SNR G349.7+0.2: A $\gamma$-RAY SOURCE IN THE FAR 3 kpc ARM OF THE GALACTIC CENTER

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ABSTRACT

We analyze the H$\textsc{i}$ absorption profile for TeV supernova remnant (SNR) G349.7+0.2 based on updated knowledge of the inner Galaxy’s structure. We significantly revise its kinematic distance from the previous $\sim$22 kpc to $\sim$11.5 kpc, indicating it is in the far 3 kpc arm of the Galactic center. We give a revised age of $\sim$1800 yr for G349.7+0.2 which has a low explosion energy of $\sim$2.5 $\times$ 10$^{50}$ erg. This removes G349.7+0.2 from the set of brightest SNRs in radio and X-ray to $\gamma$-ray wavebands and helps us to better understand $\gamma$-ray emission originating from this remnant. However, one needs to use caution when discussing old kinematic distances of Galactic objects (e.g., SNRs, pulsars, and H$\textsc{ii}$ regions) in the range of $12^\circ \leq l \leq 12^\circ$ with distance estimates of $\geq$5.5 kpc.

Key words: cosmic rays – Galaxy: center – ISM: lines and bands – ISM: supernova remnants

Online-only material: color figures

1. INTRODUCTION AND DATA

It is widely believed that most Galactic cosmic rays probably originate from supernova remnants (SNRs). Recently the TeV $\gamma$-ray emission from SNRs has attracted interest because of new TeV observations that have identified sources with SNRs [http://tevcat.uchicago.edu/ and http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/]. Most of the TeV SNRs detected so far are a short distance from Earth (e.g., Cas A: 3.4 kpc, Krause et al. 2008; RC56: 2.5 kpc, Bamba et al. 2000; IC443: 1.5 kpc, Fesen 1984; SN1006: 2.2 kpc, Winkler et al. 2003; G353.6-0.7: 3.2 kpc, Tian et al. 2008). Tian & Zhang (2013) listed 61 TeV $\gamma$-ray sources which were likely identified as SNRs/PWN/SE, and showed that most of them are less than 6 kpc away.

Many SNRs’ kinematic distances are obtained by observing radial velocities of atomic and molecular lines toward the SNRs and using a circular rotation curve model. A circular rotation curve model is generally not suitable for Galactic center (GC) objects because the gas likely follows oval orbits in the inner Galaxy, i.e., inside the 3 kpc ring. Many studies have shown that it is extremely difficult to determine precise distances along the line-of-sight to objects in the 3 kpc ring. In this case, previous kinematic distance estimates to some remnants might contain a large uncertainty or even be incorrect. Recently finished radio and infrared surveys reveal detailed kinematic images of gas and dust in the GC region (Dame & Thaddeus 2008; McClure-Griffiths et al. 2012). Several good gas flow models in the GC have been presented based on recent observations (e.g., Rodriguez-Fernandez & Combes 2008). These recent surveys and models have inspired us to revisit the issue of gas flow in the GC.

In this Letter, we study a newly detected TeV source, SNR G349.7+0.2 (Trichard et al. 2013, in preparation), which has long been believed to be at a large distance of $\sim$22 kpc away, meaning that it resides on the other side of the Milky Way, based on observations of H$\textsc{i}$, 1720 MHz OH masers, CO, H$_2$CO, etc. (Caswell et al. 1975; Frail et al. 1996; Reynoso & Mangum 2001). A high resolution radio continuum image of G349.7+0.2 at 18 cm was presented previously by Lazendic et al. (2010). We construct an H$\textsc{i}$ absorption line profile and utilize new studies of the inner Galactic structure in order to constrain the distance and other key physical parameters of SNR G349.7+0.2. The 1420 MHz radio continuum and 21 cm H$\textsc{i}$ emission data sets are from the Southern Galactic Plane Survey (SGPS), using the Australia Telescope Compact Array and the Parkes 64 m single dish telescope (Haverkorn et al. 2006). The continuum observations have a resolution of 100 arcsec and a sensitivity better than 1 mJy beam$^{-1}$. The H$\textsc{i}$ data have an angular resolution of 2 arcmin, an rms sensitivity of $\sim$1 K, and a velocity resolution of 1 km s$^{-1}$. The CO ($J = 1$–0) data for G349.7+0.2 is from survey data from the 12 m NRAO telescope (see Reynoso & Mangum 2000 for details).

