (FLAG = 0). (For the timing analysis of J1601, we used a longer exposure while choosing a smaller aperture and more strict event pattern criteria as described in Section 4.) There are stable components of instrumental background in the EPIC detectors. The primary components that could affect this work are Al–K (E ∼ 1.5 keV) and Si–K (E ∼ 1.7 keV) fluorescence lines due to the interactions of high-energy particles with the structure surrounding the detectors and the detectors themselves. We removed these events from our image analysis by excluding narrow energy bands centered on these lines. Our background-subtracted source spectra show little evidence of these lines. Thus, we believe that the impact of contamination from this instrumental background on our EPIC data analysis is negligible.

Because of the severe contamination by the flaring background, photon statistics of the filtered XMM-Newton data are significantly lower than originally intended. Thus, in addition to the XMM-Newton data, we use the Chandra data (ObsID 6687) for the spectral analysis to improve overall photon statistics.

The high angular resolution of Chandra data is also essential to measure the widths of the thin X-ray filaments of G330.2+1.0. We performed the Chandra observation of G330.2+1.0 with the I-array of the Advanced CCD Imaging Spectrometer (ACIS) on 2006 MAY 22 as part of the Guaranteed Time Observations program. The effective exposure after the data screening is ∼50 ks, and thus photon statistics for the SNR and CCO in the ACIS data are similar to those obtained by the EPIC MOS1+MOS2 data. The details of the Chandra observation and data reduction are described by Park et al. (2006).

3. X-RAY SPECTRUM OF THE CENTRAL COMPACT OBJECT

We extracted the spectrum of J1601 (∼530, 290, and 310 counts in the 0.5–10 keV band for the pn, MOS1, and MOS2, respectively) from a circular region with a radius of 15′. The background spectrum was estimated from two nearby source-free regions with a radius of 30′. The background counts contribute ∼15% to the pn spectrum and ∼9% to the MOS spectra. The background-subtracted, deadtime-corrected count rates (in the 15′ radius aperture) are ∼0.025 (pn) and ∼0.009 counts s−1 (MOS1/2). The Chandra spectrum of J1601 was extracted from a ∼2′′ circular region. The background spectrum was extracted from the surrounding annular region with the inner and outer radii of 4′ and 15′, respectively (Park et al. 2006). The background-subtracted ACIS count rate is ∼0.012 counts s−1. The total source counts combining all the XMM-Newton EPIC and Chandra ACIS data are ∼1700 counts, which is about 3 times higher than those used in the previous work. Each source spectrum was binned to contain a minimum of 20 counts per energy bin.

We simultaneously fit four spectra of J1601 obtained by the XMM-Newton pn, MOS1, MOS2, and the Chandra ACIS. Initially we fit the spectrum with a BB model. The best-fit BB temperature and the absorbing column (TBB = 5.6+0.3 −0.4 MK, NHI = 2.46+0.38 −0.25 × 1022 cm−2, χ2/ν = 73.4/74, errors are at 90% confidence level (CL), hereafter) are consistent with those by Park et al. (2006). The implied emitting area is small (R ∼ 0.44 ds km, where ds is the distance to the CCO in units of 5 kpc), which is also in agreement with the previous work. The observed flux (f = 1.22 × 10−13 erg cm−2 s−1 in the 1–10 keV band) is consistent with the previous Chandra results as well. Although a PL model may also fit the data, a very steep photon index (Γ = 5.6+0.5 −0.4) and a high NHI = (5.4 ± 0.6) × 1022 cm−2 (χ2/ν = 93.6/74) are implied (The PL fit is not acceptable with χ2/ν > 2, when NHI is fixed at (2.5–3.0) × 1022 cm−2). This PL shape is too soft for typical synchrotron emission from the neutron star’s magnetosphere, and the fit is statistically worse than that by the BB model. Thus, we conclude that X-ray emission of J1601 is consistent with a BB spectrum. Using only XMM-Newton data, we estimate the same flux (f1–10 keV ∼ 1.25 × 10−13 erg cm−2 s−1), which indicates that flux variations in the two years between the Chandra (2006 MAY 22) and XMM-Newton (2008 MARCH 20) observations are negligible (∼5%).

While the BB model can fit the overall X-ray spectrum of J1601, it may not be physically adequate to describe thermal emission from a neutron star. A neutron star is not a perfect BB, and likely has an atmosphere whose emission from the outermost H layer may dominate the observed spectrum (e.g., Pavlov & Zavlin 2000). The observed spectrum of the thermal radiation from a neutron star’s surface is substantially affected...
by the properties of its atmosphere such as chemical composition, magnetic field, gravity, and the energy-dependent opacities (Pavlov et al. 1995 and references therein). A typical observational effect may be a higher temperature and a smaller emitting area than the “true” values when the spectrum is fitted by a simple BB model (e.g., Zavlin et al. 1998; Pavlov et al. 2000). Therefore, taking advantage of the improved photon statistics in the XSPEC + Chandra data, we fit the observed X-ray spectrum of J1601 with a hydrogen neutron star atmosphere model (NSA model in XSPEC; Pavlov et al. 1995; Zavlin et al. 1996).

