TYCHO SN 1572: A NAKED Ia SUPERNOVA REMNANT WITHOUT AN ASSOCIATED AMBIENT MOLECULAR CLOUD

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ABSTRACT

The historical supernova remnant (SNR) Tycho SN 1572 originates from the explosion of a normal Type Ia supernova that is believed to have originated from a carbon–oxygen white dwarf in a binary system. We analyze the 21 cm continuum, H\(_i\), and \(^{12}\)CO-line data from the Canadian Galactic Plane Survey in the direction of SN 1572 and the surrounding region. We construct H\(_i\) absorption spectra to SN 1572 and three nearby compact sources. We conclude that SN 1572 has no molecular cloud interaction, which argues against previous claims that a molecular cloud is interacting with the SNR. This new result does not support a recent claim that dust, newly detected by AKARI, originates from such an SNR–cloud interaction. We suggest that the SNR has a kinematic distance of 2.5–3.0 kpc based on a nonlinear rotational curve model. Very high energy γ-ray emission from the remnant has been detected by the VERITAS telescope, so our result shows that its origin should not be an SNR–cloud interaction. Both radio and X-ray observations support that SN 1572 is an isolated Type Ia SNR.

Key words: cosmic rays – gamma rays – ISM – ISM: clouds – ISM: supernova remnants – radio lines: ISM – stars: distances

Online-only material: color figures

1. INTRODUCTION AND DATA

Recent observations have revealed that the historical supernova remnant (SNR) Tycho SN 1572 belongs to the class of Type Ia SN by detecting its optical spectrum near maximum brightness from the scattered-light echo (Krause et al. 2008). A red subgiant has been suggested to be the possible surviving companion of the supernova (SN) in a close binary system (Ruiz-Lapuente et al. 2004). However, the evolutionary path of the progenitor is still not understood, and this association has been questioned (Fuhrmann 2005; Ihara et al. 2007). SN 1572 is a natural candidate for high-energy observations. None of the surrounding clouds has been detected by other instruments (e.g., MAGIC) is required.

Young, massive core-collapse SNe are usually not far away from their parent molecular clouds since their progenitors evolve very quickly (a few million years). Therefore, it is expected that many Galactic Type II/Ibc SNRs are associated with large molecular clouds. Recently, Jiang et al. (2010) cataloged more than 60 possible SNR–cloud interaction systems. As the only known Type Ia remnant in this catalog, SN 1572 has been proposed to be interacting with dense ambient (atomic/molecular) clouds toward its northeast (NE; Reynoso et al. 1999; Lee et al. 2004; Cai et al. 2009; Xu et al. 2011). Cold dust overlapping the eastern part of SN 1572 has been detected (Ishihara et al. 2010) and taken as evidence of a possible interaction between SN 1572 and a molecular cloud. Extended TeV emission detected in several SNRs has been suggested to originate from the interaction between the SNR shock and an adjacent CO cloud (Enomoto et al. 2002; Aharonian et al. 2004; Albert et al. 2007; Tian et al. 2008; Tavani et al. 2010). Is TeV emission from SN 1572 associated with such an SNR–cloud interaction?

In this Letter, we take advantage of the 21 cm continuum, H\(_i\), and \(^{12}\)CO-line data from the Canada Galactic Plane Survey (CGPS) in the direction of SN 1572. We study if there exists such an interaction responsible for the TeV emission. Details on the CGPS are given in Taylor et al. (2003), the analysis methods are described in our previous papers (Tian et al. 2007, 2010).

