An Expanding Shell of Neutral Hydrogen Associated with SN 1006: Hints for the Single-degenerate Origin and Faint Hadronic Gamma-Rays

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Abstract

We report new H I observations of the Type Ia supernova remnant (SNR) SN 1006 using the Australia Telescope Compact Array with an angular resolution of 4.5’ × 1.4’ (∼2 pc at the assumed SNR distance of 2.2 kpc). We find an expanding gas motion in position–velocity diagrams of H I with an expansion velocity of ∼4 km s−1 and a mass of ∼1000 M⊙. The spatial extent of the expanding shell is roughly the same as that of SN 1006. We here propose a hypothesis that SN 1006 exploded inside the wind-blown bubble formed by accretion winds from the progenitor system consisting of a white dwarf and a companion star, and then the forward shock has already reached the wind wall. This scenario is consistent with the single-degenerate model. We also derived the total energy of cosmic-ray protons Wp to be only ∼1.2–2.0 × 1037 erg by adopting the averaged interstellar proton density of ∼25 cm−3. The small value is compatible with the relation between the age and Wp of other gamma-ray SNRs with ages below ∼6 kyr. The Wp value in SN 1006 will possibly increase up to several 1039 erg in the next ∼5 kyr via the cosmic-ray diffusion into the H I wind shell.

Unified Astronomy Thesaurus concepts: Supernova remnants (1667); Interstellar medium (847); Cosmic ray sources (328); Gamma-ray sources (633); X-ray sources (1822)

1. Introduction

Identifying the progenitor system of Type Ia supernovae is one of the important issues of modern astrophysics because of their use as standard candles for measuring the expansion history of the universe (e.g., Perlmutter et al. 1999). The single-degenerate (SD) and double-degenerate (DD) models are widely accepted to describe the progenitor systems of Type Ia SNe: the SD model in which a white dwarf accreted gaseous materials from a nondegenerate companion until the white dwarf gets close to the Chandrasekhar mass ∼1.4 M⊙ (Whelan & Iben 1973; Nomoto 1982; Iben & Tutukov 1984; Paczynski 1985), and the DD model represents the merger of two white dwarfs (Nomoto 1982; Webbink 1984). To distinguish two scenarios, a search for a surviving companion is thought to be essential because it can be seen only in the SD scenario. Despite many efforts to detect such surviving companions of Type Ia supernova remnants (SNRs), no apparent observational evidence was reported8 (see reviews by Maoz et al. 2014; Maeda & Terada 2016; Ruiz-Lapuente 2019).

An expanding shell (also known as “wind-blown bubble”) of interstellar neutral gas associated with Type Ia SNRs has received much attention as alternative evidence for the SD scenario. Because the expanding gaseous shell could be formed by accretion winds (also known as “disk wind” or “optically thick wind”) from the progenitor system consisting of a white dwarf and a nondegenerate companion (e.g., Hachisu et al. 1996, 1999a, 1999b, 2008; Hachisu & Kato 2003a, 2003b), whereas such a wind shell is not expected in the DD scenario. The first discovery of such an expanding gaseous shell was made by CO observations toward Tycho’s SNR (Zhou et al. 2016). The authors argued that the expanding shell with the mass of ∼220 M⊙ and an expansion velocity of ∼5 km s−1 could be explained by the energy injection from accretion winds, and hence concluded that Tycho’s SNR is consistent with the DD scenario. The presence of a dense-gas wall and the SD scenario were also supported by the rapid shock deceleration during the last ∼15 yr (Tanaka et al. 2021). Subsequent CO and HI studies found similar expanding shells of atomic and/or molecular clouds in the Type Ia SNRs: RCW 86 (Sano et al. 2017), N103B (Sano et al. 2018; Alsaberi et al. 2019), and G344.7−01.0 (Fukushima et al. 2020). To better understand the progenitor system of Type Ia supernovae, we need further observations of interstellar molecular and atomic clouds toward other Type Ia SNRs.