First, we fit the spectrum of J1601 with a single NSA model. The magnetic fields of CCOs may be significantly lower or higher than the “canonical” magnetic field of a pulsar, $B = 10^{12}$ G (e.g., Pavlov & Zavlin 2000; Biggami et al. 2003). Based on the lack of a strong absorption feature in the observed spectrum of J1601, which would be interpreted as an electron cyclotron line in an NSA spectrum, we can only exclude fields in the range of $\sim (2–8) \times 10^{11}$ G. We thus fit our spectrum using all three magnetic field values for which the NSA models are available in XSPEC: $B = 0$ (applicable for low fields, $B \lesssim 10^{10}$ G), $10^{12}$, and $10^{13}$ G. We fix the neutron star mass and radius at the canonical values $M_{\text{NS}} = 1.4 \ M_{\odot}$ and $R_{\text{NS}} = 10$ km, which correspond to the gravitational redshift parameter $g_{\text{r}} = (1 - 2GM_{\text{NS}}/R_{\text{NS}}c^2)^{1/2} = 0.766$, and vary the effective temperature, distance, and $N_{\text{H}}$. The fits are statistically acceptable for all three magnetic field values. For $B = 0$ and $10^{13}$ G, the redshifted best-fit effective temperatures, $T_{\text{BB}}^{\infty} = 8.2$ and 3.6 MK, respectively, are lower than the $T_{\text{BB}}$ while $T_{\text{BB}}^{\infty} = 5.7$ MK for $B = 10^{12}$ G is about the same as the BB temperature. The best-fit $N_{\text{H}}$ values, 3.1, 2.4, and $2.7 \times 10^{21}$ cm$^{-2}$, for $B = 0$, $10^{12}$, and $10^{13}$ G, respectively, are consistent with that for SNR G330.2+1.0 ($N_{\text{H}} \sim 2.5-3 \times 10^{21}$ cm$^{-2}$). The best-fit distances, 24, 169, and 55 kpc, for $B = 0$, $10^{12}$, and $10^{13}$ G, respectively, are unreasonably large for a Galactic object. To reconcile them with the distance to the SNR ($d \sim 5$ kpc; McClure-Griffiths et al. 2001), we have to assume that the sizes of the X-ray emitting areas are much smaller than $R_{\text{NS}} = 10$ km ($R \sim 2 - 0.3$, and $0.9$ km for $B = 0$, $10^{12}$, and $10^{13}$ G, respectively). Thus, although the fits with the $B = 0$ and $10^{13}$ G NSA models yield lower temperature and larger sizes than the BB fit, the observed emission cannot be interpreted as emitted from the entire neutron star surface.

Based on these results, it is natural to assume that the X-ray emission in J1601 originates from small hot spots on the neutron star’s surface, such as suggested for other CCOs (e.g., the CCO in Cassiopeia A; Pavlov et al. 2000). In this scenario, the observed thermal X-ray emission consists of two characteristic components: the hot component from a small region(s) and the cool emission from the rest of the stellar surface (e.g., Pavlov et al. 2000). Therefore, we fit the observed spectrum of J1601 with two-component NSA models, assuming $B = 0$, $10^{12}$, or $10^{13}$ G, the same for both components. For the soft component, we fix the distance to the CCO and the size of the emitting region at $d = 5$ kpc and $R = 10$ km, respectively, while varying the surface temperature. For the hard component, both the distance and surface temperature are varied. The foreground column $N_{\text{H}}$ is tied common for both components, and then is fitted. The results are summarized in Table 1. The X-ray spectrum of J1601 and the best-fit two-component NSA model with a high magnetic field ($B = 10^{13}$ G) are presented in Figure 1. We note that, although the additional soft component is statistically not required, implying only an upper limit on the observed flux (e.g., $f_{1–10 \text{keV}} < 5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at 90% CL), the two-component model likely represents a physically more realistic picture than the one-component model to account for the small hot region implied by the single NSA model. Therefore, we hereafter discuss the spectral nature of J1601 based on the two-component NSA model fits.

### Table 1

| $B$ (10$^{12}$ G) | $N_{\text{H}}$ (10$^{21}$ cm$^{-2}$) | $T_{\text{BB}}^{\infty}$ (10$^6$ K) | $R_{\text{BB}}$ (d, km) | $f_{1–10 \text{keV}}$ (10$^{-12}$ erg cm$^{-2}$ s$^{-1}$) | $L_{1–10 \text{keV}}$ (10$^{34}$ d$^2$ erg s$^{-1}$) | $\chi^2$/d.o.f. |
|------------------|-------------------|-----------------|-------------------|-----------------|-----------------|----------------|
| 0                | 3.1(0.35)         | <1.4            | 2.5(0.3)          | 2.1(0.6)        | 1.23 ± 0.06     | 1.5             | 80.5/78       |
| 1                | 3.4(0.20)         | <1.5            | 5.5(0.4)          | 0.4(0.1)        | 1.21 ± 0.06     | 1.9             | 79.9/78       |
| 10               | 3.2(0.53)         | <1.5            | 3.7(0.4)          | 0.9(0.3)        | 1.21 ± 0.06     | 1.8             | 79.7/78       |

Notes. Errors are at 90% confidence. $M_{\text{NS}}$ and $R_{\text{NS}}$ are fixed at 1.4 $M_{\odot}$ and 10 km, respectively.

* $T_{\text{BB}}^{\infty}$ and $R_{\text{BB}}^{\infty}$ are effective temperatures of the cool neutron star surface and the hot small region, respectively, as measured by a distant observer where $T_{\text{BB}} = g_{\text{r}} T$ and $g_{\text{r}} = (1 - 2GM_{\text{NS}}/R_{\text{NS}}c^2)^{1/2}$.

* The radius of the hot region scaled by $d = 5$ kpc.

* The observed flux in the 1–10 keV band. Assuming a Poisson distribution of the observed photon statistics, 2σ statistical errors are quoted.

4. SEARCH FOR PULSATIONS FROM THE CENTRAL COMPACT OBJECT

Park et al. (2006) searched for X-ray pulsations from J1601 in the 50 ks Chandra ACIS observation (3.24 s time resolution) and reported a marginally significant (at a $\approx 2\sigma$ level) periodic signal ($P = 7.48$ s, a pulsed fraction $f_p \sim 30\%$). One of the goals of our follow-up XMM-Newton observation was to test the significance of the previously reported period candidate, and to search for periodicity outside the frequency range accessible with Chandra data (the EPIC pn in the small-window mode provides much better 6 ms resolution). However, as discussed in Section 2, the flaring background hampered our timing analysis of the EPIC pn data. For the timing analysis, we performed the data reduction following the methods described in Section 2, except

