**ASCA VIEW OF THE SUPERNOVA REMNANT \( \gamma \) CYGNI (G78.2+2.1): BREMSSTRAHLUNG X-RAY SPECTRUM FROM LOSS-FLATTENED ELECTRON DISTRIBUTION**

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**ABSTRACT**

With the ASCA X-ray satellite, we perform spatial and spectral studies of the shell-type supernova remnant (SNR) \( \gamma \) Cygni that is associated with the brightest EGRET unidentified source 3EG J2020+4017. At energies below 3 keV, the bulk of the X-ray flux from the remnant is well described by the emission of thermal plasma with characteristic temperature \( kT_e \simeq 0.5-0.9 \) keV. In addition to this thermal emission, we found an extremely hard X-ray component from several clumps localized in the northern part of the remnant. This component, which dominates the X-ray emission from the remnant above 4 keV, is described by a power law with a photon index of \( \Gamma \simeq 0.8-1.5 \). Both the absolute flux and the spectral shape of the nonthermal X-rays cannot be explained by the synchrotron or inverse-Compton mechanisms. We argue that the unusually hard X-ray spectrum can be interpreted naturally in terms of nonthermal bremsstrahlung from Coulomb-loss–flattened electron distribution in dense environs with the gas density about 10–100 cm\(^{-3}\). For a given spectrum of the electron population, the ratio of the bremsstrahlung X- and \( \gamma \)-ray fluxes depends on the position of the “Coulomb break” in the electron spectrum. Formally, the entire high-energy \( \gamma \)-ray flux detected by EGRET from \( \gamma \) Cygni could originate in the hard X-ray regions. However, it is more likely that the bulk of \( \gamma \)-rays detected by EGRET comes from the radio-bright and X-ray–dim cloud at the southeast, where the very dense gas and magnetic field would illuminate the cloud in the radio and \( \gamma \)-ray bands but suppress the bremsstrahlung X-ray emission due to the shift of the Coulomb break in the electron spectrum toward higher energies.

*Subject headings:* acceleration of particles — cosmic rays — radiation mechanisms: nonthermal — shock waves — supernova remnants

1. INTRODUCTION

The origin of the unidentified EGRET \( \gamma \)-ray sources in the Galactic plane has been puzzling since their discovery. The third EGRET catalog (Hartman et al. 1999) lists 57 unidentified sources at low Galactic latitude (\(|b| \leq 10^{\circ}\)). Rotation-powered pulsars are likely to account for part of these GeV \( \gamma \)-ray sources: five pulsars have been detected at GeV energies to date. Another possible origin for some of the unidentified sources is the emission from accelerated cosmic rays at the shock of shell-type supernova remnants (SNRs). It is reported that the probability of finding EGRET unidentified sources in the vicinity of shell-type SNRs is significantly high (Sturmer & Dermer 1995). Although the relatively young SNRs, being in their Sedov phase, are natural sites of high-energy \( \gamma \)-ray production through electron bremsstrahlung and hadronic interactions, it has been recognized that in most cases the expected \( \gamma \)-ray fluxes at MeV/GeV energies are too low to be detected by EGRET (Drury, Aharonian, & Völk 1994). However, the \( \gamma \)-ray fluxes can be enhanced dramatically in SNRs having dense gas environments, e.g., in large molecular clouds overtaken by supernova shells (Aharonian, Drury, & Völk 1994). Remarkably, among the SNRs possibly detected by EGRET are the radio-bright and nearby objects \( \gamma \) Cygni, IC 443, W44, and W28 (Esposito et al. 1996), which are all associated with molecular clouds. The recent searches for SNRs in the vicinity of some of the unidentified EGRET sources revealed new evidence of \( \gamma \)-ray emission from “supernova remnant–molecular cloud” interacting systems (Combi, Romero, & Benaglia 1998; Combi et al. 2001). If \( \gamma \)-rays of such systems have hadronic origin and the acceleration of protons extends to 10 TeV and beyond, the TeV \( \gamma \)-ray emission from these objects should be detectable also by current ground-based detectors (Aharonian et al. 1994). At energies below the threshold of production of \( \pi^0 \)-decay \( \gamma \)-rays, the electron bremsstrahlung remains the only noticeable \( \gamma \)-ray production process. Therefore, the detection of \( \gamma \)-rays by EGRET down to several tens of MeV implies the existence of low-energy \(<100 \) MeV) electrons in these objects. The best information about higher energy electrons, typically between 1 and 10 GeV electrons, is provided by the synchrotron radio emission at GHz frequencies.

The accelerated electrons also produce nonthermal X-rays through the synchrotron radiation and the bremsstrahlung. Both channels contain unique information about the nonthermal electron populations at extremely high (multi-TeV) and very low (sub-MeV) energies, respectively. Thus, the X-ray observations may help to reveal the nature of the unidentified EGRET sources that are associated with SNRs by looking for ultrarelativistic and subrelativistic electrons and probing the environments of the remnants.