SN 1006 (also known as G327.6+14.6) is a historical SNR that exploded in AD 1006 (Stephenson & Green 2002). The small distance of 2.2 kpc from us (Winkler et al. 2003) is consistent with its young age of ∼1000 yr and a large diameter of 28′′ or ∼18 pc. Based on the historical record, SN 1006 is widely thought to originate from a Type Ia supernova.
(Schaefer 1996). Owing to its location far from the Galactic plane (∼550 pc), SN 1006 is an ideal object to search for a surviving companion with very little contamination along the line of sight. However, neither a nondegenerate companion nor surviving white dwarf companion has been detected to date (e.g., Schweizer & Middleditch 1980; González Hernández et al. 2012; Kerzendorf et al. 2012, 2018b). Therefore, SN 1006 is thought to be a remnant that exploded as in the DD progenitor system.

SN 1006 is also noted as an ideal site for cosmic-ray acceleration since the first detection of synchrotron X-rays from the northeast and southwest shells (Koyama et al. 1995). Subsequent observations of hard X-rays and GeV/TeV gamma-rays suggest the presence of high-energy cosmic-ray electrons up to ∼100 TeV (e.g., Bamba et al. 2008; Acero et al. 2010; Xing et al. 2016; Condon et al. 2017; Li et al. 2018). Gamma-ray emission is thought to be predominantly the leptonic origin that cosmic-ray electron energies a low-energy photon into the gamma-ray energy via inverse Compton scattering (e.g., Xing et al. 2019).

The interstellar environments of SN 1006, including both the ionized and neutral gaseous medium, have been well studied by multiwavelength observations covering radio to X-rays. Assuming the standard compression ratio for a strong shock of four, the optical, infrared, and X-ray observations estimated the preshock density of ∼0.02−0.4 cm⁻³ from the postshock electron density (e.g., Kirshner et al. 1987; Bamba et al. 2003; Acero et al. 2007; Raymond et al. 2007; Yamaguchi et al. 2008; Katsuda et al. 2009; Miceli et al. 2012; Uchida et al. 2013; Winkler et al. 2013, 2014; Li et al. 2015). For the neutral hydrogen gas surrounding SN 1006, Dubner et al. (2002) carried out H1 observations with an angular resolution of 4″×3′/0 (or 3 pc×2 pc at the distance of 2.2 kpc). The authors concluded that the H1 clouds at V_{LSR} = −25 to −15 km s⁻¹ are likely interacting with the SNR, and the derived ambient density is ∼0.3 cm⁻³. On the other hand, Miceli et al. (2014) argued that the H1 clouds at V_{LSR} = −6 to 11 km s⁻¹ are interacting with the southwest shell of the SNR, by reanalysing the same H1 data sets. They also found that the X-ray shell is slightly deformed in the direction of the southwestern H1 cloud. The spatially resolved X-ray spectroscopy along the southwestern shell indicated that the X-ray-derived absorbing column density is proportional to the H1 column densities. Moreover, the cutoff energy of the synchrotron emission decreases in the regions corresponding to the southwestern cloud, suggesting that shock–cloud interaction occurred. Therefore, SN 1006 is a suitable site to test the physical relation among the supernova shocks, ambient clouds, and high-energy radiation.

Here, we report the spatial and kinematic distributions of H1 clouds toward SN 1006 using new H1 observations. Our finding of an expanding H1 shell provides a unique solution for the cloud association with SN 1006, as well as its progenitor system and cosmic-ray acceleration. In Section 2 we present the observations and data reductions. Section 3 comprises of four subsections: Section 3.1 gives an overview of X-rays and H1 toward SN 1006, Sections 3.2 and 3.3 show the spatial and kinematical distributions of H1 while Section 3.4 represents the mass and density of H1. In Sections 4 and 5 we discuss and conclude our findings.

