Molecular and Atomic Clouds Associated with the Gamma-Ray Supernova Remnant Puppis A

M. Aruga1, H. Sano2,5, Y. Fukui1, E. M. Reynoso3, G. Rowell4, and K. Tachihara1

1 Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan; aruga@apnu.nagoya-u.ac.jp
2 Faculty of Engineering, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan
3 Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), Av. Int. Güraldes 2620, Pabellón IAFE, Ciudad Universitaria, Ciudad Autónoma de Buenos Aires, Argentina
4 School of Physical Sciences, The University of Adelaide, North Terrace, Adelaide, SA 5005, Australia
5 National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

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Abstract

We have carried out a study of the interstellar medium (ISM) toward the shell-like supernova remnant (SNR) Puppis A using NANTEN CO and ATCA HI data. We synthesized a comprehensive picture of the SNR radiation by combining the ISM data with the gamma-ray and X-ray distributions. The ISM, both atomic and molecular gas, is dense and highly clumpy, and is distributed all around the SNR, but mainly in the northeast. The CO distribution revealed an enhanced line intensity ratio of CO(J = 2−1)/J = 1−0) transitions as well as CO line broadening, which indicate shock heating/acceleration. The results support the assertion that Puppis A is located at 1.4 kpc, in the Local Arm. The ISM interacting with the SNR has a large mass of ~10^4 M_☉, which is dominated by H I, showing good spatial correspondence with the Fermi-LAT gamma-ray image. This favors a hadronic origin of the gamma-rays, while an additional contribution from a leptonic component is not excluded. The distribution of the X-ray ionization timescales within the shell suggests that the shock front ionized various parts of the ISM at epochs ranging over a few to ten thousand years. We therefore suggest that the age of the SNR is around 10^4 yr as given by the largest ionization timescale. We estimate the total cosmic-ray energy W_p to be 10^47 erg, which is well placed in the cosmic-ray escaping phase of an age–W_p plot including more than ten SNRs.

1. Introduction

The origin of cosmic rays, mainly consisting of relativistic protons, is one of the longstanding questions in modern astrophysics since their first discovery by Hess (1912). Galactic supernova remnants (SNRs) are thought to be a promising site of cosmic-ray acceleration below ~3 PeV (also known as the “knee energy”) via diffusive shock acceleration (e.g., Blandford & Ostriker 1978; Bell 1978). The latest observational studies confirmed the acceleration of cosmic-ray protons up to ~100 TeV in SNRs (e.g., Fukui et al. 2021). If the supernova origin of cosmic rays is correct, the total energy of accelerated cosmic rays, W_p, is estimated to be ~10^{49}–10^{50} erg per single supernova explosion by considering the frequency of supernova explosions, the cosmic-ray energy density, and their confinement time in the Galactic disk (e.g., Gabici 2013). One of the current challenges is to provide observational support for such theoretical predictions.

Investigating interstellar gas in gamma-ray SNRs holds a key to deriving W_p observationally, because cosmic-ray protons emit gamma-rays through p–p collisions with interstellar protons via the π0–2γ process (known as hadronic gamma-rays). Since the hadronic gamma-ray flux is proportional to the target gas density and W_p, it is essential to estimate the mass of the target interstellar protons accurately. Although interstellar protons were conventionally assumed to have a uniform density of 1 cm^-3, such an assumption is not justified as demonstrated by recent radio observations. Several detailed CO/H I radio-line studies revealed a highly clumped dense interstellar medium (ISM) distribution that corresponds overall to the SNR shape, and successfully estimated the mass of the molecular and atomic clouds including the target protons in Galactic/Magellanic gamma-ray SNRs (e.g., Fukui et al. 2003, 2012; Yoshii et al. 2013; Sano et al. 2017a; Fukui et al. 2017; Sano et al. 2019, 2020; Fukui et al. 2021). These works show that the target clouds consist of neutral molecular and atomic hydrogen gas; we note that the inclusion of atomic hydrogen is indispensable since the mass of atomic hydrogen often becomes dominant as compared to molecular hydrogen. Most recently, Sano et al. (2021a, 2021b, 2022) presented an SNR age–W_p relation for 13 gamma-ray SNRs. They discovered a tight correlation between the SNR age and W_p, the young SNRs (age < 6 kyr) show a positive correlation while the middle-aged SNRs (age > 8 kyr) display a negative correlation. The authors concluded that the latter is at least caused by the time-dependent diffusion (or escape) of cosmic rays from the SNR. W_p is here assumed to give a good measure of hadronic gamma-rays, although some leptonic gamma-ray component might be included. Recent work that quantified the hadronic and leptonic gamma-rays in RX J1713.7–3946 supports the assertion that two contributions are indeed, which are of the same order of magnitude (e.g., Fukui et al. 2021). Although the age–W_p relation is crucial for understanding the acceleration and escape mechanisms of cosmic rays in SNRs, the observed samples are not large enough, especially for middle-aged SNRs.

Puppis A is a middle-aged SNR having a shell-like morphology with a 50’ diameter in radio continuum. This SNR is a bright thermal X-ray emitter as observed with the X-ray telescopes Einstein (Petre et al. 1982), ROSAT...
(Aschenbach 1993), Suzaku (Hwang et al. 2008), Chandra (Hwang et al. 2005; Dubner et al. 2013), and XMM-Newton (Hui & Becker 2006; Katsuda 2010; Katsuda et al. 2012; Dubner et al. 2013). Such X-ray emission comes from the shocked ISM (e.g., Hwang et al. 2008). The compact central object (CCO) RX J0822−4300 was detected in X-rays inside the shell, and it is likely that the progenitor of the SNR was a high-mass star (Petre et al. 1996; Zavlin et al. 1999; Reynoso et al. 2017). Hewitt et al. (2012) reported the detection of faint GeV gamma-ray emission from Puppis A with Fermi-LAT. Considering the multiwavelength data from the radio to gamma-rays, both leptonic and hadronic models are possible with different magnetic field strengths and different energies of the relativistic particles (e.g., Xin et al. 2017).