The \( \gamma \) Cygni (G78.2+2.1) SNR has a clear position correlation with the brightest unidentified \( \gamma \)-ray source, 2EG J2020+4026/3EG J2020+4017. It is a nearby (1–2 kpc) shell-type SNR with a radio shell of \( \sim 60^{\circ} \) diameter (Higgs, Landecker, & Roger 1977). The radio flux density of 340 Jy

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at 1 GHz ranks it as the fourth-brightest SNR in the sky at this frequency (Green 2000). Almost 60% of the radio flux comes from southeastern part, which is known as DR4 (Downes & Rinehart 1966). The spectral index of the radio spectrum averaged over the whole remnant is measured as \( \alpha \approx 0.5 \) (Green 2000). Its variation across the remnant is as small as \( \Delta \alpha \approx \pm 0.15 \) (Zhang et al. 1997). The GeV source 2EG J2020+4026 has a steady flux of \( F(E > 100 \text{ MeV}) = (12.6 \pm 0.7) \times 10^{-10} \text{ photons cm}^{-2} \text{ s}^{-1} \) and a best-fit power-law index of 2.07 \( \pm 0.05 \) (Esposito et al. 1996). Prior to the EGRET detection, \( \gamma \)-ray source 2CG 078+2 was detected in the vicinity of \( \gamma \) Cygni with the Cosmic Ray Satellite B (\textit{COS B}; Pollock 1985). A pointlike \( \gamma \)-ray source RX J2020.2+4026 close to the remnant center and within the EGRET error circle is a possible candidate for a radio-quiet \( \gamma \)-ray pulsar (Brazier et al. 1996). Despite extensive searches for TeV \( \gamma \)-ray emission, significant excesses have not been detected (Buckley et al. 1998). Since a simple extrapolation of the EGRET flux exceeds the Whipple upper limit by an order of magnitude, the spectrum must have a cutoff or steepen well below the TeV energy (Gaisser, Protheroe, & Stanev 1998; Buckley et al. 1998).

Presented here are the results from and implications of \textit{ASCA} observations of \( \gamma \) Cygni SNR. Of particular interest is the discovery of hard X-ray emission localized to the northern part of \( \gamma \) Cygni. The plan of this paper is as follows. The \textit{ASCA} observations are summarized briefly in \S 2. We perform the X-ray image analysis in \S 3.1 and the spectral fits in \S 3.2. In \S 4.2, we interpret the soft X-ray data in terms of shock-cloud interaction. The origin of the hard X-ray emission is discussed in \S 4.3.

2. OBSERVATIONS

We performed \textit{ASCA} observations of \( \gamma \) Cygni SNR twice in 1996 and 1997. The northern part of the remnant was observed for 40 ks in 1996 May. Observations were carried out in 1997 May with three pointings toward the north, south, and east of \( \gamma \) Cygni with 60, 16, and 12 ks duration, respectively. The data from two Gas Imaging Spectrometer (GIS; Makishima et al. 1996) detectors were acquired in the standard pulse-height mode. Two Solid-State Imaging Spectrometer (SIS; Burke et al. 1994) detectors were operated in 4-CCD mode. Each detector is coupled to its own telescope with nested conical foil mirrors. Once all observations are combined, the field of view (FOV) of GIS covers almost all of the remnant.

The data from the detectors were screened by standard procedures, except for the strict rise-time screening in the GIS analysis, because of the mode we chose for the operation. The observed count rate for the north of \( \gamma \) Cygni was 0.57 (0.59) counts s\(^{-1}\) within a central 20' radius in the 0.7–10 keV energy band with GIS2 (GIS3). The degradation of the SIS performance due to the accumulated radiation damage in orbit is found to be substantial in our data. Even for the data taken with the faint mode, in which residual dark distribution correction can be applied, the spectral resolution of SIS is found to be of no advantage over that of GIS. In addition, the smaller effective area at high energies and the narrower FOV for SIS than those for GIS do not serve our purpose. The results presented in this paper are from the GIS data.

3. DATA ANALYSIS AND RESULTS

3.1. X-Ray Images

The \textit{ASCA} GIS data for the four pointings were combined to construct the X-ray images in selected energy bands. We discard the data outside the central region of the detector with a radius greater than 20'. By utilizing the night-Earth observation data set, we subtract the instrumental background from each pointing data. Since we did not obtain the rise-time information, the normalization of the background image is increased by 30% as compared with the nominal case. The background-subtracted images are combined with corrections for the exposure time and the vignetting effects. Finally, the images are smoothed with a function composed of a narrow core (\( \lesssim 1' \)) and a broad wing to simulate the point-spread function (PSF) of the telescope. Figures 1a, 1b, and 1c show the resulting X-ray images in the 0.7–1 (soft), 1–3 (medium), and 4–7 keV (hard) energy bands, respectively.

We find strikingly different appearances of the SNR in these energy bands. In the soft-band image, clumpy sources appear in the north and limb-brightened emission is seen in the south. The medium image shows widespread emission distributed from north to southeast, in addition to the southern bright shell. In the hard energy band, several clumpy sources in the north region stand out dramatically (Fig. 1c). Hereafter, we refer to the clump centered at a celestial coordinate (J2000.0) of R.A. = 20\(^\text{h}\)21\(^\text{m}\)12\(^\text{s}\), decl. = +40\(^\circ\)47\(\prime\)55\(''\) as C1 and the other one at R.A. = 20\(^\text{h}\)20\(^\text{m}\)00\(^\text{s}\), decl. = +40\(^\circ\)40\(\prime\)03\(''\) as C2. Since another hard source, C3, is located at the western edge of the FOV, we do not report a spectral study of C3 in this paper.

The hard source, C2, appears to be extended by a few arcminutes. In order to evaluate quantitatively, we compared the count-rate profile centered on clump C2 with the detector PSF in the 3–10 keV band, as plotted in Figure 2. The background level shown there is taken from the southern part of the remnant. It is obvious that the hard X-ray emission extends up to 4’–6’ beyond the radial profile of a single point source. In Figure 2, we also plot the simulated profile of a circular source that has uniform surface brightness with a radius of 4’ centered on C2. On the other hand, we obtain no sign of spatial extension of source C1.