2. Observations and Data Reduction

2.1. H1

We performed H1 observations at 1.4 GHz using the Australia Telescope Compact Array (ATCA), which consists of six 22 m antennas located at Narrabri, Australia. Observations were conducted during 24 hr on 2013 November 28, and 2014 March 12, with ATCA in the EW352 and EW367 array configurations (Project ID: C2857). We employed the mosaicking technique, with seven pointings arranged in a hexagonal grid at the Nyquist spatial separation of 19″. The absolute flux density was scaled by observing the quasar PKS 0823−500, which was used as the primary amplitude and bandpass calibrators. We also periodically observed the quasar PKS 1421−490 for gain and phase calibration. We utilized the MIRIAD software package (Sault et al. 1995) for the data reduction. To recover extended emission, we combined the ATCA data cube with archival single-dish data sets obtained using the Parkes 64 m radio telescope (McClure-Griffiths et al. 2009; Kalberla et al. 2010). The resulting beam size of H1 is 4″.5×1″4 with a position angle of 11°5, corresponding to the spatial resolution of 2.9 pc×0.9 pc at an SNR distance of 2.2 kpc. The typical noise fluctuations are 0.32 K per channel for a velocity resolution of 1 km s⁻¹.

2.2. X-Rays

We used archival X-ray data obtained by Chandra with the Advanced Charge Coupled Device (CCD) Imaging Spectrometer I array (Obs IDs: 3838, 4385−4394, 13738−13743, 14423, 14424, and 14435), which have been published by Cassam-Chenai et al. (2008) and Winkler et al. (2014). We used CIAO version 4.12 (Fruscione et al. 2006) with CALDB 4.9.1 (Graessle et al. 2007) for data reduction and imaging. After reprocessing for all data using the chandra_repro task, we created exposure-corrected, energy-filtered maps using the merge_obs task in the energy bands of 0.5−7.0 keV (broad band), 0.5−1.2 keV (soft band), 1.2−2.0 keV (medium band), and 2.0−7.0 keV (hard band). The resulting effective exposure time is ∼800 ks.

3. Results

3.1. Overview of X-Ray and H1 Distributions

Figure 1(a) shows the false-color image of SN 1006 obtained with Chandra. The X-ray morphology of SN 1006 is that of a nearly circular shell in the soft band (red: 0.5−1.2 keV), while the medium-band (green: 1.2−2.0 keV) and hard-band (blue: 2.0−7.0 keV) images show strong bilateral symmetry in the northeast and southwest direction. The soft-band image is dominated by thermal X-rays except for the northeast and southwest shells. The brightest northwestern limb is thought to be formed by interactions between the neutral hydrogen gas and supernova shocks (e.g., Long et al. 2003; Winkler et al. 2014). The hard-band image in the northeast and southwest shells corresponds to nonthermal synchrotron X-rays from cosmic-ray electrons (e.g., Koyama et al. 1995), which is also bright in TeV gamma-rays as shown in contours (Acero et al. 2010).

Figure 1(b) shows the integrated intensity map of H1. In the present paper, we focus on the velocity range from 4.0 to 12.0 km s⁻¹, which includes the shock-interacting H1 clouds suggested by Miceli et al. (2014). We find H1 clouds not only in the west shell, but also toward the north shell and the center of the SNR. Interestingly, no dense H1 clouds are adjacent to...
the southeast shells, where the shock velocity shows the maximum value in SN 1006 (Winkler et al. 2014). We also note that the HI intensity of SN 1006 is about 3–10 times weaker than that of the typical Type Ia SNRs interacting with HI clouds in the Galactic plane (e.g., Sano et al. 2017; Fukushima et al. 2020).

3.2. Velocity Channel Distributions of HI

Figure 2 shows the velocity channel maps of HI toward SN 1006. We find diffuse or clumpy HI clouds, some of which are along with the X-ray shell boundary. The HI clouds at \( V_{\text{LSR}} = 6.0–8.0 \text{ km s}^{-1} \) lie on the edges of the northeast and southwest X-ray limbs. The northwest shell appears to be associated with HI clumps at \( V_{\text{LSR}} = 10.0–12.0 \text{ km s}^{-1} \). The HI intensity at \( V_{\text{LSR}} = 8.0–10.0 \text{ km s}^{-1} \) decreases toward the center of the SNR, whereas HI clouds fill the remnant in the other velocity maps.