2. ANALYSIS AND RESULTS

2.1. Spectra

Methods for extracting H$\textsc{i}$ absorption spectra have been introduced in earlier papers (Tian et al. 2007; Leahy & Tian 2008; Leahy & Tian 2010). The H$\textsc{i}$ emission spectrum of SNR G349.7+0.2 is shown in the upper panel of Figure 1. In this spectrum, there are several H$\textsc{i}$ emission peaks from $-113$ km s$^{-1}$ to 35 km s$^{-1}$. The H$\textsc{i}$ absorption and CO emission spectra are shown in the lower panel of Figure 1. SNR G349.7+0.2 is a strong radio source, which results in a strong H$\textsc{i}$ absorption signal. An estimate of the error in $\exp(-\tau(v))$ of Figure 1 is the rms for velocity channels with no emission ($\geq+50$ km s$^{-1}$), which is 0.0063. Artifacts in the continuum image cause another type of error. We have analyzed absorption spectra both with the same source region and with different backgrounds. We find that the artifacts only affect the normalization and not the shape of the H$\textsc{i}$ absorption spectra. We find that the error in normalization is about 20% in depth of the H$\textsc{i}$ absorption. We find that each CO emission peak has an associated H$\textsc{i}$ absorption feature except for the 16.5 km s$^{-1}$ CO peak. The highest positive velocity absorption feature is at $6 \pm 7$ km s$^{-1}$. The lowest negative velocity absorption feature is likely at $-110 \pm 10$ km s$^{-1}$ (a weak absorption feature appears at $-189 \pm 2$ km s$^{-1}$ which is real; see Section 3.1). We calculate the absorption column density from the H$\textsc{i}$ absorption spectrum, $N_{H_1} \sim 1.44 \times 10^{22}$ cm$^{-2}$, taking a value of $T_e = 100$ K (using $N_{H_1} = 1.9 \times 10^{18} \int \tau dv T_e$ cm$^{-2}$; Dickey & Lockman 1990).
Tian & Leahy

2.2. H\textsc{i} Channel Maps

We use the H\textsc{i} channel maps to confirm the reality of all abovementioned absorption features, including the 189 km s\(^{-1}\) absorption feature. Absorption continues to appear from the channel map at a velocity of \(\sim -123\) km s\(^{-1}\) through the map at a velocity of \(\sim 13\) km s\(^{-1}\). Figure 2 shows the H\textsc{i} channel maps at 8.3 km s\(^{-1}\) and 16.5 km s\(^{-1}\) toward the SNR. The left panel of Figure 2 shows clear absorption from against the SNR. The right panel reveals that the remnant sits on a bright H\textsc{i} patch which is associated with the 16.5 km s\(^{-1}\) CO cloud. This is consistent with the above absorption spectrum analysis, i.e., no H\textsc{i} absorption associated with the H\textsc{i} and CO clouds at 16.5 km s\(^{-1}\). This directly confirms that the 16.5 km s\(^{-1}\) clouds are behind the remnant.

3. DISCUSSION AND CONCLUSION

H\textsc{i} absorption spectra toward Galactic radio-bright objects have been used to estimate line-of-sight distances based on a rotation curve model. However, it is a challenging job to constrain the distances to Galactic objects in the inner 3 kpc of the Galaxy because the objects likely follow non-circular orbits in the region (see Weiner & Sellwood 1999).