In order to compare the X-ray distribution with radio synchrotron emission, the X-ray images in gray scale are overlaid with the 4850 MHz radio contours in Figure 1. The X-ray sources at the north coincide with the radio-bright region and the southern X-ray shell with a fainter radio arc. The X-ray morphology in general coincides with the radio-bright region and the southern X-ray shell with a fainter radio arc. The X-ray source inside \( \gamma \) Cygni. In Figure 1c, we superpose their 95% confidence error contours, which are approximated as circles. Within the error...
Fig. 1.—ASC A GIS X-ray images (gray scale) of the γ Cygni supernova remnant in (a) 0.7–1 keV, (b) 1–3 keV, and (c) 4–7 keV energy bands. Two GIS detectors (GIS2 and GIS3) are summed. The brightness level indicated at the top of the images is in units of the surface brightness of the cosmic X-ray background of the relevant energy interval. Radio contour map (NRAO 4.85 GHz, 7' FWHM) is superposed on the ASC A images. A central part of strong emission around an H II region called the γ Cygni nebula at the southeast is blanked from the radio map. Also shown are the EGRET 95% confidence error circles (dotted circle: 2EG J2020+4026; thick circle: 3EG J2020+4017).
circles, no point sources were detected by our ASCA observations. Brazier et al. (1996) estimated the flux of RX J2020.2+4026 to be $4 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, assuming a photon index of 2, so the source is below the sensitivity of our observations. In §4.3, we discuss a possible connection between the hard X-ray sources and the EGRET unidentified $\gamma$-ray emission.

3.2. X-Ray Spectra

For the purpose of spectroscopic studies of the X-ray emissions associated with the $\gamma$ Cygni SNR, contaminating emission that is overlapping the remnant must be taken into account adequately because the line of sight toward $\gamma$ Cygni passes along the Orion-Cygnus spiral arm. Because of the lack of a blank field in our observations, we analyzed four ASCA archive data in neighboring fields (fields 1–4 in Table 1) to estimate the X-ray emission at the $\gamma$ Cygni field unrelated to the SNR itself. For each field, the GIS spectrum is obtained by integrated over the central detector region with a radius of 20 arcmin after eliminating resolved sources. Each spectrum is subtracted by the high-latitude blank-sky spectrum as a sum of the cosmic X-ray background and the instrumental background. Figure 3 shows the resulting spectra in the 1.2–2.5 and 3.5–8 keV bands after the correction for the integration sky area. We find similar energy spectra from these neighborhood fields, except for field 2, where the Galactic latitude is highest and the Galactic column density is lowest as compared with the other fields. Once field 2 is excluded, field-to-field variations of spectral data in the soft band are found to be insignificant. The hard 3.5–8 keV spectrum of the southern field of $\gamma$ Cygni is in agreement with those of fields 3 and 4 within their statistical uncertainties. Consequently, we consider that fields 3 and 4 provide us a good approximation of the contaminating emission that should be subtracted from the spectral data of $\gamma$ Cygni. Since no bright sources are found in the ASCA data of field 4, we have chosen field 4 as a "background" field.

We derive energy spectra of regions R1–R3 and clumps C1 and C2 (Fig. 1). The clump spectra are extracted from the circular regions of a radius of 6 arcmin. We exclude photons falling within the 6 arcmin radius centered on C1 and C2 from the spectrum of region R1. Each accumulated on-source spectrum is subtracted by the background field 4 spectrum that is extracted from an identical detector region to each on-source data point. To improve statistics, spectra of two GIS detectors are always added. Background-subtracted spectra of R1/R3 and C2 are shown in Figures 4 and 5, respectively. Several emission lines of Mg K ($\sim 1.4$ keV) and Si K ($\sim 1.9$ keV) are evident in every spectrum, indicative of thin thermal plasma with a typical temperature of $\sim 1$ keV. Remarkably, the spectrum of C2 exhibits very flat continuum emission above 3 keV. There are known errors in the calibration of the conversion of the photon energies to the pulse-invariant channels of the GIS detector below the xenon-L edge of 4.8 keV. In the following spectral fitting, an artificial energy shift of $\sim 50$ eV to each applied model is introduced to alleviate these errors (Buote 1999).

![Fig. 2.](image2.png)

**Fig. 2.**—GIS radial count rate profile of clump C2 in the 3–10 keV energy band. The histogram represents the simulated radial profile of a point source. Estimated background level is taken from the southern part of the remnant.

**Fig. 3.**—Comparison between the energy spectra integrated over the GIS field of view in the 1.2–2.5 keV energy band (top) and the 3.5–8 keV band (bottom). Filled circles: south $\gamma$ Cygni; open circles: field 1; rectangles: field 2; diamonds: field 3; triangles: field 4.

| Field | Target                  | Coordinates (l, b) (deg) | Distance (deg) |
|-------|-------------------------|--------------------------|----------------|
| $\gamma$ Cygni $^a$ | 2EG J2020+4026 2     | (77.92, 2.22)            | 0.0            |
| Field 1 | V444 Cyg               | (76.66, 1.43)            | 1.5            |
| Field 2 | NGC 6888               | (75.55, 2.42)            | 2.4            |
| Field 3 | GRO J2019+37           | (75.45, 0.61)            | 2.9            |
| Field 4 | GEV 2035+4213          | (81.22, 1.02)            | 3.5            |

$^a$ Angular distance from (l, b) = (77.92, 2.22).