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The higher $T_{\text{BB}}$ and the correspondingly larger distance in the $B = 10^{12}$ G NSA fit are caused by the fact that the high-energy part of the observed spectrum coincides with the low-energy wing of the gravitationally redshifted electron cyclotron feature, centered at $\approx 9$ keV. Therefore, the high-energy tail of the X-ray spectrum is much softer than those in the models with very low or very high magnetic fields. Although we cannot exclude this field value based on the observational data available, we note that the models with slightly lower fields ($B \sim 2–8 \times 10^{12}$ G) would not fit the data, while the models with higher fields (e.g., $B \gtrsim 2 \times 10^{12}$ G) would yield essentially the same results as the $B = 10^{13}$ G model.
data is only marginal (2σ) hence the pulsation frequency is known) for the peak in the pn data. Allowing for a nonzero period derivation typical for anomalous X-ray pulsars (AXPs), we calculate $Z_0^2$ on two-dimensional grid: $f = 5 \times 10^{-5}$–0.15 Hz and $\dot{P} = 0 - 3 \times 10^{-13}$ s$^{-1}$. The maximum value of $Z_0^2$ is 29.9 at $f = 0.1336615$ Hz and $\dot{P} = 5 \times 10^{-14}$ s$^{-1}$. Although the frequency corresponding to the maximum $Z_0^2$ is consistent with that of the peak found in the Chandra data alone, the significance of the peak found in the joint data is very low. Thus, we conclude that the tentative 7.48 s periodicity reported with Chandra is not confirmed by the XMM-Newton data.

5. SPECTRAL ANALYSIS OF THE SUPERNOVA REMNANT

**XMM-Newton** images of SNR G330.2+1.0 are presented in Figure 2. Since the small-window mode was used for the pn, the SNR is detected only on the MOS detectors. The Chandra image has revealed that G330.2+1.0 is a shell-type SNR with enhanced emission in the thin southwestern (SW) and northeastern (NE) parts of the shell (Park et al. 2006). Our XMM-Newton images confirm this general morphology. We further reveal spectral variations across the SNR: i.e., the eastern (E) region of the shell is softer than other regions (Figure 3). Also, there is a faint hard extended feature at $\sim 2'$ southwest from the CCO (marked with an arrow in Figures 2 and 3). These features were not clearly seen in the Chandra data because of their positions in the ACIS-I chip gaps.

We extracted the spectra from bright portions of the SNR shell in southwest and northeast (Figure 4). The SW spectrum was extracted from the $\sim 1'$ x $3'$ brightest filament in the SW shell, which contains $\sim 1700$ counts ($\sim 25$% of them are background) for the MOS1+MOS2 data. This SW shell contains $\sim 1300$ counts (including $\sim 13$% background) for the ACIS-I data. The NE spectrum was extracted from a circular region ($\sim 30''$ in radius) in the NE parts of the shell. This region contains $\sim 570$ counts ($\sim 30$% of them are background) and $\sim 540$ counts (including $\sim 30$% background) for the MOS1+MOS2 and the ACIS-I, respectively. We used the 0.5–10 keV band spectrum for the spectral analysis, and the source spectra were binned to contain a minimum of 20 counts per energy bin.

Because of the nonuniform particle background across the MOS detectors, the background spectrum for the XMM-Newton data was carefully selected for faint extended sources. We chose a few background regions close to the source regions while avoiding any detected (by Chandra) point sources. We find generally consistent results between the background subtracted XMM-Newton spectra and the Chandra data. Thus, we believe that our background estimates for the XMM-Newton data are acceptable.

The X-ray spectra of G330.2+1.0 extracted from the SW and NE regions are shown in Figure 5. Our Chandra and XMM-Newton data show featureless continuum-dominated spectra for the bright SW and NE filaments. For each region, we performed a simultaneous PL model fit for all the three spectra obtained by the MOS1, MOS2, and ACIS-I (Figure 5). The best-fit parameters are presented in Table 2. The high absorbing column for the SNR shell is consistent with that for the CCO J1601, supporting the SNR–CCO association. The PL photon indices are typical for synchrotron emission from highly accelerated relativistic electrons. Thus, we fit these SW and NE shell spectra with the SRCUT model, which describes X-ray synchrotron emission from the shock-accelerated electrons that are also responsible for the observed radio counterpart (Reynolds 1998; Reynolds & Keohane 1999). We assume the radio spectral-index $\alpha = 0.3$ (where $S_\nu \propto \nu^{-\alpha}$) as measured from the entire SNR.
Figure 2. *XMM-Newton* images (MOS1+MOS2) of G330.2+1.0: (a) the soft band (1–2 keV), and (b) the hard band (2–8 keV). In (a), the 1.4–1.6 and 1.7–1.8 keV bands are excluded to remove the bright instrumental lines at $E \sim 1.5$ (Al K) and 1.74 (Si K) keV. Images are exposure corrected, and darker grayscales correspond to higher intensities. For the purposes of display, the images have been binned into $\sim 5''$ pixels, and then adaptively smoothed to achieve a minimum S/N = 7. J1601 is marked with a cross at the center of the SNR. Image contours of the broadband (1–8 keV) image are overlaid in each panel. In (b), the hard feature seen in Figure 3 is marked with an arrow.

Figure 3. 2–8 keV to 1–2 keV hardness ratio map of G330.2+1.0 as obtained by the *XMM-Newton* EPIC MOS1+MOS2. In the soft band (1–2 keV) map, the 1.4–1.6 and 1.7–1.8 keV bands are excluded to remove the bright instrumental lines at $E \sim 1.5$ and 1.74 keV. For the purposes of display, each image has been binned into $15'' \times 15''$ pixels, and is adaptively smoothed to achieve a minimum S/N = 4. Green image contours are the 1–8 keV image of the SNR as shown in Figure 2. Red contours are the 843 MHz radio image taken from the MOST SNR catalog (Whiteoak & Green 1996). The angular resolution of the radio image is 43''. The position of the CCO J1601 is marked with a cross. The hard feature in the SW of the CCO is marked with a white arrow.

(Green 2001). The results of the SRCUT model fits are presented in Table 3.