This situation has improved due to recent studies of the GC’s structure. High resolution H\textsc{i} observations (McClure-Griffiths et al. 2012) of the inner Galaxy show greater detail of the region’s structure. CO observations (Dame & Thaddeus 2008) have detected the symmetric expanding 3 kpc arms, supporting the existence of a bar at the center of our Galaxy. Rodriguez-Fernandez & Combes (2008) provided a gas distribution model for the GC region by simulating the gas dynamics in the inner Galaxy. This model gives us an opportunity to better understand the H\textsc{i} and CO spectra and refine the distance estimation of G349.7+0.2. We adopt the 1985 IAU standard for Galactic parameters in this paper, i.e., \(R_0 = 8.5\) kpc (the distance between the Sun and the GC) and \(V_o = 220\) km s\(^{-1}\) (circular velocity at \(R_0\)).

3.1. Distance of G349.7+0.2

The H\textsc{i} terminal velocity at \(l = 349^\circ\) to \(350^\circ\) is about \(-190\) km s\(^{-1}\) (see Figure 2 of Weiner & Sellwood 1999 and of Burton & Liszt 1993). We detect a weak absorption feature at \(-189\) km s\(^{-1}\) in the spectrum of SNR G349.7+0.2, which is likely caused by clumps of H\textsc{i} possibly accelerated by an SNR or H\textsc{ii} region along this line of sight. The lowest-velocity major absorption feature, except for the \(-189\) km s\(^{-1}\) feature, is at \(\sim -110\) km s\(^{-1}\) in the SNR spectrum (Figure 2). This velocity is consistent with the expected radial velocity \((101.6 \pm 8.7\) km s\(^{-1}\)) of the near 3 kpc arm in the line of sight to \(l = 349^\circ\) to \(350^\circ\) (Equation (3) of Jones et al. 2013 see also Figure 1 of Dame & Thaddeus 2008). This is convincing evidence that the remnant is beyond the near 3 kpc arm.

In addition, the highest velocity absorption in the spectrum of G349.7+0.2 is at \(6 \pm 7\) km s\(^{-1}\). This is consistent with the expected radial velocity \((16.3 \pm 15.6\) km s\(^{-1}\)) of the far 3 kpc arm toward \(l \sim -10.3^\circ\) (Figure 1 and Equation (4) of Jones et al. 2013). However, in the SNR spectrum we found no H\textsc{i} absorption associated with the H\textsc{i} and CO emission clouds at 16.5 km s\(^{-1}\), which lie exactly in the far 3 kpc arm extending at least 20\(^\circ\) in longitude, starting at \(l = -12^\circ\) (Dame & Thaddeus 2008). These two pieces of evidence argue that the remnant is
SNR–cloud interaction excites the near-infrared H\textsubscript{2} emission in Churchwell et al. (2009). Near 3 kpc arm of the Galactic center. The Galactic center structure is referenced Figure 3.

1720 MHz OH masers are seen as signposts of SNR–molecular-cloud interaction. For example, SNR G349.7+0.2 has been found toward the center of the remnant as well as OH absorption at 14.3 to 16.9 km s\textsuperscript{-1}. Because most 1720 MHz OH masers (14.3–16.9 km s\textsuperscript{-1}) are nicely consistent with the velocity of shocked CO clouds (16.5 km s\textsuperscript{-1}) and with the far 3 kpc arm velocity of \sim 16.3 km s\textsuperscript{-1}. Combined with the H\textsubscript{1} absorption analysis, we conclude that the 16.5 km s\textsuperscript{-1} CO clouds are behind shocked CO clouds by SNR G349.7+0.2 and this SNR–cloud interaction excites the near-infrared H\textsubscript{2} emission and the 1720 MHz OH maser emission in the region.