2. RESULTS AND ANALYSIS

2.1. Continuum Images and Spectra

In Figure 1, we show the 1420 MHz continuum image around SN 1572. In Figures 2 and 3, we show the H\(_i\) and \(^{12}\)CO spectra extracted for SN 1572 and three nearby compact sources. As SN 1572 is extended, we employ our well-tested methods in order to obtain reliable H\(_i\) absorption spectra (Johanson & Kerton 2009; Zhou et al. 2009; Leahy & Tian 2008). First, our background region is chosen to be near the continuum peak. This is shown in Figure 1: the source and background spectra are shown by the solid-line and dashed-line boxes (the background area excludes the source area). This minimizes the difference in the background H\(_i\) distribution along the two lines of sight. Second, we select four areas to extract the H\(_i\) absorption spectra. This maximizes real absorption features in SN 1572. Third, we build H\(_i\) absorption spectra for three compact sources near SN 1572. Finally, as a comparison with the H\(_i\) spectra we show the \(^{12}\)CO emission spectra. This allows one to constrain the distance to SN 1572 and understand the H\(_i\) absorption spectra.

From the H\(_i\) spectra, we find that the highest absorption velocity is \(\sim 53 \text{ km s}^{-1}\) in all spectra toward SN 1572 (see Figures 2(a) and 3). The highest absorption velocities toward the other sources are \(\sim 110 \text{ km s}^{-1}\). These are all much higher than that of SN 1572, so they must be behind SN 1572 and...
Figure 1. 1420 MHz continuum image with contours (22, 40, 100, 160, and 225 K) around SN 1572 (left) and the zoomed SN 1572 image. North is up, the east is to the left.

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

are probably version extragalactic. For the three compact sources, any \( \text{H}_\text{I} \) emission that has brightness temperature of above 20 K shows associated \( \text{H}_\text{I} \) absorption in the whole velocity range. \( \text{H}_\text{I} \) emission with peak brightness temperatures of 70–90 K, i.e., at \( -68 \text{ km s}^{-1} \) for G119.71+1.12, \( -57 \text{ km s}^{-1} \) for G119.71+1.12, and \( -57 \text{ km s}^{-1} \) for G120.56+1.21, has associated deep \( \text{H}_\text{I} \) absorption. This is not the case for SN 1572. This is not the case for SN 1572 (see Figures 2(a) and 3). There is no associated \( \text{H}_\text{I} \) absorption for the \( \text{H}_\text{I} \) emission peak at \( -60 \text{ km s}^{-1} \) and also for the other lower peaks at \(-46,-90,-98 \text{ km s}^{-1}\). Figure 2 also shows the CO emission spectra. For G120.56+1.21, the high brightness–temperature \( \text{CO} \) component with a peak at \(-60 \text{ km s}^{-1}\) has strong associated \( \text{H}_\text{I} \) absorption. However, for SN 1572, the bright \( \text{CO} \) molecular cloud with a peak at \(-64 \text{ km s}^{-1}\) does not produce any \( \text{H}_\text{I} \) absorption.

### 2.2. \( \text{H}_\text{I} \) and \( \text{CO} \) Channel Maps

The above results are supported by the \( \text{H}_\text{I} \) and \( \text{CO} \) channel maps and find that \( \text{H}_\text{I} \) absorption toward SN 1572 appears in three velocity windows of \( 5 \) to \(-20 \text{ km s}^{-1} \), \(-27 \) to \(-33 \text{ km s}^{-1} \), and \(-47 \) to \(-53 \text{ km s}^{-1} \). \( \text{H}_\text{I} \) absorption toward the other three compact sources appears in more velocity windows including the above three velocity windows. As an example, Figure 4 shows six \( \text{H}_\text{I} \) channel maps and two \( \text{CO} \) channel maps. The \( \text{H}_\text{I} \) maps and velocities of both \(-61.65 \) and \(-65.77 \text{ km s}^{-1}\) show clear \( \text{H}_\text{I} \) absorption toward G120.56+1.21 but none toward SN 1572. The \( \text{CO} \) maps show that an extended bright \( \text{CO} \) cloud (at \( b = 1.4 \)) appears at all velocities from \(-61 \) and \(-67 \text{ km s}^{-1}\) (this can be seen in Figure 4) and sits on the eastern part of SN 1572's shell. We find \( \text{H}_\text{I} \) absorption features at velocities between \(-54 \) and \(-68 \text{ km s}^{-1}\) toward G120.56+1.21 but not in SN 1572. This supports the above spectral analysis and confirms that the \( \text{CO} \) cloud with peak at \(-64 \text{ km s}^{-1}\) is behind SN 1572. We also see \( \text{H}_\text{I} \) absorption toward SN 1572 in channel maps with velocities in the range of \(-47.63 \) and \(-52.58 \text{ km s}^{-1}\). This confirms that \( \text{H}_\text{I} \) atomic gas at velocities of \(-47 \) to \(-53 \text{ km s}^{-1}\) is in front of SN 1572.