3.3. Spatial and Kinematic Distributions of HI

Figures 3(b) and (d) show the position–velocity \((p-v)\) diagrams in the offset \( X \) and \( Y \) coordinates, which were rotated by 45 degrees clockwise from the equatorial coordinate as shown in Figure 3(a). Because the HI clouds are distributed across the SNR from northeast to southwest, the rotated image is suitable for extracting the \( p-v \) diagram along the HI distribution. We find a cavity-like distribution in each \( p-v \) diagram of HI, whose velocity range is from 4.0 to 12.0 \text{ km s}^{-1}. This trend is not significantly changed by varying the integration spatial ranges of offset \( X \) and \( Y \). It is noteworthy that the spatial extent of each HI cavity in the offset \( X \) or \( Y \) direction is roughly consistent with the apparent diameter of the X-ray shell. We also calculated an average brightness temperature of HI on annuli in about the center of the SNR using the tool KSHELL in the KARMA (Gooch 1996). Figure 3(d) shows the radius–velocity \((r-v)\) diagram centered at...

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**Figure 1.** (a) RGB X-ray image of SN 1006 obtained with Chandra (Cassam-Chenaï et al. 2008; Winkler et al. 2014). The red, green, and blue colors correspond to the energy bands 0.5–1.2 keV, 1.2–2.0 keV, and 2.0–7.0 keV, respectively. The superposed contours indicate TeV gamma-ray significance obtained with HESS (Acero et al. 2010). The contour levels are 3, 4, 5, 6, and 7\( \sigma \). (b) Velocity integrated intensity map of HI obtained with ATCA and Parkes. The integration velocity range is from 4.0 to 12.0 \text{ km s}^{-1}. The superposed contours indicate the median-filtered Chandra X-ray intensity in the energy band of 0.5–7.0 keV. The contour levels are 2.5, 4.2, 9.3, 17.8, 29.7, and \( 45.0 \times 10^{-7} \) photons \text{s}^{-1} \text{ pixel}^{-1}.

**Figure 2.** Velocity channel distributions of HI superposed on the Chandra X-ray contours as shown in Figure 1(b). Each panel shows HI intensity map integrated every 2.0 \text{ km s}^{-1} in a velocity range from 4.0 to 12.0 \text{ km s}^{-1}.
We find a similar cavity-like distribution of HI with the velocity range of $V_{\text{LSR}}: 4.0 - 12.0 \text{ km s}^{-1}$ and a radius of 0\degree.24 that is compatible with the shell radius of SN 1006.

3.4. Mass and Density of the H I Clouds

To derive the mass of the H I clouds $M_{\text{HI}}$ at $V_{\text{LSR}}: 4.0 - 12.0 \text{ km s}^{-1}$, we used the following equation:

$$M_{\text{HI}} = m_p \Omega D^2 \sum_i N_i(\text{H I}),$$

where $m_p$ is the mass of hydrogen, $\Omega$ is the solid angle for each data pixel, $D$ is the distance to the SNR, and $N(\text{H I})$ is the atomic hydrogen column density. In general, $N(\text{H I})$ can be derived as $1.823 \times W(\text{HI})$, where $W(\text{HI})$ is the H I integrated intensity. Note that Equation (1) is valid for the optical depth of $\text{H I} \ll 1$. However, the latest observational and theoretical studies indicate that almost all H I clouds are optically thick (e.g., Fukui et al. 2014, 2015, 2018; Okamoto et al. 2017; Hayashi et al. 2019; Wang et al. 2020; Seifried et al. 2022). According to Fukui et al. (2015), the optical-depth-corrected H I column density $N_p(\text{H I})$ is typically twice higher than $N(\text{H I})$ calculated using Equation (1). Since the result was derived using the dust opacity map at 353 GHz (Planck Collaboration.
et al. 2014) toward the intermediate- and high-galactic latitude clouds, this is applicable to SN 1006 at the intermediate latitude of $\sim 15^\circ$. Here, we use a relation presented by Fukui et al. (2015, 2017) that derives $N'_H$(H I) as a function of W(H I). We then calculated the mass of the H I clouds within the shell radius of $0.24^\circ$ (or $\sim 9$ pc; Acero et al. 2010) is $\sim 1000M_\odot$, and the averaged atomic hydrogen column density is $\sim 4 \times 10^{20}$ cm$^{-2}$.