$^b$ This pointing covers the southern part of the $\gamma$ Cygni SNR.
We attempt first to fit the 0.7–8 keV spectrum of R3 by a thin thermal plasma model (Mewe, Gronenschild, & van den Oord 1985; Liedahl et al. 1990) in which collisional equilibrium ionization (CEI) is realized. Photoelectric absorption along the line of sight is taken into account using the cross sections from Morrison & McCammon (1983). Elemental abundances are fixed to the solar values of Anders & Grevesse (1989) throughout this paper unless otherwise mentioned. The CEI plasma model cannot give an acceptable fit owing to a large discrepancy between the actual data and the model between Mg and Si K emission lines. Even when the abundances of alpha elements Ne, Mg, Si, S, and Fe are allowed to vary individually ranging from 0.1 to 10 solar, the spectral data cannot be described properly. In order to model emission-line features, we take into account the effects of nonequilibrium ionization (NEI; Itoh 1979) by adopting a plasma emission code based on Masai (1994). In an NEI plasma, degree of ionization and consequently line emissivities depend on the ionization timescale $n_e t$, where $n_e$ represents the electron density and $t$ the passage time after being shocked. The NEI plasma model yields an acceptable fit with a reduced $\chi^2$ of $1.92(26)$. The best-fit temperature and ionization timescale with 1 $\sigma$ errors are $kT_e = 0.76^{+0.10}_{-0.09}$ keV and $n_e t = 5.8^{+1.2}_{-1.3} \times 10^{10}$ cm$^{-3}$ s, respectively.

We found that the R1 spectrum, as compared with R3, shows distinctive features, namely, a strong emission at $\approx 0.9$ keV and a hard continuum above 3 keV. The former is consistent with the fact that R1 is very bright, particularly in the 0.7–1 keV energy band; the latter could be contamination by the hard sources C1 and C2. Regarding the spectral fit of R1, we include a helium-like neon (Ne IX) Kα line (0.923 keV), in addition to the CEI plasma model that predominantly describes the 1–3 keV emission. The CEI plasma plus Ne IX line model, however, cannot give a statistically acceptable fit owing to residuals by the hard continuum. Then, by adding a power law as a third component to describe the hard continuum, we obtain an acceptable fit for the R1 spectrum as summarized in Table 2. The best-fit temperature is $kT_e = 0.56^{+0.03}_{-0.05}$ keV; the photon index of the power-law component is $\Gamma = 1.2^{+0.1}_{-0.05}$.

The spectrum of region R2 is fitted by a CEI plasma model alone. The simple model yields an acceptable fit with a temperature of $kT_e = 0.53 \pm 0.07$ keV, which is in complete agreement with the value obtained for region R1.

We discovered hard X-ray sources C1 and C2 at the north of $\gamma$ Cygni through our image analysis. The spectral data of clump C2 revealed the presence of a hard continuum emission in the 3–8 keV energy band. The hard emission is found in the spectrum of C1 as well. As in the case of R1, we employ a three-component model composed of the Ne IX line (0.92 keV), CEI thermal plasma, and power-law spectrum. We find that a good fit cannot be obtained if we omit the power-law component. We fitted the three-component model to the 0.7–8 keV spectral data of clumps C1 and C2 by freezing the plasma temperature to the best-fit value of region R1 and attenuating all components with a common absorption column of $N_H = 0.84 \times 10^{22}$ cm$^{-2}$ that is also obtained for R1. The power-law components are found to be very flat; the best-fit photon indices are $\Gamma = 1.5 \pm 0.5$ and $0.8 \pm 0.4$ for C1 and C2, respectively. Instead of adding a power law, we attempted also to add a thermal bremsstrahlung component to model the high-energy part of the C2 spectrum. The 90% lower limit on the temperature of the thermal bremsstrahlung emission is set to be $kT_e = 5.8$ keV.

4. DISCUSSION

4.1. Estimation of SNR Distance and Age

Higgs et al. (1977) derived the distance to $\gamma$ Cygni as $1.8 \pm 0.5$ kpc based on the $\Sigma$-$D$ relation, which is a statistical property of the radio brightness of SNRs. Landecker, Roger, & Higgs (1980) estimated the distance as $1.5 \pm 0.5$
kpc and pointed out that the progenitor of the γ Cygni remnant was possibly a member of the Cyg OB 9 association at 1.2 ± 0.3 kpc. The absorbing column density provides additional information about the distance. Maeda et al. (1999) reported that the Wolf-Rayet binary V444 Cyg, located close to the Cyg Cygni sky field, is attenuated by the interstellar column density of \( N_H = (1.1 ± 0.2) \times 10^{22} \) cm\(^{-2}\), similar to the γ Cygni remnant. Thus, we expect that the distance to γ Cygni is probably close to the distance to V444 Cyg, 1.7 kpc. In view of these arguments, we take the distance \( D = 1.5 \) kpc as the most probable value.

The X-ray distribution of region R3 shows clear arclike morphology along the outer boundary of the shell structure observed at radio frequencies. The X-ray spectrum was modeled by a single-temperature thermal emission with the solar abundance. These features are indicative of a thin thermal plasma in the immediate postshock region of the primary blast wave propagating through the interstellar matter.

Assuming the equipartition between the shocked electrons and ions and Rankine-Hugoniot jump conditions for a strong shock, the electron temperature is related to the shock velocity \( v_s \) as \( kT_e = (3/16)\mu m_p v_s^2 \), where \( \mu = 0.6 \) is a mean mass per particle in units of the proton mass \( m_p \). The best-fit value of \( kT_e = 0.76_{-0.09}^{+0.10} \) keV corresponds to the shock velocity \( v_s = 800_{-50}^{+60} \) km s\(^{-1}\).

Provided that the remnant is the Sedov adiabatic expansion phase, the age of γ Cygni can be estimated to be \( t_{age} = (2/5)R/v_s \), where \( R \) is the radius of the supernova shock front. Given the angular radius of \( \theta \approx 30\arcmin \), we have the physical radius \( R = D\theta \approx 13.5D_{1.5} \) pc, where \( D_{1.5} \) is the distance in units of 1.5 kpc. Thus, we obtain an age estimate of \( t_{age} \approx 6600D_{1.5} \) yr.