The ISM interacting with the SNR is essential for understanding the origin of the high- and very-high-energy radiation. Dubner & Arnal (1988) observed with the H I 21 cm line and the CO(J = 1−0) 2.6 mm line and found a molecular cloud coincident with the SNR shell. These authors interpreted that this coincidence shows an interacting cloud at ~16 km s⁻¹. An H I study with the Very Large Array (VLA) supported this velocity based on morphological coincidence (Reynoso et al. 1995, 2003), and these works suggested a kinematic distance of 2.2 kpc. Follow up studies of CO and OH lines, however, did not give conclusive results on the interacting clouds via non-detections due to too-small spatial coverage and low resolution (CO; Paron et al. 2008; 1720-MHz OH; Frail et al. 1996; four lines of OH; Woermann et al. 2000). Subsequently, Reynoso et al. (2017) conducted new H I absorption measurements with Australia Telescope Compact Array (ATCA), and found that ~1.3 kpc is a more likely distance, in contrast to their early results. In summary, more extensive efforts are desirable in order to have a comprehensive physical picture of the ISM in Puppis A and better constrain its distance.

In the present work, we have undertaken a new study of the ISM toward Puppis A by employing CO and H I data, which are combined with X-ray and gamma-ray data as well as the visual extinction. The present paper is organized as follows. Section 2 describes the data sets and Section 3 presents the results, including the distributions of CO and H I intensity and their kinematic properties. Section 4 discusses the ISM associated with the SNR, including that located in front of the SNR, along with the relationship with the X-rays and gamma-rays. New pieces of evidence for the associated ISM are presented and a distance is established. Section 5 concludes the paper.

2. Observations and Data Reduction

2.1. CO

Observations of $^{12}$CO(J = 2−1) at 230.538 GHz were conducted from 2014 December to 2015 January using the NANTEN2 4 m millimeter/submillimeter telescope at Pampa la Bola in northern Chile (4,865 m above sea level). We used the on-the-fly (OTF) mode with Nyquist sampling, and the observed area was 75' × 30'. The front end was a 4 K cooled Nb superconductor-insulator-superconductor (SIS) mixer receiver. The typical system temperature including the atmosphere was ~200 ± 40 K in the double sideband. The back end was a digital Fourier transform spectrometer (DFS) with 1 GHz bandwidth and 16,384 channels, corresponding to a velocity resolution of 0.08 km s⁻¹ and a velocity coverage of 1300 km s⁻¹. The pointing offset was better than ~10″, verified by observing Jupiter and IRC+10216. The absolute intensity was calibrated by observing Orion-KL [α(J2000) = 05°35'13.471, δ(J2000) = −5°22'27.55′'] (Berné et al. 2014), obtaining a main beam efficiency of ~0.63. After convolution using a three-dimensional Gaussian function of 60″ (FWHM), the final beam size was ~100″. The typical noise fluctuations are ~0.14 K at a velocity resolution of 1 km s⁻¹.

In addition, we used $^{12}$CO(J = 1−0) emission line data at 115.271 GHz taken with the NANTEN 4 m telescope, which were already published by Moriguchi et al. (2001). Observations were carried out in the position-switching mode with a 2′ grid spacing. The angular resolution of the data was 2.6′ (FWHM) and the velocity resolution was 0.65 km s⁻¹. The typical noise fluctuations are ~0.16 K at a velocity resolution of 1 km s⁻¹ (for more detailed information, see Moriguchi et al. 2001).

2.2. H I

We used the 21 cm H I data taken with the ATCA and single-dish data from the Parkes 64 m radio telescope. Details on the observing techniques and data processing are given in Reynoso et al. (2017). The beam size of H I was 118″ × 88″, with a position angle of −4°.3. The typical noise level is ~0.71 K at a velocity resolution of 1 km s⁻¹.

2.3. X-Rays

To compare the spatial distributions of CO/H I and X-rays in detail, we analysed archival X-ray data obtained by XMM-Newton and Chandra (e.g., Katsuda 2010; Katsuda et al. 2012; Dubner et al. 2013; Katsuda et al. 2013; Luna et al. 2016). Archival XMM-Newton data taken with both EPIC-pn and EPIC-MOS were reduced using the XMM-Newton Science Analysis System (SAS; Gabriel et al. 2004) version 19.1.0 and HEAsoft version 6.28. We reprocessed the observation data following the procedure provided in the XMM-Newton extended source analysis software (ESAS; Kuntz & Snowden 2008), except for the EPIC-pn data taken in the large-window mode. After filtering soft proton flares using the “mos/-pn-filter” tasks, we generated quiescent particle background (QPB) images and exposure maps for each observation using the tasks “mos/-pn-spectra” and “mos/-pn-back”. We also used the “eimageget” task for the EPIC-pn data taken in the large-window mode. The “merge_comp_xmm” task was used to combine all the XMM-Newton data. Here we created the background, exposure, and counts maps for the energy bands of 0.5−7.0 keV, 0.36−0.46 keV, and 1.14−1.27 keV. The former energy band represents the broadband image, and the others correspond to the continuum bands without any strong line emission (see Hwang et al. 2008).

In the Chandra analysis, we used nine individual observational data sets that were taken with the Advanced CCD Imaging Spectrometer (ACIS). All the data sets were reduced using the Chandra Interactive Analysis of Observations (CIAO; Fruscione et al. 2006) software version 4.12 with CALDB 4.9.1 (Graebeck et al. 2007). We utilized the “chandra_repro” task to reprocess the data with the latest calibration. We then created the background, exposure, and counts maps for each energy band using the “fluximage” task.