The spectrally hard, extended emission feature at $\sim 2'$ SW of the CCO is faint: we obtain $\sim 490$ counts from this feature (MOS1+MOS1) in which $\sim 60\%$ of the photons are the background. There is no evidence for line features, and the X-ray spectrum may be fitted by a PL of $\Gamma \sim 2$ with $N_{\text{H}}$ fixed at $2.6 \times 10^{22}$ cm$^{-2}$. This overall spectral shape, the filamentary morphology and size (about a few $d_5$ pc), and the proximity to J1601 raise an intriguing possibility that this feature might be related to the CCO (e.g., the pulsar wind nebula). Alternatively, it could be a part of the SNR shell. However, reliable spectral modeling of this faint feature is difficult because of the poor photon statistics. Thus, we do not attempt any further analysis or discussion on this feature. Follow-up deep X-ray observations are required to reveal the origin of this potentially intriguing feature.
Table 2
Best-Fit Power-Law Model Parameters for SNR G330.2+1.0

| Region | $N_{\text{H}}$ $(10^{22} \text{ cm}^{-2})$ | $\Gamma$ | $kT$ (keV) | $n_e$ $(10^{11} \text{ cm}^{-3})$ | EM $(10^{64} \text{ cm}^{-3})$ | $\chi^2/\nu$ |
|--------|------------------------------------|---------|-----------|-------------------------------|-----------------|-------------|
| SW     | 2.60$^{+0.40}_{-0.34}$             | 2.13    | 2.13$^{+0.24}_{-0.22}$ | $\cdots$ | $\cdots$ | 163.9/137  |
| NE     | 3.04$^{+0.63}_{-0.51}$             | 2.52    | 2.52$^{+0.40}_{-0.34}$ | $\cdots$ | $\cdots$ | 51.9/51    |
| E      | 2.45$^{+0.57}_{-0.52}$             | 2.3     | 0.70$^{+1.54}_{-0.32}$ | $\cdots$ | $\cdots$ | $\cdots$   |

Notes. Errors are at 90% confidence. For region E, parameters from the best-fit two-component model (plane-shock + power law, where $\Gamma = 2.3$ is fixed) are presented.

Figure 4. Broadband (1–8 keV) grayscale image of G330.2+1.0 obtained by XMM-Newton EPIC MOS1+MOS2. The image has been processed in the same way as those in Figure 2. SW, NE, and E regions of the SNR shell are marked with solid lines. Background regions are marked with dashed circles.

On the other hand, the E parts of the SNR shell are spectrally softer than other regions (Figures 2 and 3). The E region spectrum is extracted from an $\sim 1'3 \times 2'$ region in the E parts of the shell (Figures 4 and 6). This region contains $\sim 730$ counts ($\sim 45\%$ of them are background) for the MOS1+MOS2 data. Since the central part of this region falls in the ACIS-I chip gap, we use only the XMM-Newton data for the spectral analysis. The best-fit PL photon index for region E is significantly steeper ($\Gamma \sim 4–5$, $\chi^2/\nu \sim 1.3–1.4$, depending on the assumed $N_{\text{H}}$) than those for the SW and NE regions. In fact, the PL of $\Gamma = 2.3$ (as an average for SW and NE shell) cannot fit the observed spectrum of region E ($\chi^2/\nu \sim 1.8–3.2$, depending on assumed $N_{\text{H}}$) because of a soft excess emission at $E \lesssim 2$ keV. This suggests the presence of soft thermal emission in the E part of the shell. Thus, we fit the region E spectrum with a plane-shock (PSHOCK) model (Borkowski et al. 2001). Since the photon statistics are poor for this faint feature, we fixed the metal abundances at the solar values (Anders & Grevesse 1989). Initially we fit the observed spectrum with a single PSHOCK model, assuming that X-ray emission in region E is entirely thermal in origin. Then, we used a two-component model (PSHOCK + PL) assuming that there is underlying nonthermal emission as seen in the SW and NE filaments. Results from these two model fits are statistically indistinguishable ($\chi^2/\nu \sim 1.2$ for either model fit). The main difference is that the best-fit electron temperature ($kT = 1.4^{+0.9}_{-0.6}$ keV) for the single PSHOCK model appears to be somewhat higher than that for the PSHOCK + PL model ($kT = 0.7^{+1.3}_{-0.3}$ keV). The best-fit volume emission measure (EM) for

Figure 5. X-ray spectrum from the shell of G330.2+1.0. (a) The SW and (b) the NE shell. The best-fit PL model for each regional spectrum is overlaid. The lower panels are the residuals from the best-fit model.
the two-component model is higher by a factor of \( \sim 2 \) than that for the single PSHOCK model. Since the uncertainties of these measurements are large because of poor photon statistics, it is difficult to discriminate these modeled parameters. Thus, we assume plausible ranges of the best-fit electron temperature and emission measure in the following discussion, based on the estimated temperature of a young neutron star, and that the estimated emitting area is too small to be a neutron star. It was also noted by Park et al. (2006) that the suggested candidate pulsations with a long period, if confirmed, would have been typical for an AXPs.

Our results from the XMM-Newton and Chandra data analysis indicate that the hot component emission \( (T^\infty < 2.5-5.5 \text{ MK}) \), depending on the assumed \( B \) must originate from a small region of \( R_h \sim 0.4-2 \, d_S \) km. The estimated size of the hot region varies depending on the assumed values of the magnetic field and the distance to the CCO. Nonetheless, within the ranges of parameters that we consider in this work (\( B = 0, 10^{12}, \text{ or } 10^{13} \text{ G} \), and \( d = 5-10 \text{ kpc} \)), the size of the hot region is significantly smaller than the canonical size of the neutron star; i.e., the largest area could be \( R_h \sim 4 \text{ km} \), where \( B = 0 \) and \( d \sim 10 \text{ kpc} \). A small hot region(s) has been suggested in other CCOs, probably indicating X-ray emission from a locally heated region such as the hot polar cap (e.g., Pavlov et al. 2000). On the other hand, the estimated surface temperature of the neutron star is significantly lower \( (T^\infty < 1.5 \text{ MK}) \) than that of the hot region. According to the standard cooling curves of a neutron star (e.g., Tsuruta 1998; Yakovlev & Pethick 2004), this temperature limit corresponds to a lower limit of several \( 10^5-10^6 \text{ yr} \) for the neutron star’s age. This neutron star age is in plausible agreement with the estimated age of SNR G330.2+1.0 (see Sections 6.2 and 6.3, and Torii et al. 2006). The overall characteristics such as the low \( T^\infty \), the high \( T^\infty \), and the small \( R_h \) are consistent with those found in the prototype CCOs in Galactic SNRs such as Cas A and Vela Jr. (Pavlov et al. 2000; Pavlov et al. 2001).