### 4.2. Signatures of Shock-Cloud Interaction

On the basis of the H I line emission and absorption toward the γ Cygni SNR, Landecker et al. (1980) suggested that the supernova explosion took place in the slab of an interstellar cloud oriented north to southeast. The soft (1–3 keV) X-ray emission “belt” from north to southeast appears to agree fairly well with the spatial distribution of the H I line features. A possible scenario explaining this coincidence is that the X-ray emission belt is due to thermal evaporation of clouds (White & Long 1991) as a consequence of the collision between the supernova blast wave and the dense clouds. The supernova shock may expand into a cavity produced by progenitor stellar winds and then encounter the cavity wall composed of the clouds (Chevalier 1999).

We found possible evidence of the strong emission line of helium-like Ne from the R1 spectrum. The X-ray map in the 0.7–1 keV band suggests the clumpy nature of the Ne lines. The X-ray spectrum was observed at radio frequencies. The X-ray spectrum was modeled by a single-temperature thermal emission with the solar abundance. These features are indicative of a thin thermal plasma in the immediate postshock region of the primary blast wave propagating through the interstellar matter.

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### 4.3. On the Origin of Hard X-Ray Emission

An important finding of our observations is the clumpy hard X-ray emissions from regions C1 and C2 (the hard X-
The gas density of electrons, i.e., ignoring the Coulomb losses of electrons. The thermal-bremsstrahlung interpretation of the high-energy part of the C2 spectrum requires very high temperature \((kT_e > 5.8 \text{ keV})\). Since the shocks of an evolved SNR are not sufficiently energetic to heat the gas to such temperatures, the nonthermal origin of the hard X-ray emission seems a more favorable option. Synchrotron radiation, inverse Compton scattering, and nonthermal bremsstrahlung of shock-accelerated electrons are three natural production mechanisms of hard X-rays. The overall flux of the HXC in the 2–10 keV interval is estimated as \(F_X \approx 4.5 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}\), which corresponds to the source luminosity \(L_X \approx 1.2 \times 10^{33}D_{15}^2 \text{ ergs s}^{-1}\).

The nonthermal luminosity of this SNR peaks at high-energy \(\gamma\)-rays if the association with the EGRET source is real. The \(\gamma\)-ray spectrum measured by EGRET is shown in Figure 6, together with the HXC spectrum. The observed photon flux of the EGRET source is translated into a luminosity of \(L_\gamma \approx 1.4 \times 10^{35}D_{15}^3 \text{ ergs s}^{-1}\) (100 MeV to 2 GeV) for the photon index 2.1. The reported positions of the EGRET \(\gamma\)-ray source 2EG J2020+4026/3EG J2020+4017 do not coincide with the HXC. However, the large systematic errors in the EGRET position, which depend strongly on the chosen diffuse \(\gamma\)-ray emission model (Hunter et al. 1997), do not allow certain conclusions concerning the location of the \(\gamma\)-ray production region. Therefore, it is interesting to test whether the HXC can be a counterpart of the unidentified GeV \(\gamma\)-ray source on theoretical grounds.

4.3.1. Coulomb Cooling and Nonthermal Bremsstrahlung

The emission region of the HXC is supposed to be the dense cloudlet engulfed by the supernova blast wave, therefore the density is presumably high \((n \sim 10–100 \text{ cm}^{-3})\). Possible sites of enhanced electron acceleration could be the secondary shocks generated by the interaction between the primary forward shock and the dense cloudlets. Bykov et al. (2000) considered electron acceleration at a slow shock (on the order of 100 km s\(^{-1}\)) transmitted inside a dense cloudlet. A tail shock could be formed behind the cloudlets (Jones & Kang 1993) as well, although an efficient particle acceleration at the tail shock is not obvious. The energy spectrum of accelerated electrons depends on the acceleration mechanism, the discussion of which is beyond the scope of this paper. For simplicity, we assume that the electron production rate in momentum space is described by a single power-law function \(Q(p) \propto p^{-\kappa}\). Such a function implies power-law distributions of energies in the kinetic-energy space as well, although in the nonrelativistic and ultrarelativistic regimes, the power-law indices are different, namely, \(Q(E) \propto E^{-(\nu+1)/2}\) at \(E \ll m_e c^2\) and \(Q(E) \propto E^{-\nu}\) at \(E \gg m_e c^2\), where \(\nu = \kappa - 2\). In the case of diffusive shock acceleration at the shock front, according to the standard model, the spectral index is determined by the compression ratio of the shock as \(s = (r + 2)/(r - 1)\). For strong shocks with \(r \approx 4\), the spectral index is close to 2.

We assume that electrons are continuously injected in the HXC by the accelerators being located either outside or inside the HXC. For simplicity, we suppose that the accelerated electrons are effectively trapped in the HXC. The present-day electron spectrum is formed by accumulation of freshly accelerated electrons, or those arriving from external accelerations, during the entire history of the HXC. In particular, if energy losses can be neglected, the electron spectrum becomes \(N(E) = \tau_{age} Q(E)\), where presumably the age of the accelerator is approximately equal to the age of \(\gamma\) Cygni, i.e., \(\tau_{age} \approx 7000 \text{ yr}\). Such an approximation is valid, however, only in the intermediate-energy region, typically between 300 MeV and 10 GeV, where the bremsstrahlung dominates the radiative losses. Indeed, the characteristic lifetime of electrons against the bremsstrahlung losses, \(\tau_{br} \approx 4.3 \times 10^7 (n/10 \text{ cm}^{-3})^{-1} \text{ yr}\), is considerably longer than the age of \(\gamma\) Cygni as long as the gas density does not exceed \(6 \times 10^4 \text{ cm}^{-3}\).