To combine both the XMM-Newton and Chandra data sets, we corrected vignetting and weighting according to their respective effective areas for each energy band. After applying
adaptive smoothing using the “adapt_merge” task in ESAS, we then finally obtained exposure-corrected, energy-filtered, and background-subtracted images covering the entire SNR.

2.4. Other Wavelength Data Sets

Hα and radio continuum data are used to derive the spatial distribution of the ionized gas and synchrotron radiation, respectively. We used the Hα data that appear in the Super Cosmos Hα Survey (SHS; Parker et al. 2005), and the 1.4 GHz radio continuum data taken with ATCA and the Parkes 64 m radio telescope (Reynoso et al. 2017). The angular resolution is 0°67 for the SHS Hα data and 82°2 x 50°6 with a position angle of −0°55 for the radio continuum data.

3. Results

3.1. Distributions of Gamma-Rays, Radio Continuum, and X-Rays

Figure 1(a) shows the distribution of the 1.4 GHz radio continuum obtained by ATCA & Parkes (Reynoso et al. 2017). The radio continuum shows a shell, which is bright and flat on the northeastern side. The shell also has additional components in the west at Decl. ~–43°, R.A. ~8°20′, and in the south at Decl. ~–43°25′, R.A. ~8°22′, which are not continuous with the shell.

Figure 1(b) shows a composite X-ray image of Puppis A in the energy band 0.5–7.0 keV (e.g., Katsuda et al. 2008; Dubner et al. 2013). The X-rays are completely thermal and are distributed nearly within the boundaries set by the radio emission shell, with an intensity gradient decreasing from the bright eastern edge to the west. A broad strip of harder X-ray emission covers the center of the SNR in the northeast–southwest direction. There is a CCO in the center of the SNR. In addition, the X-rays are bright in the northeastern half and have good correspondence with the radio continuum radiation.

Figure 1(c) shows the GeV gamma-ray distribution obtained with Fermi-LAT (Xin et al. 2017). The major peak coincides with the X-ray shell and the two additional peaks in the west and south seem to correspond to the radio and X-ray components, respectively, (Figures 1(a) and (b)).

3.2. Velocity Channel Distributions of CO and H I

Figure 2 (upper panel) shows integrated velocity channel maps of the NANTEN 12CO(J = 1–0) every 4 km s−1 from −4 km s−1 to 20 km s−1. We find the largest CO cloud in the field is located at V_{LSR} = 0–8 km s−1 and is elongated from the northeast to the southwest over ~1°. Several smaller CO clouds are distributed toward the SNR shell at V_{LSR} = 0–20 km s−1.

Figure 2 (lower panel) shows the velocity channel distributions of the ATCA & Parkes H I in the same velocity ranges as Figure 2 (upper panel). The H I emission is brighter than 400 K km s−1 at V_{LSR} = 8–16 km s−1, while the H I intensity at V_{LSR} = 0–8 km s−1 is significantly weaker toward the radio shell of the SNR. The H I clouds at V_{LSR} = 8–20 km s−1 are distributed along the eastern half of the SNR shell, and the edge of the H I clouds at V_{LSR} = 16–20 km s−1 shows good spatial correspondence with the northeastern shell of the SNR. A more detailed comparison of the clouds with the shell is shown later in Figure 4.

3.3. The CO 2–1/1–0 Ratio

Figures 3(a) and (b) show maps of the 12CO(J = 2–1/1–0) intensity ratio (hereafter R_{CO}) in the two velocity ranges from 0 km s−1 to 8 km s−1 and from 8 km s−1 to 20 km s−1. The J = 1–0 mapping is limited to the rectangular area shown by the white lines, which includes the northeastern part of the shell. The ratio between the two transitions is convolved to the beam size of the J = 2–1 transition. The CO cloud at 3 km s−1 shows a low R_{CO} value of ~0.5 in the entire cloud, whereas the cloud at 11 km s−1 shows a higher R_{CO} value of ~0.8–1.1. Figure 3(c) shows the averaged 12CO(J = 2–1) and 12CO(J = 1–0) profiles enclosed by the red rectangular area in Figures 3(a) and (b). We find wing-like profiles in both of the CO profiles at V_{LSR} = 12–18 km s−1. Since the typical noise fluctuations of the averaged profiles are ~0.07 K/ch for the 12CO(J = 1–0) and ~0.06 K/ch for the 12CO(J = 2–1) emission lines, the wing-like profiles have signal-to-noise ratios >4. The ratio distribution indicates that the cloud at 11 km s−1 is more highly excited than the cloud at 3 km s−1. A ratio of more than ~1 is typical of clouds shocked by SNRs, while a ratio of ~0.5 is typical of non-shocked gas (e.g., for W44 see Yoshiike et al. 2013). Along with the broad CO wings, the high line intensity ratio of CO indicates that the cloud at 11 km s−1 only is interacting with the SNR. H I or molecular features below...
Figure 2. Velocity channel distributions of the NANTEN $^{12}$CO($J = 1$–0) and the ATCA & Parkes H I. The superposed contours are 1.4 GHz radio continuum from ATCA & Parkes (Reynoso et al. 2017). The contour levels are 40, 100, 220, 340, and 460 mJy beam$^{-1}$. Each panel of CO/H I shows distributions every 4 km s$^{-1}$ in the velocity range $-4$ to $20$ km s$^{-1}$. The color bars for CO and H I are shown at the top of the set of panels.
8 km s\(^{-1}\) are hardly related to Puppis A, since the previous absorption studies place the SNR well beyond this velocity (e.g., Woermann et al. 2000; Reynoso et al. 2017). Besides, the peak at 3 km s\(^{-1}\) shown in Figure 3(c) is narrow, as expected for undisturbed gas. In all, this component is most likely foreground to the SNR; hence, we will focus on the 8–20 km s\(^{-1}\) cloud hereon.