4. Discussion

4.1. Atomic Hydrogen Gas Associated with SN 1006

Miceli et al. (2014) proposed that the southwest H I cloud, peaked at $\sim 8$ km s$^{-1}$, is interacting with the SNR, by comparing spatial distributions of the H I cloud, the indentation of the X-ray shell, and the cutoff energy of synchrotron emission. Here, we suggest that the H I clouds at $v_{LSR} = 4.0$–$12.0$ km s$^{-1}$ are most likely associated with the SNR from a kinematic point of view.

We first argue that the cavity-like distributions of H I in the $p$–$v$ and $r$–$v$ diagrams provide us with a hint for the physical association with the atomic hydrogen gas at the velocity range of $4.0$–$12.0$ km s$^{-1}$. Because such cavity-like distributions in an SNR represent an expanding gas, they are thought to be formed by shock waves and/or strong winds from the progenitor system of the SNR (e.g., Koo et al. 1990; Koo & Heiles 1991; Hachisu et al. 1999a, 1999b). In the case of SN 1006, the expansion velocity is $\sim 4$ km s$^{-1}$ centered at the systemic velocity of $8 \pm 2$ km s$^{-1}$. It is also noteworthy that the projected wind shell gives the maximum extent near the systemic velocity, where we find a hollowed-out distribution of H I as shown in Figure 2(c). Moreover, the maximum spatial extent of the expanding shell is found to be roughly the same size of the SNR shell as shown in Figure 3. This indicates that the forward shock has already reached the wind shell, because the free expansion phase inside the shell is short enough owing to a much lower density (e.g., Weaver et al. 1977). In fact, Badenes et al. (2007) have already predicted such a situation using the one-dimensional numerical simulation. This can naturally explain the indentation of the X-ray shell toward the southwest H I cloud suggested by Miceli et al. (2014).

Next, we emphasize that the H I-derived systemic velocity at $\sim 8$ km s$^{-1}$ coexists with the conventional source distance of $2.2$ kpc. Although the systemic velocity at the distance of $2.2$ kpc represents about $32$ km s$^{-1}$ by adopting the Galactic rotation curve model (Brand & Blitz 1993) with conventional Galactic parameters of $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s$^{-1}$ (IAU recommended values; Kerr & Lynden-Bell 1986), the velocity difference about $40$ km s$^{-1}$ is not a problem since SN 1006 is placed almost 600 pc away from the Galactic plane. This implies that SN 1006 and its surrounding gas do not follow the Galactic rotation as also pointed out by Dubner et al. (2002) and Miceli et al. (2014).

The almost circular shape of SN 1006 without strong deformation is naturally expected by considering the column density of the shocked clouds (e.g., Lopez et al. 2009; Bozzetto et al. 2017). In general, the shell morphology approaches a circular shape with decreasing the density of shock-associated clouds (e.g., Filipović et al. 2022). The young TeV gamma-ray SNR RX J0852.0–4622 ($\sim 1700$ yr) is a good example because the SNR shows an almost circular shell. The total interstellar proton column density of shock-associated clouds is $\sim 3 \times 10^{21}$ cm$^{-2}$ for RX J0852.0–4622 (Fukui et al. 2017; Maxted et al. 2018). By contrast, young ($\sim 1600$ yr) TeV gamma-ray SNR RX J1713.7–3946 shows a strongly deformed X-ray shell owing to shock-interactions with dense clouds of $\sim 7 \times 10^{21}$ cm$^{-2}$ as averaged column density (e.g., Fukui et al. 2003, 2012, 2021; Sano et al. 2010, 2013, 2015). In the case of SN 1006, the column density of the shocked H I cloud is $\sim 4 \times 10^{20}$ cm$^{-2}$ (see Section 3.4). Because the cloud density in SN 1006 is at least one order of magnitude smaller than that in the three similar SNRs, the almost circular shape of SN 1006 is expected even if the shock–cloud interactions occurred.