The high density and presumably strong magnetic field in the HXC, however, make the cooling processes nonnegligible in the formation of the electron spectrum at low and very high energies. The relevant cooling processes are Coulomb (or, in the neutral gas, ionization) losses for low-energy electrons and synchrotron losses for high-energy electrons. The inverse Compton losses could be omitted if the magnetic field in the HXC exceeds 10 \(\mu\)G. Also, it should be noticed that even in the case of significant bremsstrahlung losses \(\tau_{br} \leq \tau_{age}\), the process does not modify the electron spectrum.

Below several hundred MeV, the energy losses of electrons are dominated (independent of the gas density) by the Coulomb losses (see, e.g., Hayakawa 1969). The cooling time of electrons due to Coulomb interactions is given by (Rephaeli 1979)

\[
\tau_{Coul} = \frac{E}{(3/2)n_c c \sigma_T (m_e c^2) \beta^{-1} \ln \Lambda}
\]

\[
= 4.3 \times 10^7 \beta \left(\frac{n}{10 \text{ cm}^{-3}}\right)^{-1} \left(\frac{E}{\text{MeV}}\right) \text{ yr},
\]

where \(\sigma_T\) is the Thomson cross section, \(c\) is the velocity of
light, $E$ and $\beta$ are the kinetic energy and the velocity of nonthermal electrons in units of $c$, $m_e$ is the electron mass, and $\ln \Lambda$ is the Coulomb logarithm, which is set to be 40. Equating $\tau_{\text{Cou}}$ and $\tau_{\text{age}}$ gives the break energy $E_{\text{Cou}}$, the "Coulomb break," below which the electron spectrum is flattened:

$$E_{\text{Cou}} \sim 1.6 \left( \frac{n}{10 \text{ cm}^{-3}} \right) \left( \frac{\tau_{\text{age}}}{7000 \text{ yr}} \right) \text{ MeV},$$

where we use the approximation of $\beta \sim 1$. At energies below $E_{\text{Cou}}$, the Coulomb losses significantly modify the acceleration spectrum, $N(E) = \tau_{\text{Cou}} E/Q(e)$; namely, at relativistic energies, $N(E) \propto E^{-\delta+1}$. The differential energy spectrum of the bremsstrahlung emission from these electrons is calculated as (see, e.g., Blumenthal & Gould 1970)

$$I(\varepsilon) \simeq \int dE N(E)c\beta \left( n_{H} \frac{d\sigma_{\text{He}}}{d\varepsilon} + n_{H_e} \frac{d\sigma_{\text{He}}}{d\varepsilon} + n_e \frac{d\sigma_{\text{ele}}}{d\varepsilon} \right),$$

where $n_{H}, n_{H_e},$ and $n_e$ are hydrogen, helium, and electron number density, respectively, and $d\sigma/d\varepsilon$ is the differential cross section for emitting a bremsstrahlung photon in the energy interval $\varepsilon$ to $\varepsilon + d\varepsilon$. We adopt ratios $n_{H_e}/n_H = 0.1$ and $n_e/n_H = 1.2$. In the ultrarelativistic regime, the electron-electron bremsstrahlung becomes comparable to the electron-proton bremsstrahlung.

Since the bremsstrahlung cross section is in inverse proportion to the emitted photon energy, $d\sigma/d\varepsilon \propto \varepsilon^{-1}$, and depends only slightly on the electron energy in the relativistic regime, the bremsstrahlung photon spectrum almost repeats the power-law spectrum of parent electron distribution of $N(E) = kE^{-\delta}$, i.e., $I(\varepsilon) \propto \varepsilon^{-9}$ if $\alpha \gtrsim 1$. Remarkably, for the electron spectrum harder than $E^{-1}$, the bremsstrahlung photons obey a standard $\varepsilon^{-1}$ type spectrum independent of the details of the electron spectrum. Assuming that the electrons are accelerated continuously with a power-law spectral index $s$, for the resulting bremsstrahlung radiation we should expect a broken power-law spectrum with $I(\varepsilon) \propto \varepsilon^{-1}$ at $\varepsilon \geq E_{\text{Cou}}$ and $I(\varepsilon) \propto \varepsilon^{1-s}$ at $\varepsilon < E_{\text{Cou}}$. Thus, the energy spectrum of bremsstrahlung photons is determined essentially by the gas density and is characterized below the Coulomb break by a hard differential spectrum with a photon index less than 1.5 for any reasonable acceleration index of $s < 2.5$.

4.3.2. Synchrotron Radiation

The synchrotron cooling time of electrons in the magnetic field $B$ is given by

$$\tau_{\text{syn}} = \frac{\gamma m_e c^2}{(4/3)c \sigma_T U_B \gamma},$$

$$= 1.2 \times 10^3 \left( \frac{B}{10^{-5} \text{ G}} \right)^{-2} \left( \frac{E}{10^{14} \text{ eV}} \right)^{-1} \text{ yr},$$

where $\gamma$ is the electron Lorentz factor and $U_B = B^2/(8\pi)$ is the magnetic field of the electronic magnet. Equating $\tau_{\text{syn}}$ and $\tau_{\text{age}}$ gives the break energy $E_{\text{syn}}$ above which the electron spectrum is steepened:

$$E_{\text{syn}} \sim 18 \left( \frac{B}{10^{-5} \text{ G}} \right)^{-2} \left( \frac{\tau_{\text{age}}}{7000 \text{ yr}} \right)^{-1} \text{ TeV}.$$
tron emission at the relevant radio frequency is

\[ \frac{f_{\text{IC}}(\epsilon, \nu)}{f_{\text{syn}}(\nu)} = \frac{U_{\text{CMB}}}{U_B}, \]

where \( U_{\text{CMB}} = 0.25 \text{ eV cm}^{-3} \) is the energy density of the CMB radiation. The spectral power of the observed radio emission from the whole remnant, in the frequency range from 408 MHz to 4.8 GHz (Wendker, Higgs, & Landecker 1991; Higgs et al. 1977), is well described as

\[ f_{\text{radio}}(\nu) = 5 \times 10^{-12} \left( \frac{\nu}{10^{10} \text{ Hz}} \right)^{0.5} \text{ ergs cm}^{-2} \text{ s}^{-1}. \]