3.4. Detailed Comparison of CO and H\(^{\text{1}}\) with the SNR Shell

We focus on the 8–20 km s\(^{-1}\) cloud and compare it with the SNR shell more detail. Figures 4(a), (c), and (e) show CO and H\(^{\text{1}}\) in the velocity range 8–20 km s\(^{-1}\), which are superposed on the radio continuum, respectively, and are superposed with each other. Figures 4(b), (d), and (f) show position–velocity (p–v) diagrams of the 8–20 km s\(^{-1}\) cloud in CO and H\(^{\text{1}}\). The p–v diagrams at 8–20 km s\(^{-1}\) show a cavity at −42°25′ to −42°42′, which corresponds to the SNR shell.

We compare the spatial distributions among the CO, X-rays, radio continuum, and H\(^{\text{1}}\) toward the two areas in the northeast and in the east of the shell, as indicated in Figure 4(a). In the upper panels of Figure 5, for the northeast of the shell, we compare the \(^{12}\text{CO}(J = 2–1)\) contours with the radio continuum image (Figure 5(a)), the X-ray image (Figure 5(b)), and the H\(^{\text{1}}\) image (Figure 5(c)). In the lower panels of Figure 5, for the east of the shell, we compare the \(^{12}\text{CO}(J = 2–1)\) contours with the radio continuum image (Figure 5(d)), the X-ray image (Figure 5(e)), and the H\(^{\text{1}}\) image (Figure 5(f)).

We find that the X-rays at Decl. < −42°39′ and R.A. > 8°22′250′ tend to be anticorrelated with the CO (Figure 5(b)), and that the H\(^{\text{1}}\) at Decl. = −42°35′ to 30′ and R.A. < 8°22′250′ tends to be anticorrelated with the CO (Figure 5(c)). Similar trends are recognized in the radio continuum image compared with the CO (Figure 5(a)). Further, we find that X-ray features and H\(^{\text{1}}\) features are located within the small CO cavity at Decl. = 43°00′ to 42°55′ and at R.A. = 8°23′250′ to 8°24′00′ (Figures 5(e) and (f)). These X-ray features were suggested to be interacting with the ISM by Hwang et al. (2005) without a direct comparison with the ISM. The present result (Figure 5(e)) indicates a small CO clump of 1 arcmin size toward the X-rays, which shows a possible interaction candidate. To summarize, the intense parts of the SNR shell show a trend that the 8–20 km s\(^{-1}\) CO cloud is anticorrelated with the ionized or hot gas/high-energy electrons, lending support for the association of the 8–20 km s\(^{-1}\) cloud with the SNR.

4. Discussion

4.1. Molecular and Atomic Clouds Associated with the SNR Puppis A

4.1.1. Comparison with the X-Ray Hardness Ratio and \(A_V\)

In order to test the interstellar absorption of the X-rays, we compare the hardness ratio map of X-rays with the total interstellar proton column density \(N_p(H_2 + H^{\text{1}})\) of the 0–8 km s\(^{-1}\) and 8–20 km s\(^{-1}\) clouds. We use the following equations to derive \(N_p(H_2 + H^{\text{1}})\) for each cloud:

\[
N_p(H_2 + H^{\text{1}}) = N_p(H_2) + N_p(H^{\text{1}}),
\]

where \(N_p(H_2)\) is the proton column density of the molecular component and \(N_p(H^{\text{1}})\) is the proton column density of the atomic component.

\(N_p(H_2)\) can be derived from the following relationships between the molecular hydrogen column density \(N(H_2)\) and the \(^{12}\text{CO}(J = 1–0)\) integrated intensity \(W(\text{CO})\):

\[
N(H_2) = X \cdot W(\text{CO}) \text{(cm}^{-2}),
\]

\[
N_p(H_2) = 2 \times N(H_2) \text{(cm}^{-2}),
\]

where \(X\) is the \text{CO}-to-H\(_2\) conversion factor between the \(N(H_2)\) and \(W(\text{CO})\). We use \(X = 1.5 \times 10^{20} \text{ cm}^{-2} \text{(K km s}^{-1})^{-1}\), which is derived in Appendix A.

For calculating the \(H^{\text{1}}\) column density \(N_p(H^{\text{1}})\), we used a conversion factor between the optical-depth-corrected \(N_p(H^{\text{1}})\) and \(W(H^{\text{1}})\) (Fukui et al. 2015, 2017), and obtained the average optical-depth-corrected \(N_p(H^{\text{1}})\) to be \((4.3 \pm 0.4) \times 10^{21} \text{ cm}^{-2}\) in the Puppis A region, which is ∼2.2 times greater than the optically thin case.
Figure 4. Integrated intensity maps and position–velocity (p–v) diagrams of $^{12}$CO ($J = 1–0$) (top panels) and H I (middle and bottom panels). The integration range is 8 to 20 km s$^{-1}$ (left panels) in the velocity for each intensity map; and from 124°98 to 126°22 in the R.A. for each p–v diagram. The superposed contours in Figures 4(a) and (c) indicate the radio continuum at 1.4 GHz, whose contour levels are the same as shown in Figure 2. The superposed contours in the bottom panels indicate $^{12}$CO ($J = 1–0$), whose contour levels are 3, 6, 9, 12, 15, 18, and 21 K km s$^{-1}$ for Figure 4(e); and 0.10, 0.28, 0.46, 0.64, 0.82, 1.00, 1.18, 1.36, 1.54, 1.72, 1.90, and 2.08 K degree for Figure 4(f).
Figures 6(a) and (b) show the hardness ratio map of X-rays overlaid with N_p(H_2 + HI) contours of the 0–8 km s\(^{-1}\) and 8–20 km s\(^{-1}\) clouds. Figure 6(c) shows the correlation plots between the hardness ratio and N_p(H_2 + HI). The 0–8 km s\(^{-1}\) cloud shows spatial anticorrelation with N_p(H_2 + HI), indicating that the 0–8 km s\(^{-1}\) cloud is absorbing soft X-rays. On the other hand, the 8–20 km s\(^{-1}\) cloud shows almost no correlation with the hardness ratio, indicating that the 8–20 km s\(^{-1}\) cloud is mostly not responsible for absorbing soft X-rays. The correlation coefficient is ∼0.66 in the 0–8 km s\(^{-1}\) cloud, and is ∼0.0 in the 8–20 km s\(^{-1}\). We however cannot exclude the possibility of a spatial correlation at (α_2000, δ_2000) = (8^h23^m45^s, -42°48'), as shown in dashed circle in Figure 6(b), where the hardness ratio may become high due to some local mixing between the cloud and the SNR shell along the line of sight.