Moreover, the previous proper-motion measurements may also be consistent with the H I distributions at $v_{LSR} = 4.0$–$12.0$ km s$^{-1}$. According to Winkler et al. (2014), the highest velocity of $\sim 7400 \pm 800$ km s$^{-1}$ was found in the southeast shell where no dense H I clouds are located (see Figure 1(b)). On the other hand, the slower shock velocities of $\sim 5000$ km s$^{-1}$ are seen in the northeast and southwest shells with rich H I clouds (see also Figure 1(b)). By considering the forward shock interaction with the inner wall of the H I shell, we can possibly find rapid deceleration of the shock wave toward the northeast and southwest shells of SN 1006 (e.g., Tanaka et al. 2021).

In conclusion, we claim that the H I clouds at $v_{LSR} = 4.0$–$12.0$ km s$^{-1}$ are likely associated with SN 1006 in terms of their spatial distributions, kinetics, and physical properties.

4.2. A Hint for a Single-degenerate Origin

As described in Section 3.4, the expanding H I shell associated with SN 1006 has a mass of $\sim 1000M_\odot$. If the ambient medium with this large mass was uniformly distributed over the present volume of the remnant before being blown out, the initial ambient density is estimated to be $\sim 12$ cm$^{-3}$ (here we assumed the shell radius of $\sim 9$ pc; Acero et al. 2010). On the other hand, previous X-ray studies indicated the low preshock density of $\sim 0.02$–$0.4$ cm$^{-3}$, based on the high velocity of the SNR forward shock (e.g., Katsuda et al. 2009; Winkler et al. 2014) and low ionization state of the postshock interstellar medium (ISM) and Fe ejecta (Acero et al. 2007; Yamaguchi et al. 2014). This discrepancy implies that the expanding H I shell was first formed by the strong preexplosion winds and subsequently the progenitor of SN 1006 exploded inside the low-density cavity.

Because such wind activity prior to a Type Ia supernova explosion is thought to be associated with the SD scenario, we discuss whether the typical SD progenitor system can form the expanding H I shell discovered in SN 1006. Hachisu et al. (1999a, 1999b) presented that the typical wind mass-loss rate is $\sim 2 \times 10^{-6}M_\odot$ yr$^{-1}$ (up to $\sim 10^{-4}M_\odot$ yr$^{-1}$; see also Nomoto et al. 2005) and the wind velocity is $\sim 2000$ km s$^{-1}$. If we adopt the dynamical timescale of an expanding H I shell as the wind duration period, we derive the momentum of accretion winds to be $\sim 8000M_\odot$ km s$^{-1}$ or more. On the other hand, the momentum of an expanding H I shell is to be $\sim 4000M_\odot$ km s$^{-1}$, by adopting the expansion velocity of $\sim 4$ km s$^{-1}$ and the H I cloud mass of $\sim 1000M_\odot$. Therefore, the SD scenario can adequately explain the momentum of the observed expanding H I shell.

Finally, we discuss whether only the SD channel can produce the optically thick winds through a phase of accreting material from a companion. According to Ivanova et al. (2013), the DD channel also undergoes several phases in their evolution that are not clear, in particular, the “common envelope phase.” The DD
channel also experiences stages of accretion but may be not stable enough or extended sufficiently in time compared to the SD channel. Since there are phases that we do not understand well in the DD channel, this uncertainty is a limitation of the present study to distinguish the SD and DD models. Another possibility is that a red supergiant with strong stellar winds happened to be in the line of sight. This possibility has been eliminated by the previous dedicated studies of a companion star search (e.g., Schweitzer & Middleditch 1980; González Hernández et al. 2012; Kerzendorf et al. 2012, 2018b). In any case, we would emphasize that the present H I results and current knowledge also favor the SD scenario as the explosion mechanism of SN 1006, nevertheless, no surviving companion has been detected.