Since the X-ray flux from the small hot region contributes a significant fraction of the observed flux (greater than 50% of the total flux in the 1–10 keV band), the observed X-ray emission from J1601 may be expected to pulsate. However, our XMM-Newton data do not show any conclusive evidence for pulsations, indicating that the previously suggested pulsations are unlikely real. We note that the low photon statistics in the EPIC-pn data are not sufficient to detect pulsations with an intrinsic pulsed-fraction \( f_p \sim 40\% \). With the combined Chandra and XMM-Newton data, the detection of pulsations with \( f_p \sim 25\% \) is not feasible. Thus, the presence of an X-ray pulsar for J1601 is not ruled out by the current data. The neutron star’s magnetic field, which would provide critical information on the nature of the object, remains unknown. Deep X-ray observations of J1601 are required to make conclusive remarks on the nature of J1601 such as pulsations, magnetic field, age, and the origin of its X-ray emission.

6.2. Nonthermal X-ray Emission of the Supernova Remnant

Our joint spectral analysis of the XMM-Newton and Chandra data of G330.2+1.0 shows that X-ray emission from the bright filaments of the SNR shell is dominated by a PL continuum. We find that this PL spectrum prevails for the most parts of the SNR, which was also suggested by a previous study (Torii et al. 2006). The best-fit PL model for the bright SW and NE regions of the shell indicates photon indices of \( \Gamma \sim 2.1-2.5 \) which are typical for synchrotron emission from shock-accelerated relativistic electrons. Although thermal plasma models may also fit the observed spectra, the estimated electron temperatures are high \( (kT \sim 4-5 \text{ keV}) \), and low metal abundances \( (\lesssim 0.1 \text{ solar}) \).
Anders & Grevesse 1989) are required. While a thermal origin of X-ray emission from the SNR shell may not be completely ruled out by the current data, the estimated plasma temperature and abundances appear to be unusual for SNRs. Thus, except for region E (Section 6.3), we discuss this SNR based on the nonthermal interpretations of X-ray emission.

According to our SRCUT model fits of the SW and NE filaments, the best-fit exponential roll-off frequency, $\nu_{\text{rolloff}} \sim 1.6-3.3 \times 10^{17}$ Hz, is relatively high among Galactic SNRs (Reynolds & Keohane 1999), while being similar to those for SN 1006 (Bamba et al. 2003) and the bright TeV $\gamma$-ray emitting SNR G347.3–0.5 (Lazendic et al. 2004). If the particle (electron) acceleration is limited by synchrotron losses, the cutoff frequency corresponding to the maximum electron energy $E_{\text{max}}$ is $\nu_{\text{m}}(\text{loss}) \propto B E_{\text{max}}^{2}(\text{loss})$. Since $E_{\text{max}}(\text{loss}) \propto B^{-2}$, $\nu_{\text{m}}(\text{loss})$ is independent of $B$, and depends only on the shock velocity; e.g., assuming a strong shock of the compression ratio of greater than 4 and the shock normal perpendicular to $B$, the cutoff frequency is $\nu_{\text{m}}(\text{loss}) \gtrsim 3 \times 10^{16} \eta \nu_{\text{i}}^{2}$ Hz, where $\nu_{\text{i}}$ is the shock velocity in units of $10^{3}$ km s$^{-1}$, and the ratio of the electron scattering mean free path to the gyroradius $\eta \gtrsim 1$ (e.g., Reynolds 1998; Lazendic et al. 2004). As discussed below and in Section 6.3, the shock velocity appears to be roughly $\nu_{\text{i}} \sim 4000$ km s$^{-1}$ for G330.2+1.0, and thus we estimate $\nu_{\text{m}}(\text{loss}) \gtrsim 5 \times 10^{17}$ Hz. Unless the shock velocity is much higher and/or the particle acceleration is inefficient ($\eta \gg 1$), the estimated $\nu_{\text{m}}(\text{loss})$ is comparable with the observed $\nu_{\text{rolloff}}$, suggesting that the particle acceleration of electrons in G330.2+1.0 is likely limited by synchrotron losses rather than the age of the SNR. The peak frequency of a synchrotron emitting electron is $\nu_{\text{p}} = 1.8 \times 10^{18} E_{\text{e}}^{2} B$ Hz, where $B$ is the postshock magnetic field perpendicular to the shock normal, and $E_{\text{e}}$ is the electron energy. For $\nu_{\text{p}} \sim 7 \times 10^{17}$ Hz (or $\sim 3$ keV) representing the typical X-ray photons based on the observed spectrum of the nonthermal filaments of G330.2+1.0, the corresponding electron energy is $E_{\text{e}} = 0.62 B^{-2}$ erg. The characteristic synchrotron loss timescale for such electrons can then be estimated to be $\tau_{\text{loss}} = 630 E_{\text{e}}^{-1} B^{-2} s = 1017 B^{-2} s$.

We estimate $\tau_{\text{loss}}$ by measuring the widths of the bright nonthermal filaments of G330.2+1.0 using Chandra images (Figure 7). We construct projected intensity profiles across the bright SW filaments by averaging the photon counts (in 4" pixel bins) over the 40" segments along the filaments. We fit these one-dimensional intensity profiles with a Gaussian to estimate the widths of the filaments. We note that high-resolution Chandra images of bright X-ray synchrotron filaments in young SNRs show typical substructures of a broad exponential downstream region and a much steeper flux decay in the upstream (e.g., Bamba et al. 2003). G330.2+1.0 is more distant than other young SNRs (that show bright nonthermal filaments), and the X-ray shell is relatively faint, which does not allow us to resolve such a substructure. Since the downstream region is observed to dominate the width of the filaments, we assume a negligible contribution from the upstream emission in the widths of the filaments to measure the downstream widths of the filaments with a simple Gaussian model. The measured widths are $\sim 12"-16"$ (FWHM) which correspond to physical sizes $D \sim 0.3-0.4 d_{5}$ pc. Because of the far distance and faint surface brightness of G330.2+1.0, our width measurements could be an overestimate from superpositions of thinner filaments. Nonetheless, the estimated widths are comparable with an average value for the individual filaments in SN 1006 ($\sim 0.2$ pc; Bamba et al. 2003). Therefore, we take our measurements as a first-order estimate, and certainly as an upper limit.