Further, we calculate N_p(A_V), the hydrogen column density from A_V (Dobashi et al. 2005), by using the relationship N_p(A_V) ∼ 1.87 × 10^{21} A_V(cm\(^{-2}\)) (Bohlin et al. 1978). Figure 7 shows a scatter plot between N_p(A_V) and N_p(H_2 + HI) of the 0–8 km s\(^{-1}\) cloud. They are correlated with each other with a correlation coefficient of ∼0.62, supporting the trend in Figure 6. The anticorrelation in Figures 6 and 7 and the lack of shock excitation in the 0–8 km s\(^{-1}\) cloud (see Figure 3(a)) are all consistent with the 0–8 km s\(^{-1}\) cloud lying in front of the SNR and is not interacting with the SNR shock. This also explains the intensity decrease of the H I emission toward the radio continuum shell as due to absorption in Figure 2.

4.1.2. Shock Interaction and the ISM Cavity

We presented signatures of shock interaction in part of the CO gas in the 8–20 km s\(^{-1}\) cloud, which include the enhanced CO line intensity ratio R_{CO} and the broadened CO wing toward the northeast of the shell. R_{CO} is used for identifying the molecular gas associated with a SNR (Seta et al. 1998). The rotational state with J = 2 has a temperature of 16 K from the ground level J = 0, and a comparison of the state with J = 1 state at 5 K provides an indicator of the rotational excitation. R_{CO} therefore gives a measure of the excitation state driven by temperature and/or density (e.g., Seta et al. 1998; Yoshiike et al. 2013). Toward Puppis A, R_{CO} in the 0–8 km s\(^{-1}\) cloud is
as low as 0.5, while \( R_{CO} \) in the 8–20 km s\(^{-1}\) cloud toward the northeast of the SNR \( R_{CO} \) is as high as \( \sim 0.8–1.1 \) (Figures 3(a) and (b)). This high ratio is likely due to shock heating by the SNR because there is no other heating source. The CO wing is also a common signature of shock acceleration. In the middle-aged SNRs W28, W44, and IC 443, broad 12CO wings of 20–40 km s\(^{-1}\) are observed and are interpreted as due to shock acceleration (e.g., Wootten 1977; Denoyer 1979; Wootten 1981). The present 12CO broad feature has a moderate velocity span of \( \sim 5 \) km s\(^{-1}\) and the acceleration seems to be not as strong as in the other SNRs. Nonetheless, the feature is well recognized independently from the quiescent narrow component (Figure 3(c)) and is associated with the high \( R_{CO} \), lending support for the shock interpretation.

The ISM associated with the SNR shell is expanding by acceleration due to the supernova explosion and/or the stellar winds of the progenitor star. Puppis A is a remnant of a core-collapse explosion, and the progenitor was likely a high-mass star which produced strong stellar winds (Petre et al. 1996; Zavlin et al. 1999; Reynoso et al. 2017). We showed that the CO gas in the 8–20 km s\(^{-1}\) cloud shows a cavity in p-v diagrams (Figures 4(b) and (f)). Such a cavity-like distribution is a possible signature of an explosive event (e.g., Chevalier & Gardner 1974). The 0–8 km s\(^{-1}\) cloud also shows correlation with the radio continuum shell (Figure 2), but it is likely that the correlation is very close to the radio continuum emission, suggesting an absorption origin of the radio continuum emission that is in the background of the 0–8 km s\(^{-1}\) cloud.

A cloud associated with a SNR sometimes shows enhanced X-rays or radio continuum emission near and toward the SNR shell (e.g., Sano et al. 2010, 2013, 2017b). We find such a trend in the 8–20 km s\(^{-1}\) CO cloud, which shows peaks of the radio continuum emission and X-rays separated from the SNR by a few tens of arcsec (Figure 5). This suggests that the 8–20 km s\(^{-1}\) cloud is heated up by the SNR. In addition, the H\(\alpha\) emission shows an anticorrelated distribution with the 8–20 km s\(^{-1}\) CO cloud (see also Figure 5), suggesting that the gas is ionized by shock/winds and/or FUV photons produced by X-ray ionization (e.g., Prasad & Tarafdar 1983); see also the discussion in Paron et al. (2008).