An H\textsubscript{1} 21 cm absorption line study of G347.9+0.2 has previously been done using the Parkes hydrogen line interferometer (Caswell et al. 1975). Our absorption spectrum confirms the previous major absorption features near $-110$ km s\textsuperscript{-1}, $-62.5$ km s\textsuperscript{-1}, and $6$ km s\textsuperscript{-1}, but we find more fine structure because of the better quality of the SQPS data (higher continuum sensitivity and H\textsubscript{1} spectral resolution) and the improved methods. We find new absorption features at $-35$ and $-189$ km s\textsuperscript{-1}, no absorption at 20 and 38 km s\textsuperscript{-1}, and much lower noise for baselines above 20 km s\textsuperscript{-1} and below $-125$ km s\textsuperscript{-1}. Caswell et al. (1975) explained the $-62.5$ km s\textsuperscript{-1} feature as from the far ring of the 3–4 kpc arm and the 6 km s\textsuperscript{-1} feature as from local gas, based on 1970s knowledge of the GC, so they suggested a distance of 13.7 kpc $\leq d \leq 23$ kpc for SNR G349.7-0.2. However, our analysis utilizes new information that the near and the far 3 kpc arms have kinematic velocities of $-110$ and $-16.5$ km s\textsuperscript{-1}, respectively, toward G347.9+0.2, combined with our new result of reliable absorption at $6 \pm 7$ km s\textsuperscript{-1}. Thus, we find the SNR has no absorption associated with the 16.5 km s\textsuperscript{-1} clouds in the far 3 kpc arm. In this case, the $-62.5$ km s\textsuperscript{-1} feature is likely caused by much closer H\textsubscript{1} clouds whose motion follows the normal rotation curve model. Our conclusion is strongly supported by other evidence: the H\textsubscript{1} absorption at $-62.5$ km s\textsuperscript{-1} is also clearly seen in absorption spectra of the nearby SNRs G348.5+0.1 and G348.5-0.0, both of which have distances of less than 9.5 kpc (Tian & Leahy 2012); and the remnant is interacting with 16.5 km s\textsuperscript{-1} clouds in the far 3 kpc arm. Previously, the 1720 MHz OH masers at 14.3 to 16.9 km s\textsuperscript{-1} were assumed to be outside of the solar circle based on the circular rotation curve model, so SNR G349.7+0.2 was suggested to have a kinematic distance of $\sim 22$ kpc. Now we know that the circular rotation curve model is not valid near the GC, so we conclude that the SNR and its nearby clouds are located in the far 3 kpc arm, well within the solar circle.

SNR G349.7+0.2 is located at the near edge of the far 3 kpc arm because there is no absorption from the main part of the far 3 kpc arm (which has a center velocity of 16.5 km s\textsuperscript{-1}). The far 3 kpc arm is at a distance of $\sim 11.5$ kpc (Dame & Thaddeus 2008; Jones et al. 2013). No precise thickness of the 3 kpc arm scale is available so far, so we here give an approximate distance of $\sim 11.5$ kpc for SNR G349.7-0.2.

Previous Chandra X-ray observations of SNR G349.7+0.3 gave a column density of $7 \times 10^{22}$ cm\textsuperscript{-2}. This is consistent with the estimate from adding H\textsubscript{1} (2.8 $\times 10^{22}$ cm\textsuperscript{-2}), assuming $T_\text{e} = 140$ K and H\textsubscript{2} (4.6 $\times 10^{22}$ cm\textsuperscript{-2}), assuming CO-to-H\textsubscript{2} conversion factor $X = 1.8 \times 10^{20}$ cm\textsuperscript{-2} K km s\textsuperscript{-1}) emission (Lazendic et al. 2005). Our calculation of the column density against G349.7+0.2 by H\textsubscript{1} absorption (using $T_\text{e} = 100$ K) is $1.4 \times 10^{22}$ cm\textsuperscript{-2}, similar to Lazendic et al. (2005). The H\textsubscript{1} column density measures neutral hydrogen, whereas the X-ray column density is sensitive to the heavier element component in the total gas (H\textsubscript{1}, H\textsubscript{2}, and H\text{II}) plus dust. So the X-ray column density could easily be three or more times higher than the H\textsubscript{1} column density. In addition, it is generally known that the column density value is strongly related to the direction of a source because Galactic H\textsubscript{1} has a different distribution along different lines of sight. For example, SNR G18.8+0.3 has a different distribution along different lines of sight. For example, SNR G18.8+0.3 has a column density of $1.8 \times 10^{22}$ cm\textsuperscript{-2} from H\textsubscript{2} (Tian et al. 2007). Generally, there are more clouds toward the GC than in other directions, so there is no inconsistency in column densities with G349.7+0.2 being at 11.5 kpc.