### 3. DISCUSSION AND CONCLUSIONS

#### 3.1. The \( \text{CO} \) Cloud at \(-64 \text{ km s}^{-1}\) is Behind SN 1572

We have found that the \( \text{H}_\text{I} \) gas at velocities of \(-47 \) to \(-53 \text{ km s}^{-1}\) is in front of SN 1572. Both the \( \text{CO} \) at \(-64 \text{ km s}^{-1}\) and the \( \text{H}_\text{I} \) at \(-60 \text{ km s}^{-1}\) do not produce associated \( \text{H}_\text{I} \) absorption, so both are likely behind SN 1572. Is it possible that the \( \text{CO} \) cloud could still be in front of SN 1572 but the amount of cold \( \text{H}_\text{I} \) gas in the molecular cloud is too small to produce detectable \( \text{H}_\text{I} \) absorption against SN 1572?

Figure 2(a) shows that the \( \text{CO} \) at \(-64 \text{ km s}^{-1}\) has associated \( \text{H}_\text{I} \) emission (\( T_B \sim 75 \text{ K} \)). Technically, a minimum optical depth of \( \tau \sim 0.1 \) may be detected. This requires that \( \text{H}_\text{I} \) atomic gas against background continuum source has at least column density of \( N_{\text{H}_1} = 2.3 \times 10^{19} \text{ cm}^{-2} \) (\( N_{\text{H}_1} = 1.823 \times 10^{18} T_c \Delta \nu \); Dickey & Lockman 1990), given \( T_c \sim 25 \text{ K} \) (Schwarz et al. 1995) and the FWHM \( \Delta \nu \) of the typical \( \text{H}_\text{I} \) absorption line \( \sim 5 \text{ km s}^{-1}\). Taking the theoretical mean \( \text{H}_\text{I}/\text{H}_2 \) ratio of 0.2 (Goldsmith & Li 2005; Anderson & Bania 2009), this respective molecular cloud has an \( \text{H}_2 \) column density of \( \sim 1.2 \times 10^{20} \text{ cm}^{-2}\).

The \(^{13}\text{CO}\) spectrum from box 1 (Figure 2(a)) gives \( W_{\text{^{13}CO}} \sim 7 \text{ K km s}^{-1} \) for the cloud component. Taking the \(^{13}\text{CO} \) to \( \text{H}_2 \) conversion factor of \( X = 3 \times 10^{20} \text{ cm}^{-2} \) (K km s\(^{-1}\)) \(^{-1}\), this gives an \( \text{H}_2 \) column density of \( \sim 2.1 \times 10^{21} \text{ cm}^{-2} \) for the respective cloud. This is enough to produce measurable \( \text{H}_\text{I} \) absorption at \( 18 \sigma \) level if the cloud component is in front of SN 1572. So the \( \text{CO} \) molecular cloud at \(-64 \text{ km s}^{-1}\) is behind SN 1572.

#### 3.2. Does There Exist an SN 1572–\( \text{CO} \) Cloud Interaction?

Previous multi-band observations of SN 1572 (Strom et al. 1982; Ghavamian et al. 2000; Hughes 2000; Douvion et al. 2001; Hwang et al. 2002; Lee et al. 2007; Yang et al. 2009) have revealed limb-brightened radio and X-ray shell, Hα filament along the NE boundary of the shell, the mid-IR emission from SN 1572, suggesting that SN 1572 is surrounded by an inhomogeneous environment. A possible SNR–cloud interaction along SN 1572’s NE boundary is able to trigger some observed phenomena, e.g., the NE bright part in radio and X-ray images,
the decelerated expansion of the NE rim in radio, optical and X-rays, the dust emission at the NE boundary, etc. We have concluded that the CO cloud at $-64$ km s$^{-1}$ is behind SN 1572, but is it possible that the CO is adjacent and interacting with SN 1572?