The advection distance of the downstream electrons from the shock is $D_{\text{ad}} = \nu_{\text{s}} \tau_{\text{loss}} R^{-1}$, where $r$ is the compression

Figure 7. Radial intensity profiles of the SW shell of G330.2+1.0 obtained by the Chandra data. (a) The bright northern parts (SW1) and (b) the faint southern parts (SW2) of the SW shell. (c) The 1–7 keV band Chandra ACIS-I image of G330.2+1.0. SW1 and SW2 regions (180′ × 40′ for each region) are marked. The image has been binned into 4" size pixels for the purposes of display. In (a) and (b), each regional image has been binned into 8 × 8 pixels (≈4" size), and then is averaged over 40′ column along the shell to produce a projected one-dimensional radial intensity profile. The best-fit Gaussian model (with a constant underlying background) is overlaid. In (a), the small intensity bump just inside of the shell (∼25°–45° toward the SNR center) is excluded in the fit.
ratio in the shock. Since the direct measurements of the shock velocity of G330.2+1.0 are not available, we consider some plausible estimates for the shock velocity based on several independent approaches. Assuming an electron–ion temperature equipartition in the postshock region, the detected thermal emission of G330.2+1.0 (region E) implies $v_s \sim 1000$ km s$^{-1}$ (Section 6.3). This value may be considered as a lower limit for $v_s$, because the assumed temperature equilibration between electrons and ions may have not been established in relatively young SNRs with $v_s \gtrsim$ several $10^2$ km s$^{-1}$ (Ghavamian et al. 2007). G330.2+1.0 shows similar characteristics (e.g., the SNR age, $v_{\text{rolloff}}$, and the physical width of the nonthermal filaments, etc.) to those of G347.3–0.5 and SN 1006 in which the shock velocities are high ($v_s \sim 3000–4000$ km s$^{-1}$, e.g., Parizot et al. 2006 and references therein). The ambient density for G330.2+1.0 ($n_0 \sim 0.1$ cm$^{-3}$, Section 6.3) is not unusually high compared with other SNRs (e.g., Bamba et al. 2003). Thus, the actual shock velocity of G330.2+1.0 is likely higher than $v_s \sim 1000$ km s$^{-1}$, perhaps close to $v_s \sim 3000–4000$ km s$^{-1}$. In fact, models predict high shock velocities of $v_s \gtrsim 2000$ km s$^{-1}$ for an efficient particle acceleration (e.g., Ellison et al. 2000, 2004). Although a small sample is used, an empirical relationship between $v_{\text{rolloff}}$ and the physical width of the nonthermal filaments $D$ is derived to be $v_{\text{rolloff}} D^{-2} = 2.6 \times 10^{27}$ TeV$^{-1}$ for several young historical SNRs (Bamba et al. 2005). This empirical relation suggests an SNR age $\tau_{\text{SNR}} \sim 1000–1200$ yr for G330.2+1.0 for the measured $v_{\text{rolloff}} \sim (2–3) \times 10^{17}$ Hz. The inferred young age and the low ambient density suggest that the SNR may be in a free expansion or an adiabatic phase, or could be in transition between the two. Assuming an adiabatic phase, the suggested SNR ages imply $v_s \sim 2300–2800$ km s$^{-1}$ for the SNR radius of $R = 7.3$ pc (see Section 6.3 for the SNR radius). For a free-expansion phase, $v_s \sim 5800–7000$ km s$^{-1}$ is implied. These high velocities are consistent with those estimated for young SNRs showing an efficient particle acceleration (e.g., Parizot et al. 2006 and references therein). Thus, as a rough estimate by averaging several values discussed above, we for simplicity adopt a shock velocity $v_s \sim 4000$ km s$^{-1}$ for G330.2+1.0. This shock velocity is admittedly not a measurement and thus only a crude first-order estimate. (We would allow a factor of $\sim 2$ uncertainty in this velocity estimate, and within this range, our conclusions as discussed below are not affected.)

Assuming $\gamma \sim 5–8$ for an efficient particle acceleration (e.g., Ellison et al. 2007), we estimate $\tau_{\text{flux}} \sim 350–600$ yr for the measured $D \sim D_{\text{ad}} \sim 0.3$ d$_{15}$ pc, and thus $B \sim 14–20$ $\mu$G. The maximum electron energy can be estimated by $E_{\text{max}} = 2.5 \times 10^{-7} v_{\text{rolloff}}^{-1} B^{1/2}$ TeV = 100–144 $B_{\mu\text{G}}^{1/2}$ TeV, where $B_{\mu\text{G}}$ is the postshock magnetic field in units of $\mu$G (Reynolds & Keohane 1999; Lazendic et al. 2004). Thus, $E_{\text{max}} \sim 22–38$ TeV (depending on measured $v_{\text{rolloff}}$) is derived. In addition, if we consider a geometrical projection effect in measuring the widths of the nonthermal filaments (e.g., the observed width is $\sim 4.6 \times$ the actual width assuming a spherical shock with an exponential emission profile; Ballet 2006), the estimated $B$ can be a few times higher ($\sim 50$ $\mu$G).