It should be noted that kinematic distances to Galactic objects always include uncertainty due to uncertain parameters of different rotation curve models and widespread non-circular streaming motions. This uncertainty may reach up to 20% at the particular longitude of some objects (Jones et al. 2013). SNR G349.7+0.2 is within the far 3 kpc arm: its distance’s uncertainty from the $R_o$ value and the width of the arm. The IAU standard is $R_o = 8.5$ kpc, but recent measurements show a smaller value, e.g., $8.4 \pm 0.6$ kpc from very long baseline interferometry (VLBI) trigonometric parallax measurements (Reid et al. 2009), $8.05 \pm 0.45$ kpc from VLBI astrometry (Honma et al. 2013), $8.33 \pm 0.19$ kpc from optical and near-infrared observation of known RR Lyrae stars in the bulge (Dekany et al. 2013), etc. The uncertainty of $R_o$ is about 0.5 kpc. The width of the far
3 kpc arm is not yet known but should be smaller than the error of \(R_o\). We therefore estimate a distance of 11.5 \(\pm 0.7\) kpc for the far 3 kpc arm.

In summary, we significantly revise the distance to G349.7+0.2 from a previous 22 kpc to 11.5 kpc, based on better understanding of the GC structure. We previously revised distances to three other SNRs near G349.7+0.2 (Tian & Leahy 2012). One should use caution when considering old kinematic distances of Galactic objects (e.g., SNRs, pulsars, and H\(\alpha\) regions) in the range of \(-12^\circ \leq l \leq 12^\circ\) and having distance estimates of \(\geq 5.5\) kpc.

### 3.2. Luminosity, Age, Density, and Explosion Energy of G349.7+0.2

G349.7+0.2 has been suggested to be one of the brightest Galactic sources in the radio (Shaver et al. 1985), X-ray (Slane et al. 2002), and GeV \(\gamma\)-ray wavebands (Castro & Slane 2010) because of its large distance. We give its luminosity based on the new distance measurement of 11.5 kpc obtained here: \(L_{\text{1GHz}} \sim 3.2 \times 10^{37}\) Watt Hz\(^{-1}\), \(L_X(0.5-10\text{keV}) \sim 1.0 \times 10^{37}\) erg s\(^{-1}\), \(L_{\gamma}(0.1-10\text{GeV}) \sim 3.6 \times 10^{34}\) erg s\(^{-1}\).

The angular diameter of G349.7+0.2 (\(\sim 2\)\') from Chandra (Lazendic et al. 2005) yields a radius of \(R = 3.3\) pc \(d = 11.5\) kpc) for the SNR. Lazendic et al. (2005) find a shock velocity of \(\sim 710\) km s\(^{-1}\) based on the X-ray measured plasma temperature. The small remnant size and fast shock velocity indicate that the remnant is still evolving in the Sedov phase. So we estimate its age of \sim 1800 yr by applying the Sedov model (Cox 1972; also see Equations (4) and (5) of Reynoso & Mangum 2001) using the known remnant radius and shock velocity. The supernova explosion energy depends on the environment density \(n_0\). Using the X-ray emission measure from the *Chandra* spectrum of 9.9 \times 10^{39} \text{cm}^{-3} (Lazendic et al. 2005) and a Sedov interior density profile (see Leahy et al. 2013), the interstellar medium density is \(n_0 \sim 10 \text{ cm}^{-3}\) \((d = 11.5\) kpc). G349.7+0.2 is then found to have a low explosion energy of \(2.5 \times 10^{50}\) erg.

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