This cloud has an H$_2$ column density of $2.1 \times 10^{21}$ cm$^{-2}$, so its density is $\sim 200$ cm$^{-3}$, assuming that half of the SNR is surrounded by the cloud ($R_{SN1572} \sim 4$ arcmin) and taking a distance of 3 kpc (see Section 3.5 for detail). This is inconsistent with recent Chandra X-ray observations of the cloud surrounding the remnant. Cassam-Chenaï et al. (2007) and Katsuda et al. (2010) analyzed X-ray spectra from the thin rim between the blast wave and contact discontinuity, and found that there is little thermal emission from the pre-shock ambient medium. This requires that the ambient medium density in the vicinity of SN 1572 is less than 0.2 cm$^{-3}$. This is three orders of magnitude lower than the density of the CO cloud. Therefore, the CO cloud is not adjacent to SN 1572. We conclude that there is no physical association between SN 1572 and the $^{12}$CO cloud at $-64$ km s$^{-1}$, although they are overlapping along the light of sight.

Ishihara et al. (2010) detected cold dust IR emission outside the NE and northwest (NW) boundaries of SN 1572's shell and suggested that the NE dust emission comes from a possible molecular cloud interacting with the shock front. The origin of the NW dust emission is rather unclear because of the absence of
Figure 4. First three rows show the H\textsubscript{i} channel maps. The last row shows the $^{12}$CO channel maps. Overlaid in all panels is the 1420 MHz continuum emission with contours: 40, 100, 160, and 225 K. The H\textsubscript{i} map at $-47.63$ km s$^{-1}$ shows an extended H\textsubscript{i} along the eastern part of SN 1572. The H\textsubscript{i} map at $-52.58$ km s$^{-1}$ shows a small H\textsubscript{i} clump at the NE site of SN 1572 (see the text for detail).

(A color version of this figure is available in the online journal.)
any interstellar cloud nearby. However, our study reveals that the origin of the NE dust emission is also unclear, probably from the molecular cloud at $-64 \text{ km s}^{-1}$ but unrelated to SN 1572. We note that weak TeV emission from SN 1572 is also detected (Acciari & VERITAS 2010). Although TeV emission from several SNRs has been suggested to originate from interaction between the SNR shock and an adjacent cloud, our result reveals that it is not this case for SN 1572 at least.

### 3.3. Does There Exist an SN 1572–H I Cloud Interaction?

Reynoso et al. (1999) studied 21 cm spectra in the velocity range of $-41$ to $-106 \text{ km s}^{-1}$ toward SN 1572 using Very Large Array (VLA) archive data and single-dish H I observations. They detected H I absorption from $-46.4$ to $-56.8 \text{ km s}^{-1}$ toward SN 1572 and found an extended H I absorption along the eastern side of the shell between the velocities of $-47.7$ and $-50.3 \text{ km s}^{-1}$. They also found a small high-density H I clump (160–325 cm$^{-3}$) observed as an absorption feature at $-51.5 \text{ km s}^{-1}$ toward the eastern part of the shell. Our study reproduces some of these results: the extended H I structure and the small H I clump seen in our Figure 4 (at velocities of $-47.6$ and $-52.58 \text{ km s}^{-1}$) are found. By examining the H I channel maps from $-50.3$ to $-60.6 \text{ km s}^{-1}$ shown in their Figure 2, we see a clear deficit of H I brightness between $-52.9$ and $-56.8 \text{ km s}^{-1}$ surrounding SN 1572. This is inconsistent with being an H I absorption feature because it does not correspond with bright continuum emission. It could be either H I self-absorption (HISA) or artifacts. Our H I absorption spectra clearly reveal reliable H I absorption features in the velocity range of $-47$ to $-53 \text{ km s}^{-1}$ but not beyond $-53 \text{ km s}^{-1}$. Our methods to build H I absorption spectra have reduced false absorption features as much as possible. We do not find any reliable absorption toward SN 1572 in our H I channel maps in the range of $-54$ to $-66 \text{ km s}^{-1}$. So any H I absorption feature beyond $-53 \text{ km s}^{-1}$ is likely not real.