The estimated $E_{\text{max}}$ for G330.2+1.0 suggests that this SNR is a candidate $\gamma$-ray source. For instance, the $\gamma$-ray emission by the inverse Compton (IC) scattering off interstellar photons can be estimated by $E_{\gamma} \sim 5.1 \times 10^{-12} E_{\nu}^2$ eV, where $E_{\nu}$ is the average final energy of the up-scattered photons, and $E_{\nu}$ is the typical energy for the seed photons (Tatischeff 2008). Using $E_{\nu} \sim 7 \times 10^{-24}$ eV for the cosmic microwave background (CMB) and $E_{\nu} = E_{\text{max}} \sim 30$ TeV, we estimate $E_{\gamma} \sim 3$ TeV. However, G330.2+1.0 is not identified in the HESS Galactic plane survey catalog (Aharonian et al. 2006). It is probably because G330.2+1.0 is more distant and thus apparently fainter than other TeV-bright SNRs (e.g., G347.3–0.5 and G266.2–1.2). The IC to synchrotron flux ratio $f_{\text{IC}}/f_{\text{syn}} = 8 \pi U_{\text{rad}} B^2 \pi \sim 10 B_{\mu\text{G}}^{-2} \sim 0.004–0.1$ (where the energy density of the seed CMB photons $U_{\text{rad}} \sim 0.25$ eV cm$^{-3}$) for the plausible range of $B \sim 10–50$ $\mu$G in G330.2+1.0. These $f_{\text{IC}}/f_{\text{syn}}$ are in fact similar to the observed $f_{\text{IC}}/f_{\text{syn}}$ for SNRs G347.3–0.5 and G266.2–1.2 (e.g., Matsumoto et al. 2007 and references therein). Then, the overall X-ray flux of $f_{\text{syn}} \sim 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for G330.2+1.0 (Torii et al. 2006) implies $f_{\text{IC}} \sim 10^{-11}–10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

The sky position of G330.2+1.0 was at the edge of the HESS survey, in which the exposure was short (less than 5 hr). Considering the small angular size ($\sim 10^\circ$) of G330.2+1.0, which is close to the point-spread function of the HESS (several arcminutes), and the short exposure in the survey, the estimated IC flux is likely close to or below the HESS detection limit of $f \sim 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at $E \gtrsim 1$ TeV (e.g., Aharonian et al. 2005). Thus, if the $\gamma$-ray emission from G330.2+1.0 is dominated by the IC process of the same electrons to produce X-ray synchrotron emission, the nondetection of G330.2+1.0 with the current HESS survey data is not surprising. A deep search of $\gamma$-ray emission for G330.2+1.0 using ground-based TeV telescopes and Fermi (formerly GLAST) is warranted.

It is notable that nonthermal X-ray emission in G330.2+1.0 is generally anticorrelated with the radio emission (Torii et al. 2006). Our high-resolution Chandra and XMM-Newton images reveal that there actually exist radio counterparts for the bright X-ray filaments in SW and NE, but the radio emission is faint (Figure 3). The brightest radio emission is in the E parts of the SNR, where X-ray emission is faint and spectrally soft (Figure 3). Thus, the bright radio emission likely traces high-density regions where soft (thermal) X-ray emission is enhanced. Based on our SRCUT model fits, X-ray emission in SW and NE filaments implies the 1 GHz radio flux of $(0.7–1.5) \times 10^{-4}$ Jy, while the MOST 843 MHz image of the SNR suggests $\sim 0.1$ Jy for these regions (assuming that the total 1 GHz flux for the entire SNR is 5 Jy; Green 2001). Although our radio flux estimates are crude and should be considered only as an order-of-magnitude approximation based on a simple “normalization” of the total image intensity to the area corresponding to the X-ray-bright SW and NE filaments, the discrepancy is substantial by 3 orders of magnitudes, and should thus be real. We do not have an immediate answer as to what causes the large difference between the modeled and observed radio fluxes corresponding to the X-ray bright filaments. One speculation is that the radio spectral index might not be uniform across the SNR. While the overall radio spectrum is fitted by $\alpha = 0.3$, the faint radio filaments corresponding to the bright X-ray shell might have a steeper spectrum. For instance, if we assume a plausible range of the observed radio flux $\sim 0.01–0.1$ Jy for the SW region and vary the radio spectral index in our SRCUT model fit, we obtain a best-fit $\alpha \sim 0.53–0.66$ ($\chi^2 = 1.2$). These radio spectral indices are not unusual for shell-type SNRs (Green 2001). The best-fit roll-off frequencies are high, but are poorly constrained ($v_{\text{rolloff}} \sim 13–19 \times 10^{17}$ Hz when the 1 GHz radio flux of 0.1 Jy is assumed, and $v_{\text{rolloff}} \sim 8–25 \times 10^{17}$ Hz for the radio flux of 0.01 Jy). Although the high roll-off frequency, $v_{\text{rolloff}} \sim 10^{18}$ Hz, implies somewhat higher estimates for the shock velocity and the maximum electron energy, these changes do not make a significant effect on our conclusions presented here.
High resolution radio observations with a deep exposure would be essential to study the detailed relationship between the X-ray and the radio emission in this SNR.

### 6.3. Thermal X-ray Emission of the Supernova Remnant

In the E region, soft thermal emission is a significant component in the observed X-ray spectrum. The best-fit electron temperature is $kT \sim 0.7$–1.4 keV, depending on models (Section 5). The best-fit ionization timescale appears to be high ($n_{e}t \gtrsim 10^{13}$ cm$^{-3}$ s) suggesting that the plasma could be in collisional ionization equilibrium, but the $n_{e}t$ parameter is not well constrained because of the low photon statistics. Detecting thermal emission in SNRs in which nonthermal emission dominates is critical to reveal the environmental conditions (e.g., ambient density) and the supernova energetics that should have affected the SNR evolution and the particle acceleration. In fact, G330.2+1.0 is the only example to reveal thermal X-ray emission in SNRs with normal composition, and $V$ region $E$.

Therefore, although it is difficult to perform a thorough spectral analysis of thermal emission and to draw firm conclusions on the faint thermal component, we present a brief discussion on some fundamental SNR parameters based on our spectral analysis of region E.