Since almost 60% of the radio flux comes from the southeast of \( \gamma \) Cygni, from equations (10) and (11) we find that the IC spectral power cannot exceed \( 1.7 \times 10^{-14} \left( \frac{\gamma}{B_{1.5}} \right)^{-0.5} \text{ ergs cm}^{-2} \text{ s}^{-1} \). This upper limit is less than 1% of the flux of the hard X-ray emission detected. Thus, the IC radiation can hardly explain the flux of the HXC, unless the magnetic field is extremely weak (<1 \( \mu \)G).

4.3.4. Nonthermal Bremsstrahlung X/\( \gamma \)-Radiation

The nonthermal bremsstrahlung from the accelerated electrons is a natural source of the HXC flux, because the shocked dense cloudlets act as an effective target for energetic electrons. Because of Coulomb interactions, the high-density gas leads to significant hardening of low-energy electrons below the Coulomb break, giving rise to the standard \( \epsilon^{-1} \) type bremsstrahlung spectrum at the X-ray band, which agrees perfectly with the ASCA data. The bremsstrahlung spectrum above the Coulomb break essentially repeats the acceleration spectrum of electrons. For the given spectral index of accelerated electrons, the ratio of the X- and \( \gamma \)-ray fluxes depends only on the Coulomb break energy, which in its turn depends on the gas density and the age of the accelerator.

In Figure 6, we show the results of numerical calculations for two sets of parameters that describe the gas density and the acceleration spectrum of electrons by assuming that the electron bremsstrahlung is responsible for both the ASCA hard X-ray and the EGRET \( \gamma \)-ray fluxes. For the electron spectrum with the acceleration index \( s = 2.1 \), the best fit is achieved for a gas density of \( n = 34 \text{ cm}^{-3} \). A steeper acceleration spectrum with \( s = 2.3 \) requires larger gas density, \( n = 130 \text{ cm}^{-3} \). Note that the adopted acceleration spectra are consistent with the reported radio spectral index \( \alpha = 0.5 \pm 0.15 \). We suppose an exponential cutoff in the electron spectrum at 10 TeV.

If the electron distribution with \( s = 2.3 \) (2.1) extends beyond GeV energies, for the magnetic field \( 10^{-5} \text{ G} \) the calculated radio flux density amounts to about 10% (60%) of the measured radio flux density integrated over the whole remnant. Furthermore, if the electron distribution extends beyond TeV energies, we found the bremsstrahlung spectrum with \( s = 2.1 \) exceeds the Whipple upper limit, whereas the spectral index \( s = 2.3 \) is still in agreement with the Whipple result. Meanwhile, both combinations of model parameters quite satisfactorily fit the spectral shape and the absolute flux of hard X-rays. The ignorance of energy losses of electrons would lead to significantly steeper X-ray spectra and would result also in overproduction of absolute X-ray fluxes (Fig. 6, dotted curves). Note that the main contribution to X-rays comes from relatively high energy electrons with energies close to 10 MeV for the acceleration index \( s = 2.3 \).

Because of poor angular resolution, the EGRET measurements do not provide clear information about the site(s) of production of high-energy \( \gamma \)-rays. Nevertheless, it is likely that only a part (perhaps, even only a small part) of the reported high-energy \( \gamma \)-ray fluxes originates in the HXC region. The \( \gamma \)-ray fluxes could be suppressed by assuming lower gas densities. Indeed, such an assumption would lead to the shift of the Coulomb break energy in the electron spectrum to lower energies, and the predicted high-energy \( \gamma \)-ray spectra would appear significantly below the reported EGRET fluxes (Fig. 6, solid curve).

A more likely candidate for production of the bulk of high-energy \( \gamma \)-rays is region DR4, from which most of the radio emission emerges. A massive cloud with a density of \( \sim 300 \text{ cm}^{-3} \) occupying \( \sim 5\% \) of the SNR volume has been suggested to exist in the vicinity of DR4 to explain the \( \gamma \)-ray flux (Pollock 1985). Actually, the EGRET error circle reported is somewhat away from the HXC but closer to DR4. A density of \( \sim 300 \text{ cm}^{-3} \) is higher than the upper-limit density of the HXC. Such high gas density implies a high (about 50 MeV) Coulomb break energy in the electron spectrum and considerable suppression of X-ray flux. This could naturally explain the lack of noticeable hard X-ray fluxes from the DR4 region, which is bright in radio and probably \( \gamma \)-rays.

Another possible explanation of anticorrelation between X-ray (as representative of low-energy electrons) and radio/\( \gamma \)-ray (as representative of high-energy electrons) emitting regions could be the effect of the escape of electrons. In the calculations presented in Figure 6, we assume that all electrons are trapped in the proximity of the HXC. It may be more realistic, however, that relativistic electrons can escape from the HXC, whereas subrelativistic electrons are effectively confined within the HXC volume. Obviously, this would result in reduction of the \( \gamma \)-ray to X-ray flux ratio. On the other hand, we should expect enhanced \( \gamma \)-ray and radio fluxes and suppressed X-ray flux from the dense region where these runaway electrons interact.