This extended H I cloud along the eastern side of the shell is in front of SN 1572, but is it possible that it could be adjacent to SN 1572? The H I cloud’s density of $\sim 10 \text{ cm}^{-3}$ ($\tau \lesssim 0.8$, $\Delta v \sim 3 \text{ km s}^{-1}$) from Figures 2(a) and 3; $T_e = 25 \text{ K}$ from Schwarz et al. (1995) is much higher than the ambient medium density of $0.2 \text{ cm}^{-3}$ from the X-ray measurements, so the H I cloud is not adjacent to SN 1572.

Reynoso et al. (1999) suggested an interaction between SN 1572 and the small NE H I clump because of two factors: the H I clump is near the site of the lowest expansion velocity along the eastern part of the shell. However, Lee et al. (2007), using the Subaru Telescope, obtained a systemic velocity of $-30.3 \pm 0.2$ km s$^{-1}$ for the H I knot G. So we need further new independent observations to distinguish if the knot has relation with the H I clump or not.

In summary, there is no direct evidence that the extended H I cloud along the eastern part of SN 1572 is physically associated with SN 1572.

### 3.4. Tycho SN 1572, A Naked Ia SNR

Massive stars have a lifetime of about $10^6$ yr, so Type II/Ibc SNe are expected to take place in a dense, star-forming region where their progenitors are formed. This is different for Type Ia SNe because of the longer time needed for the system to evolve ($\sim 10^7$ yr). SN 1572’s progenitor has wandered $\sim 1 \text{ kpc}$ far away from the star-forming site, given an average birth velocity of $10 \text{ km s}^{-1}$, therefore is far outside of its parent molecular cloud (generally the size of individual giant molecular cloud is $\sim 100 \text{ pc}$). Although SN 1572 might encounter other clouds as it wanders through the interstellar medium (ISM), X-ray observations of 1572 show low ISM density. So we believe SN 1572 is likely a naked SNR.

#### 3.5. Distance to Tycho SN 1572

The distance to SN 1572 has previously been suggested to be between 2 and 5 kpc by radio, optical, X-ray, and $\gamma$-ray observations (Figure 6 of Hayato et al. 2010 shows a summary). As the Perseus arm is influenced by the spiral shock (leading to a velocity reversal; Roberts 1972), it is challenging to estimate kinematic distances to objects in the Perseus arm of the outer Galaxy. This velocity reversal causes a distance ambiguity for gas and objects with radial velocities of $-40 \text{ km s}^{-1}$ to $-55 \text{ km s}^{-1}$ in the line of sight to SN 1572, for $v \lesssim -55 \text{ km s}^{-1}$ the radial velocity decreases monotonically with distance (see Figure 2 of Albinson et al. 1986). Previously, H I absorption observations have been made toward SN 1572. Albinson et al. (1986) made aperture synthesis observations of H I using the Cambridge Half-Mile Telescope and suggested a distance in the range 1.7–3.7 kpc. Schwarz et al. (1995) used the VLA to study H I absorption toward SN 1572 and nearby compact sources including G120.56+1.21 and G119.74+2.4 and estimated a distance of 4.6 $\pm$ 0.5 kpc. The distance difference between Albinson et al. (1986) and Schwarz et al. (1995) is caused by how they deal with a possible weak absorption feature at $-60 \text{ km s}^{-1}$. Albinson et al. (1986) thought that the absorption could be either from H I in a turbulent state around a filament or could be spurious caused by small-scale variation in H I emission. Schwarz et al. (1995) believed that it is real and SN 1572 is farther than the region of distance ambiguity.