4.2. Distance, ISM Mass, and Age of the SNR Puppis A

An early VLA H I study placed Puppis A at a distance of \( \sim 2.2 \) kpc (Reynoso et al. 1995). Additional hints supporting such a distance were reported in a subsequent H I survey toward the inner region of the SNR (Reynoso et al. 2003). However, a more recent H I absorption study with improved sensitivity and resolution (both spatial and spectral) covering the full SNR and its surroundings, in which single-dish data were combined with interferometric data so as to ensure that large-scale structures were sampled, revised the distance to \( \sim 1.3 \) kpc (Reynoso et al. 2017). In the present work, we used the CO \( J=2-1 \) distribution obtained with NANTEN, which covers the whole SNR at 1/3 resolution in conjunction with the H I and X-rays, and identified the interaction signatures of CO with the SNR shell. The 8–20 km s\(^{-1}\) cloud has been confirmed to be interacting with the SNR. From Figure 3(c), it is clear that the narrow component of the 8–20 km s\(^{-1}\) cloud, which indicates the cloud’s systemic velocity, peaks at \( \sim 10–11 \) km s\(^{-1}\). This result is in excellent agreement with Reynoso et al. (2017) based on H I absorption. Following the Galactic rotation model by Fich et al. (1989), this velocity corresponds to \( d \sim 1.4 \pm 0.1 \) kpc. Since we have demonstrated that Puppis A is interacting with this cloud, hereafter we will adopt this distance for both the cloud and the SNR. The 8–20 km s\(^{-1}\) cloud has been confirmed to be interacting with the SNR and the distance of 1.4 kpc is supported. Since the CO velocity range of the interacting cloud is narrower than the velocity range derived from the H I absorption study by Reynoso et al. (2017), we are able to pinpoint the cloud’s systemic velocity with higher accuracy and thus improve the precision of the distance determination.

We then derive interstellar proton density \( n_H (H_2 + H I) \) and the total mass of the interstellar protons by assuming a distance of 1.4 kpc. In order to estimate the H\(_2\) molecular mass of the CO clouds \( M_{CO} \), we used the following equation:

\[
M_{CO} = \mu m_H \Sigma_1[D^2 \Omega N(H_2)],
\]

where \( \mu \) is the mean molecular weight, \( m_H \) is the mass of the atomic hydrogen cloud, \( D \) is the distance to the SNR, \( \Omega \) is the solid angle of a square pixel, and \( N(H_2) \) is the molecular
The data sets used here are smoothed with a Gaussian function to the half-power beam width of the integrations is 0–8 km s$^{-1}$. (a) Column density map of $N_p$ estimated from $A_V$ (Dobashi et al. 2005) (hereafter the “$N_p(A_V)$”). The superposed contours indicate the 1.4 GHz radio continuum, as shown in Figure 2. (c) Correlation plots between $N_p(A_V)$ and $N_p(H_2 + H_1)$. The dashed line represents the equality of the two values. All the data sets used here are smoothed with a Gaussian function to the half-power beam width of the $A_V$ distribution ($\sim 6'$).

The hydrogen column density of each pixel $i$. We used $\mu = 2.8$ including the contribution from helium. The hydrogen column density $N(H_2)$ is derived by using the equation $(X = 1.5 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}, N(H_2) = X \cdot W(\text{CO}) \text{ (cm}^{-2})).$ We estimated the mass of the molecular clouds within the radio shell extent (=shell radius + 1/2 shell thickness) to be $\sim 0.1 \times 10^6 M_{\odot}$. The mass of atomic hydrogen $M_{\text{HI}}$ is derived by the Equation (5):

$$M_{\text{HI}} = m_{\text{HI}} D^2 \Omega \Sigma [N_p(H \text{ I})],$$

where the $N_p(H \text{ I})$ is given by the optical-depth-corrected $N_p(H \text{ I})$ (see Section 4.1.1). We thus estimated the mass of the atomic clouds to be $\sim 1.3 \times 10^6 M_{\odot}$, which is about 10 times larger than that of the molecular clouds. The averaged number densities within the radio shell were estimated to be $\sim 10 \text{ cm}^{-3}$ for the molecular hydrogen $n(H_2)$, and $\sim 220 \text{ cm}^{-3}$ for the atomic hydrogen $n(H \text{ I})$ by adopting a shell radius of 23/8 ($\sim 9.7$ pc) and a shell thickness of 6.73 ($\sim 2.7$ pc). Then, we derived the number density of the total interstellar protons $n$ to be $2 \times n(H_2) + n(H \text{ I}) \sim 230 \text{ cm}^{-3}$.

The estimated age of Puppis A is scattered in a large range of $\sim 2000$–$10,000$ yr in the literature (e.g., Culhane 1977; Caswell & Lerche 1979; Aschenbach 2015; Mayer et al. 2020). We briefly summarize the previous studies below.

The ionization timescale is given as $4200$ yr, $7000$ yr, and $10,000$ yr at various places of the SNR (Mayer et al. 2022). Other age estimates come from the proper motion of various parts of the SNR or the Sedov solution: 3700 $\pm 300$ yr (the optical filament; Winkler et al. 1988), 4450 $\pm 750$ yr (the CCO; Becker et al. 2012), 1990 $\pm 150$ yr (the ejecta with a decelerated model; Aschenbach 2015), 4600 yr (the CCO; Mayer et al. 2020), and 4000–8000 yr (Sedov solution; Culhane 1977; Caswell & Lerche 1979).

Among these, we may adopt here the ionization age estimated from X-rays, which is defined as $\tau = n_e \tau_e$ ($n_e$ is the electron density and $\tau_e$ is the time since the emitting material was first struck by the shock wave; Borkowski et al. 2001; Mayer et al. 2022). The age gives the upper limit to the ionization timescale required to achieve the ionization state in the plasma, which in turn quantifies the degree of departure from collisional ionization equilibrium (CIE). It is correlated with the ISM identified in the present work (will be presented in a forthcoming paper), and we assume that the largest age of $10,000$ yr is close to the true age of the SNR. Such a middle age seems to be consistent with the spectral properties of Puppis A, which has no synchrotron X-rays or bright TeV gamma-rays (e.g., Funk 2015; Xiang & Jiang 2021).