Finally, we discuss briefly the power consumption due to the rapid Coulomb losses. For the gas density of about 100 cm\(^{-3}\) in the HXC, the X-ray flux is produced predominantly by electrons with energies of about 10 MeV. The X-ray flux is roughly proportional to the product of the gas density and the number of relativistic electrons because the relativistic bremsstrahlung cross section depends only logarithmically on the electron energy. On the other hand, the Coulomb energy-loss rate of relativistic electrons, \( dE/dt \propto E/\tau_{\text{Coul}} \), is proportional to the gas density and almost independent of the electron energy. Therefore, the energy-loss rate of the bulk of electrons can be determined uniquely by the hard X-ray luminosity, independent of the density and the shape of the electron energy distribution. The estimated hard X-ray luminosity, \( L_X \sim 1.2 \times 10^{33} D_{1.5}^{2} \text{ ergs s}^{-1} \), can be converted to the energy-loss rate of \( L_{\text{Coul}} \sim 5 \times 10^{39} D_{1.5}^{2} \text{ ergs s}^{-1} \). The energy released in relativistic electrons would be estimated as \( W_\gamma \sim \tau_{\text{agn}} L_{\text{Coul}} \sim 10^{40} D_{1.5} \text{ ergs} \). This enormous energy deposition due to Coulomb collisions would heat the emission region of the HXC. Subsequently, the heat is radiated away in the far-infrared band by molecular line emission if the gas is composed of molecules. The observed infrared luminosity of \( \gamma \) Cygni (Saken, Fesen, & Shull 1992) is comparable to the energy-
loss rate estimated above. On the other hand, if the emission regions of the HXC are predominantly shock-heated plasmas, the deposited energies by the accelerated electrons would heat up the plasmas.

5. SUMMARY AND CONCLUSIONS

The X-ray emissions emerging from the γ Cygni SNR are found to be complex. Spatial and spectral studies of the X-ray data reveal the presence of four components: (1) limb-brightened thermal emission with a temperature of \( \cong 0.8 \) keV; (2) widespread emission with a temperature of \( \cong 0.6 \) keV aligned from north to southeast bounded by the radio-bright regions; (3) strong emission lines from Ne IX ions in the vicinity of the northern radio-bright region; and (4) clumpy hard emissions, which are best described by unusually hard power-law spectral distributions with photon index \( \Gamma \cong 0.8–1.5 \).

The limb-brightened component is considered to be thermal plasma emission from the immediate postshock region of the SNR blast wave that is propagating through the interstellar medium. The temperature gives the age estimate of \( T_{\text{age}} \cong 6600 \) yr based on the Sedov evolution of the remnant. The soft X-ray emissions from north to southeast are likely to be caused by the interaction between the supernova shock and the cavity wall composed of ambient clouds. In particular, the intense neon line emission would be attributable to the low-temperature plasma generated by the shock-cloud interaction.

The extremely hard X-ray emission of the HXC is naturally explained by the nonthermal bremsstrahlung from the loss-flattened electron distribution. By assuming that the HXC is a counterpart of the EGRET unidentified γ-ray source 3EG J2020+4017, we estimate the density of the emission region to be \( \sim 130 \) cm\(^{-3} \) for the electron index 2.3. If the HXC region contributes only a fraction of the EGRET high-energy γ-ray flux, the gas density estimate of 130 cm\(^{-3} \) should be considered as an upper limit. The bremsstrahlung interpretation requires a very large Coulomb energy-loss rate of \( \sim 5 \times 10^{37} \) erg s\(^{-1} \) and consequently the total amount of the energy loss of \( \sim 10^{46} \) ergs, regardless of the gas density and the energy of electrons responsible for the hard X-radiation. Given the limited energy budget of γ Cygni, it is more comfortable to attribute this huge energy release to the HXC region, rather than to assume that the electrons are supplied by external accelerators. The spatial structures of the HXC will be studied comprehensively by our forthcoming Chandra observation. The origin of the γ-ray emission from γ Cygni, it is more comfortable to attribute this huge energy release to the HXC region, rather than to assume that the electrons are supplied by external accelerators. The spatial structures of the HXC will be studied comprehensively by our forthcoming Chandra observation. The origin of the γ-ray emission from γ Cygni, it is more comfortable to attribute this huge energy release to the HXC region, rather than to assume that the electrons are supplied by external accelerators. The spatial structures of the HXC will be studied comprehensively by our forthcoming Chandra observation. The origin of the γ-ray emission from γ Cygni, it is more comfortable to attribute this huge energy release to the HXC region, rather than to assume that the electrons are supplied by external accelerators. The spatial structures of the HXC will be studied comprehensively by our forthcoming Chandra observation. The origin of the γ-ray emission from γ Cygni, it is more comfortable to attribute this huge energy release to the HXC region, rather than to assume that the electrons are supplied by external accelerators. The spatial structures of the HXC will be studied comprehensively by our forthcoming Chandra observation. The origin of the γ-ray emission from γ Cygni, it is more comfortable to attribute this huge energy release to the HXC region, rather than to assume that the electrons are supplied by external accelerators. The spatial structures of the HXC will be studied comprehensively by our forthcoming Chandra observation. The origin of the γ-ray emission from γ Cygni, it is more comfortable to attribute this huge energy release to the HXC region, rather than to assume that the electrons are supplied by external accelerators. The spatial structures of the HXC will be studied comprehensively by our forthcoming Chandra observation. The origin of the γ-ray emission from γ Cygni, it is more comfortable to attribute this huge energy release to the HXC region, rather than to...