4.3. Total Energy of Cosmic-Ray Protons

SNRs are thought to be promising acceleration sites for cosmic-ray protons, up to at least a few Peta electronvolts through the diffusive shock acceleration (DSA; e.g., Bell 1978; Blandford & Ostriker 1978). By considering the injection rate of cosmic rays and the total power of supernova explosions, the conventional value of the total energy of cosmic-ray $W_p$ is to be $\sim 10^{49} - 10^{50}$ erg per supernova explosion. Since $W_p$ is proportional to the gamma-ray luminosity and the inverse of gas density, we can constrain the value of $W_p$ for each SNR by observations. However, observational values of $W_p$ still had large ambiguities because of the lack of unified quantification for shock-interacting molecular/atomic clouds through the CO/H I radio line observations.

Most recently, Sano et al. (2021a, 2021b) summarized observational $W_p$ values for 12 gamma-ray SNRs by adopting the number densities of shocked clouds using CO/H I data sets. The authors found a tight relation between the SNR age and $W_p$ for 12 gamma-ray SNRs: The young SNRs below $\sim 6$ kyr show a positive correlation between them, while the older SNRs more than $\sim 8$ kyr show a steady decrease of $W_p$. The authors proposed that this trend can be explained as a combination of the age-limited acceleration (e.g., Ohira et al. 2010) and the energy-dependent diffusion of cosmic rays (e.g., Aharonian & Atoyan 1996; Gabici 2013). If the trend is real, SN 1006 shows a much lower value of $W_p$ because of the low gamma-ray luminosity and gas density as well as its young age. In the present section, we derive the $W_p$ value of SN 1006 and compare it with other gamma-ray SNRs.

According to the latest broadband spectral modeling of SN 1006, gamma-ray emission is leptonic-dominated, which was produced from the inverse Compton scattering between accelerated cosmic-ray electrons and interstellar photons. On the other hand, hadronic gamma-rays, produced by interactions between cosmic-ray protons and interstellar protons, are thought to be partially contributed. The total energy of accelerated cosmic-ray protons $W_p$ is derived by Xing et al. (2019) as:

$$W_p = 1.5 - 2.5 \times 10^{49} (n/0.2 \text{ cm}^{-3})^{-1} \text{ erg},$$

where $n$ is the number density of interstellar protons. In SN 1006, the averaged interstellar proton density is estimated to be $\sim 25 \text{ cm}^{-3}$ by adopting a shell radius of $0.24$ or $\sim 9.2$ pc and a shell thickness of $0.05$ or $\sim 1.9$ pc (Acero et al. 2010). We then obtained $W_p = 1.2 - 2.0 \times 10^{47}$ erg, which corresponds to $\sim 0.02\%$ of the typical released kinetic energy of a supernova explosion of $\sim 10^{51}$ erg.

Figure 4 shows the scatter plot between the SNR age and $W_p$ for 13 gamma-ray SNRs that are listed in Table 1. Note that the hadronic gamma-ray luminosity for deriving the $W_p$ value in each SNR was calculated by the spectral energy distribution (SED) modeling alone except for RX J1713.7−3946 (see also Fukui et al. 2021). We find that SN 1006 lies on the regression line, which was fitted using the data points with the ages of SNRs below 6 kyr, suggesting that the positive relation between the SNR age and $W_p$ is applicable to gamma-ray SNRs with ages at least $\sim 1$−6 kyr. If so, the $W_p$ value of SN 1006 will increase up to several $10^{49}$ erg in the next 5 kyr, even if the
Table 1