4.3. Comparison with the Gamma-Ray Distribution

4.3.1. Estimation of the Cosmic-Ray Energy from the Hadronic Gamma-Rays

In the previous works of the gamma-rays in SNRs, unfortunately not much attention has been paid to the details of the ISM distribution, and it has been often the case that the ISM density was simply assumed to be uniform and as low as $1 \text{ cm}^{-3}$. Such assumptions obviously have no justification and lead to significant overestimation of the cosmic-ray energy in order to compensate for a lack of target protons in the p-p reaction. In RX J1713.7−3946, Fukui et al. (2021) showed that the quantification of the hadronic gamma-rays is only possible by identifying the detailed ISM distribution.

Figure 8 shows that the GeV gamma-ray distribution has spatial correspondence with the 8–20 km s$^{-1}$ cloud, whereas the correspondence is not conclusive given the limited angular resolution of the gamma-rays. Instead, it suggests that the ISM density was simply assumed to be uniform and as low as $1 \text{ cm}^{-3}$. Such assumptions obviously have no justification and lead to significant overestimation of the cosmic-ray energy in order to compensate for a lack of target protons in the p-p reaction. In RX J1713.7−3946, Fukui et al. (2021) showed that the quantification of the hadronic gamma-rays is only possible by identifying the detailed ISM distribution.

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to be as follows (e.g., Aharonian et al. 2006):

$$W_p^{\text{tot}} \sim t_{pp} \rightarrow \tau_0 \times L_\gamma,$$

where $t_{pp} \rightarrow \tau_0 \sim 4.5 \times 10^3 \left(\frac{n}{100 \text{ cm}^{-3}}\right)^{-1} \text{s}$ is the characteristic cooling time of the protons and $L_\gamma$ is the gamma-ray luminosity derived by Xin et al. (2017). An upper limit for $W_p$ is given as follows:

$$W_p \sim 1.21 \times 10^{48} \left(\frac{n_p}{100 \text{ cm}^{-3}}\right)^{-1} \left(\frac{d}{1.4 \text{ kpc}}\right)^2 \text{erg}.$$  

(6)

If we adopt $n_p = 230 \text{ cm}^{-3}$ and $d = 1.4 \text{ kpc}$, we find $W_p \sim 5.3 \times 10^{47} \text{ erg}$. Figure 9 shows a plot between the SNR age and $W_p$ (Sano et al. 2021a, 2021b, 2022), which indicates that Puppis A is located in a position consistent with the cosmic-ray escaping phase, as suggested by comparison with more than ten other SNRs (Sano et al. 2022).

4.3.2. Escape of the Cosmic-Ray Protons

We consider that a significant part of the cosmic-ray protons have escaped from the SNR shell over a timescale of $10^4 \text{ yr}$. The cosmic-ray diffusion length $l_{\text{diff}}$ can be described as (Gabici et al. 2009):

$$l_{\text{diff}} = \sqrt{4D(E)t_{\text{age}}}.$$  

(8)
Here, $D(E)$ is the diffusion coefficient in units of cm$^{-2}$ s$^{-1}$ and $t_{\text{age}}$ is the age of the SNR in units of second. The diffusion coefficient $D(E)$ can be written using the particle energy $E$ and the magnetic field strength $B$ as:

$$D(E) = 3 \times 10^{20} \left( \frac{E}{10 \text{ MeV}} \right)^{0.5} \left( \frac{B}{3 \mu \text{G}} \right)^{-0.5}. \quad (9)$$

Here, by adopting $t_{\text{age}} > 10,000$ yr, $E = 10$ GeV, and $B < 20$ $\mu$G (Reynoso et al. 2018), we obtain a cosmic-ray diffusion length of $l_{\text{diff}} > 22$ pc. The length becomes large with $E$ and is larger than the SNR radius of $\sim 10$ pc, supporting the escape of the cosmic rays. The gamma-ray energy spectrum of Puppis A, which peaks in the GeV range, is also consistent with cosmic-ray escape (e.g., Funk 2015; Xiang & Jiang 2021). Araya et al. (2022) suggested that the nearby gamma-ray source 4FGL J0822.8–4207 may be an object which is illuminated by escaping cosmic rays from Puppis A. An alternative idea is that the object is illuminated by cosmic rays produced in the star-forming region. In the future, we need a detailed comparison of the ISM and gamma-ray distribution in order to explore this issue further.

5. Conclusions

We have investigated the ISM toward Puppis A and identified that the clumpy CO clouds and the H$\text{I}$ gas in the velocity range of 8–20 km s$^{-1}$ are associated with the SNR shell. Following this identification, we have examined the shock–cloud interaction, the gamma-ray emission mechanism, as well as the escaping cosmic rays from the SNR. The main conclusions are summarized below.

1. The CO and H$\text{I}$ distribution toward Puppis A has two velocity ranges, i.e., 0–8 km s$^{-1}$ and 8–20 km s$^{-1}$, as inferred from their spatial distributions.
2. The 8–20 km s$^{-1}$ cloud consists of small clumps that are distributed around the SNR shell, and which show an enhanced $^{12}$CO $J = 2–1/1–0$ ratio of 0.8–1.1, indicating its higher excited state toward the northeastern part of the SNR shell, where the 8–20 km s$^{-1}$ cloud also shows a moderate wing-like feature with a 5 km s$^{-1}$ velocity span.

The high ratio and broad feature suggest the gas is shock-excited/accelerated by interaction with the SNR shell. Based on these properties, we identify that the 8–20 km s$^{-1}$ cloud is interacting with the SNR. These signatures of the interaction support its derived distance of 1.4 kpc.