We obtain H I absorption features with higher quality than previous studies and find clearly that the highest absorption velocity is $-53 \text{ km s}^{-1}$ toward SN 1572. Therefore, we exclude the large distance of 4.6 kpc. Due to the absence of H I absorption between $-40$ and $-45 \text{ km s}^{-1}$ toward SN 1572, Albinson et al. (1986) further proposed that the H I emission between $-40$ and $-45 \text{ km s}^{-1}$ could be behind SN 1572, and that SN 1572 most likely is located at the near distance of the major absorption feature at $-50 \text{ km s}^{-1}$. Anyway, they kept an option that SN 1572 has small probability to be at the far side distance of 3.7 kpc of the same absorption feature.

Figure 2 show that the H I gas at $-41$ to $-46 \text{ km s}^{-1}$ has no associated obvious H I absorption toward SN 1572 and definitely produces associated H I absorption toward G120.56+1.21. We note that the H I channel maps in this velocity range show more H I gas with brightness temperature above 20 K surrounding G120.56+1.21 than SN 1572. Could absence of H I absorption in the velocity range toward SN 1572 be due to insufficient H I gas to produce measurable optical depth in front of SN 1572? However, the H I gas has column density of $\sim 3 \times 10^{19} \text{ cm}^{-2}$ ($N_{\text{HI}} = 1.832 \times 10^{18} T_B \Delta v$, $T_B = 35 \text{ K}$; see Figure 2(a)) which is enough to produce detectable H I absorption, because $\tau \geq 0.1$ requires a minimum H I column density of $\sim 7 \times 10^{19} \text{ cm}^{-2}$ (here $T_e = 75 \text{ K}$, which is an average value in the low velocity range from Schwarz et al. 1995). They also noticed that it goes below 25 K near $-50 \text{ km s}^{-1}$). So this gives an upper limit distance for SN 1572 which is in front of the H I at $-41$ to $-46 \text{ km s}^{-1}$. In addition, Schwarz et al. (1995) detected HISA at $-49 \text{ km s}^{-1}$. HISA is generally produced by foreground cold H I in front of background warm H I at same velocity. Because of the velocity...
reversal in the Perseus Arm, HISA features are widely observed in the CGPS (Gibson et al. 2005; Tian et al. 2010). The HISA at $-49$ km s$^{-1}$ likely originates from the same cause, i.e., cold HI at near side of the velocity reversal absorbs emission from warm HI at the far side at the same velocity of $-49$ km s$^{-1}$. Because the $-49$ km s$^{-1}$ HI is in front of SN 1572 (Figures 2 and 3), SN 1572 must be between the HI at near side with $-48$ km s$^{-1}$ and the HI at far side with $-41$ to $-46$ km s$^{-1}$. In other words, the distance to SN 1572 is between 2.5 and 3.0 kpc. We use the Foster & MacWilliams’ (2006) model which is similar with the Roberts’ model but puts the spiral shock front at 2.5 kpc in the direction to SN 1572 (also see Figure 14 of Schwarz et al. 1995).

A kinematic distance of 2.5–3.0 kpc is roughly consistent with new estimates from other independent methods. V¨olk et al. (2008) suggested that SN 1572’s distance is greater than 3.3 kpc by modeling the existing $\gamma$-ray measurements from SN 1572. Krause et al. (2008) estimated distance of 3.8$^{+0.5}_{-0.4}$ kpc using classic brightness–distance relation and accounting for interstellar foreground extinction. Hayato et al. (2010) made new Suzaku observations of SN 1572 and estimated an average spherical expansion velocity of $\sim$4700 km s$^{-1}$. They gave a direct distance estimate of 4$\pm$1 kpc by combining the observed ejecta velocities with the ejecta proper-motion measurement by Chandra.

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