| Name       | Distance (kpc) | Diameter (pc) | Age (kyr) | n<sub>p</sub> (cm<sup>-3</sup>) | W<sub>p</sub> (10<sup>49</sup> erg) | References |
|------------|---------------|---------------|-----------|-------------------------------|---------------------------------|------------|
| SN 1006    | 2.2           | 18            | 1.0       | 25                            | 0.016±0.004                     | This work  |
| RX J1713.7–3946 | 1.0       | 18            | 1.6       | 130                           | 0.10±0.05                      | Fukui et al. (2021) |
| RX J0852.0–4622 | 0.75      | 24            | 1.7 (a)   | 100                           | 0.07±0.02                      | Fukui et al. (2017) |
| RCW 86     | 2.5           | 30            | 1.8       | 75                            | 0.11±0.01                      | Sano et al. (2019b) |
| HESS J1731–347 | 5.7       | 44            | 4.0       | 60                            | 0.66±0.32                      | Fukuda et al. (2014) |
| G39.2−0.3  | 6.2           | 14            | 5.0±0.2   | 400                           | 3.2±1.1                        | de Oña Wilhelmi et al. (2020) |
| W49B       | 11.0          | 16            | 6.0±1.0   | 650                           | 2.1±0.8                        | Sano et al. (2021b) |
| Kes 79     | 5.5           | 16            | 8.3±0.5   | 360                           | 0.5                             | Kuriki et al. (2018) |
| G346.6−0.2 | 11.1          | 21            | 14.0±2.0  | 280                           | <0.09                           | Sano et al. (2021a) |
| W44        | 3.0 (e)       | 27            | 20.0 (f)  | 200                           | 1.0                             | Yoshikawa et al. (2013) |
| IC 443     | 1.5 (g)       | 20            | 25.0±5.0  | 680                           | 0.09                            | Yoshikawa et al. (2022) |
| LMC N132D  | 50.0          | 25            | 2.5±0.2   | <2000                         | >0.5                            | Sano et al. (2020) |
| LMC N63A   | 50.0          | 18            | 3.5±1.5   | 190                           | 0.9±0.5                        | Sano et al. (2019a) |

Note. Column (1): name of SNRs. Column (2): distance to SNRs in units of kiloparsec. Column (3): diameter of SNRs in units of parsec. Column (4): age of SNRs in units of kiloyears. Column (5): averaged number density of total interstellar protons n<sub>p</sub> in units of centimeter<sup>-3</sup>. Column (6): total energy of cosmic-ray protons W<sub>p</sub> in units of 10<sup>49</sup> erg. Column (7): references for CO/H I-derived n<sub>p</sub> and W<sub>p</sub> for each SNR. Other specific references are also shown as follows: (a) Winkler et al. (2003), (b) Katsuda et al. (2008), (c) Su et al. (2011), (d) Zhou & Vink (2018), (e) Caswell et al. (1975), (f) Wolszczan et al. (1991), (g) Welsh & Sallmen (2003), (h) Olbert et al. (2001), Lee et al. (2008), (i) Law et al. (2020), (j) Hughes et al. (1998).
then the forward shock of SN 1006 has already reached its wind wall. This scenario coexists with the conventional
distance of 2.2 kpc because SN 1006 and its surroundings do not follow the Galactic rotation owing
to their large distances from the Galactic plane.

3. We proposed a possible scenario that the progenitor system of SN 1006 consists of a white dwarf and a
companion star, namely the single-degenerate system because the kinematics of the H I expanding shell can be
explained by accretion winds from the progenitors.

4. The total energy of accelerated cosmic-ray protons \( W_p \) is derived to be only \( \sim 1.2 - 2.0 \times 10^{49} \) erg by adopting the averaged interstellar proton density of \( \sim 25 \text{ cm}^{-3} \). This small value is compatible with a positive correlation between the age and \( W_p \) of other gamma-ray supernova remnants with an age less than \( \sim 6 \) kyr. Since the forward shock of SN 1006 has already reached the wind shell and was decelerated, a time-dependent evolution of \( W_p \) is possibly relating the cosmic-ray diffusion into the H I wind shell. The cosmic-ray diffusion can increase the \( W_p \) value in SN 1006 up to several \( 10^{49} \) erg in the next \( \sim 5 \) kyr.

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Software: IDL Astronomy User’s Library (Landsman 1993), MIRIAD (Sault et al. 1995), CIAO (v 4.12; Fruscione et al. 2006), CALDB (v 4.9.1; Graessle et al. 2007), KARMA (Gooch 1996).

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