3. The 0–8 km s$^{-1}$ cloud is elongated from the southwest to the northeast across the SNR, and shows a uniform and low $^{12}$CO $J = 2–1/1–0$ ratio of 0.5, which is consistent with no extra excitation. The 0–8 km s$^{-1}$ cloud is associated with a lower hardness ratio of X-rays and shows an intensity depression similar to the radio continuum shell. These properties suggest the cloud is located in front of the SNR, and the cloud is not physically interacting with the shell.

4. The H$\text{I}$ mass of the 8–20 km s$^{-1}$ cloud was calculated to be $\sim 10^3 M_{\odot}$, and the H$_2$ molecular mass of the CO cloud is about 1/10 of the atomic hydrogen mass. Based on the mass we estimate the cosmic-ray proton energy $W_p$ to be $\sim 5.3 \times 10^{47}$ erg. We also argue for an age of the SNR to be 10,000 yr, the largest value derived from the X-ray ionization timescale. Then, we find that Puppis A is placed in the cosmic-ray escaping phase in an age–$W_p$ plot constructed from 13 SNRs.

5. Puppis A shows a shell-like radio continuum distribution similar to another middle-aged SNR, W44. It seems that both SNRs have a relatively large ISM cavity with a 10–15 pc radius. The primary gamma-ray peak overlaps with the high column density ISM protons, suggesting that at least part of the gamma-rays in the primary peak have a hadronic origin. The gamma-rays have their peak on one side of the shell, while the gamma-rays from the inside are not dominant compared to those in the shell. The angular resolution of the gamma-rays is, however, not high enough to explore further details of the gamma-ray properties including the contribution of any leptonic component, which must await future, high-resolution observations with the Cherenkov Telescope Array.

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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), SAS (v19.1.0: Gabriel et al. 2004), ESAS (Kuntz & Snowden 2008), HEAsoft (v6.28: Nasa High Energy Astrophysics Science Archive Research Center (Heasarc) 2014).

Facilities: NANTEN, NANTEN2, Australia Telescope Compact Array (ATCA), Parkes, Chandra, XMM-Newton, and Fermi-LAT.

Appendix A

Determination of the CO-to-H$_2$ Conversion Factor

To derive the specific CO-to-H$_2$ conversion factor $X$ (also known as the $X$-factor) in the Vela region, we used maps of the NANTEN $^{12}$CO($J = 1-0$) integrated intensity $W$(CO), Planck dust opacity $\tau_{353}$ at a frequency of 353 GHz, and the Planck dust temperature, following the method presented by Okamoto et al. (2017).

Figures 10(a), (b), and (c) show large-scale (20 degree$^2$) maps of the NANTEN $^{12}$CO($J = 1-0$) integrated intensity, Planck dust opacity $\tau_{353}$, and Planck dust temperature, respectively. We found clumpy and filamentary molecular clouds around Puppis A, which spatially correspond to regions of large optical depth in $\tau_{353}$ (see Figure 10(b) image and black contours). We also noted that the southern half of the map shows a high dust temperature greater than 17.5 K, which was likely caused by shock heating due to the overlapping Vela SNR (see also Moriguchi et al. 2001).

According to Okamoto et al. (2017), the total interstellar proton column density $N_p$ is given by:

$$N_p = 9.0 \times 10^{24} \tau_{353}^{1/1.3} ,$$  \hspace{1cm} (A1)

where the nonlinear term of 1/1.3 is known as the dust-growth factor (e.g., Roy et al. 2013; Fukui et al. 2015; Okamoto et al. 2017).

Figure 11 shows a scatter plot between $W$(CO) and $N_p$ derived using Equation (A1). We fitted data points of CO with a $5\sigma$ or higher significance using the MPFITEXY procedure, which provides the slope, intercept, and reduced-$\chi^2$ values of the linear function (Williams et al. 2010). We found best-fit values with a reduced-$\chi^2 \sim 1.01$ (degree of freedom = 3500) when we used only data points with a dust temperature below 17.5 K. We finally obtained a slope of $(3.0 \pm 0.2) \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ and an intercept of $(9.4 \pm 0.3) \times 10^{21}$ cm$^{-2}$. From Equations (1) and (2), we then obtained the CO-to-H$_2$ conversion factor, finding $X = 1.5 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ for the Vela region.

Appendix B

Radial Profile for the Radio Continuum Shell

To derive the apparent diameter and shell thickness of the radio continuum shell, we fitted its radial profile using a three-
radial profile by moving the original position around the geometric center of the SNR, and we obtained the central position of the shell as $(\alpha_{2000}, \delta_{2000}) = (125^\circ 59, -43^\circ 03)$ with the minimum chi-square value of the least-squares fitting. Figure 12 shows the radial profile of the radio continuum, centered at $(\alpha_{2000}, \delta_{2000}) = (125^\circ 59, -43^\circ 03)$. We derived a shell radius $r_0$ of $0^\circ 40 \pm 0^\circ 08$ and a thickness of $0^\circ 11 \pm 0^\circ 19$ as the best-fit parameters, where the shell thickness is defined as the FWHM of the Gaussian function, or $2\sigma/\sqrt{2\ln(2)}$.

**ORCID iDs**

M. Aruga @ https://orcid.org/0000-0001-5069-5988
H. Sano @ https://orcid.org/0000-0003-2062-5692
Y. Fukui @ https://orcid.org/0000-0002-8966-9856
E. M. Reynoso @ https://orcid.org/0000-0002-1875-7701
G. Rowell @ https://orcid.org/0000-0002-9516-1581
K. Tachihara @ https://orcid.org/0000-0002-1411-5410

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