Based on the best-fit volume emission measure ($EM = n_{e}n_{H}V$, where $n_{e}$, $n_{H}$, and $V$ are the postshock electron, proton densities, and the X-ray emitting volume, respectively), we estimate $n_{e} \sim 0.4$–0.5 $f^{-1}d_{5}^{-1}$ cm$^{-3}$ (where $f$ is the X-ray emitting volume filling factor). These postshock electron densities correspond to the preshock hydrogen density $n_{H} \sim 0.1 f^{-1}d_{5}^{-2}$ cm$^{-3}$. In these estimates, we assume $n_{e} = 1.2 n_{H}$ for the mean charge state with normal composition, and $n_{H} = 4n_{0}$ for a strong shock. We use the emission volume $V \sim 4 \times 10^{56}$ cm$^{-3}$ assuming that the path length through region E is comparable to the physical size corresponding to the angular size ($\sim 2'$) of region E at $d = 5$ kpc. Assuming an ion–electron temperature equilibration, the measured electron temperature implies a shock velocity of $v_{s} \sim 800$ ($kT = 0.7$ keV) – 1100 ($kT = 1.4$ keV) km s$^{-1}$. However, equipartition of the electron-ion temperatures may not have been reached, and thus the actual shock velocity could be higher than $v_{s} \sim 1000$ km s$^{-1}$, probably by a factor of a few (Section 6.2). We estimate the SNR radius of $R \sim 5'$ (the half of the angular distance between the bright SW and NE filaments), which corresponds to the physical distance of $\sim 7.3$ $d_{5}$ pc. Then, assuming an adiabatic phase for the SNR, we apply the Sedov solution to derive the SNR age $t_{SNR} \sim 1100$ $d_{5}$ yr (e.g., for $v_{s} \sim 2500$ km s$^{-1}$, Section 6.2). For a free-expansion phase, the SNR age is also derived to be $t_{SNR} \sim 1100$ yr (e.g., for $v_{s} \sim 6500$ km s$^{-1}$, Section 6.2). Using a Sedov solution, the explosion energy is estimated to be $E_{0} \sim 2$–9 $\times 10^{50}$d$^{2}_{5}$ erg for $t_{SNR} \sim 1000$–2000 yr.

### 7. SUMMARY AND CONCLUSIONS

Based on the ASCA data, the overall X-ray emission from SNR G330.2+1.0 was suggested to be continuum dominated with no evidence for line features (Torii et al. 2006). The high-resolution Chandra images subsequently revealed that X-ray emission from this SNR originates primarily from the thin shell with enhanced filaments in the SW and NE parts of the shell (Park et al. 2006). Park et al. (2006) have also discovered the CCO J1601 at the center of the SNR. We performed follow-up observations of G330.2+1.0 with XMM-Newton to investigate the nature of the CCO and the SNR. Although our spectral and temporal analyses of J1601 and G330.2+1.0 are limited by poor photon statistics of the XMM-Newton data caused by significant contamination from flaring particle background, we find several important characteristics of these objects utilizing the XMM-Newton and Chandra data.

The X-ray spectrum of J1601 can be described by two-component neutron star atmosphere models. X-ray emission primarily originates from a small hot region ($R \sim 0.4$–2 km, $T \sim 2.5$–5.5 MK). The rest of the neutron star’s surface is cooler ($R \sim 10$ km, $T < 1.5$ MK), suggesting an $\gtrsim 10^{3}$ yr old neutron star based on the standard cooling models. The neutron star atmosphere models do not provide useful constraints on the magnetic field of J1601 with the current data. The previously suggested pulsations ($P \sim 7.48$ s) are not confirmed by the XMM-Newton data. These characteristics are similar to those found for CCOs in other Galactic SNRs such as Cas A and Vela Jr. The spectrally hard, faint nebulosity at $\sim 2'$ southwest from the CCO could be the associated PWN, but its true nature is uncertain with the current data because of the poor photon statistics. Follow-up deep X-ray observations are required to reveal the detailed nature of J1601.

Assuming that X-ray emission in the shell of G330.2+1.0 is synchrotron radiation from the shock accelerated electrons, the roll-off frequency of $\nu_{rolloff} \sim 1.6$–3.3 $\times 10^{17}$ Hz is estimated. It is difficult to measure the shock velocity with the currently available data. Based on several independent approaches, we make a rough estimate of the shock velocity $v_{s} \sim 4000$ km s$^{-1}$ (with a factor of $\sim 2$ uncertainty). Based on this shock velocity and the measured roll-off frequency, we find that the particle (electron) acceleration in G330.2+1.0 is likely limited by synchrotron losses rather than the SNR age. Using the Chandra images, we measure the widths of the bright nonthermal X-ray filaments ($D \sim 0.3$–0.4 pc). Using these widths and the shock velocity, we estimate the synchrotron loss time of $t_{loss} \sim 350$–600 yr and the magnetic field of $B \sim 10$–50 $\mu$G. The maximum electron energy is derived to be $E_{max} \sim 22$–38 TeV. These electron energies suggest that G330.2+1.0 is a candidate $\gamma$-ray source (up to $\sim$TeV) by the IC scattering of the CMB photons. The nondetection of G330.2+1.0 in the current HESS survey with a short exposure is perhaps expected, because G330.2+1.0 is more distant and likely a fainter $\gamma$-ray source than the bright TeV SNRs like G347.3–0.5 and Vela Jr.

G330.2+1.0 is particularly intriguing because this is the only SNR in which we detect a thermal component among the four Galactic SNRs known to be dominated by nonthermal X-ray emission. Although the uncertainties are large due to the poor photon statistics, the estimated density ($n_{0} \sim 0.1$ cm$^{-3}$) is low, suggesting that $\gamma$-ray emission, if it exists, would be dominated by the IC process. The detection of $\gamma$-ray emission as well as thermal X-ray emission with high photon statistics from G330.2+1.0 will be essential to test and constrain models for $\gamma$-ray production from shock-accelerated particles. Follow-up deep observations with X-ray detectors on board XMM-Newton and Suzaku are necessary for a thorough study of thermal X-ray emission. Deep $\gamma$-ray observations using Fermi and the ground-based TeV telescopes will be critical to reveal the nature of nonthermal radiation produced by shock accelerated particles.
apparent inconsistency between the radio and nonthermal X-ray emission, such as the radio spectral-index variation across the SNR.

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