A KINEMATIC DISTANCE STUDY OF THE PLANETARY NEBULAE–SUPERNOVA REMNANT–H II REGION COMPLEX AT G35.6–0.5

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ABSTRACT

Two possible planetary nebulae (PN G035.5–00.4 and IRAS 18551+0159), one newly re-identified supernova remnant (SNR G35.6–0.4), and one H ii region (G35.6–0.5) form a line-of-sight-overlapping complex known as G35.6–0.5. We analyze 21 cm H i absorption spectra toward the complex to constrain the kinematic distances of these objects. PN G035.5–00.4 has a distance from 3.8 ± 0.4 kpc to 5.4 ± 0.7 kpc. IRAS 18551+0159 is at 4.3 ± 0.5 kpc. We discuss the distance for SNR 35.6–0.4, for which the previous estimate was 10.5 kpc, and find a plausible distance of 3.6 ± 0.4 kpc. The new distance of SNR G35.6–0.4 and the derived mass for the ~55 km s⁻¹ CO molecular cloud can accommodate an association with HESS J1858+020. We also conclude that SNR G35.6–0.4 is unlikely to be associated with PSR J1857+0210 or PSR J1857+0212, which are projected onto the SNR area.

Key words: H ii regions – ISM: supernova remnants – planetary nebulae: individual (PN G035.5–00.4, IRAS 18551+0159)

Online-only material: color figures

1. INTRODUCTION

Supernova remnants (SNRs) and H ii regions are two classes of bright radio objects in the Galactic plane. These kinds of sources play a key role in understanding the structure and evolution of the Milky Way. Planetary nebulae (PNe) are an important probe of nucleosynthesis processes and are responsible for a large fraction of the chemical enrichment of the interstellar medium. The complex G35.6–0.5, near the Galactic coordinates l = 35.6, b = −0.5, consists of the SNR G35.6–0.4, PNe (PN G035.5–00.4, IRAS 18551+0159), and the H ii region G35.6–0.5 (see Figure 1). This region has been studied since 1969 (e.g., Beard & Kerr 1969; Lockman 1989; Kuchar & Bania 1990; Parker et al. 2006; Kwok et al. 2008; Paron & Giacani 2010). However, some basic issues related to the complex are still unclear.

PN G035.5–00.4 and IRAS 18551+0159 were discovered and identified as possible PNe by Kistiaikowsky & Helfand (1995). Their angular sizes are about 10’ and 3’, respectively, based on infrared and radio observations (Kwok et al. 2008; Phillips & Zapata-Garcia 2009). IRAS 18551+0159 is extremely red and has no optical counterpart. This fact implies that IRAS 18551+0159 just left the asymptotic giant branch (AGB) recently (Jiménez-Esteban et al. 2005). Lockman (1989) and Phillips & Onello (1993) detected radio recombination lines (RRLs) at a position l = 35.588, b = −0.489, close to PN G035.5–00.4. They identified this RRL source as the likely H ii region G35.6–0.5. Green (2009) questioned the existence of the H ii region G35.6–0.5 because there is no 100 μm emission from it and the RRLs may instead plausibly come from the nearby PN G035.5–00.4.

SNR G35.6–0.4 has the most convoluted discovery history. It was first identified as an SNR due to its deep spectral index derived by both Velusamy & Kundu (1974) and Dickel & Denoyer (1975). Angerhofer et al. (1977) also suggested that G35.6–0.4 was an SNR. However, other opposing claims also existed; e.g., this source has a flat spectral index (Caswell & Clark 1975) and RRLs are detected within the source. However, Green (2009) reanalyzed previous measurements and derived a deep spectral index to G35.6–0.4. Moreover, the IRAS 100 μm image shown in his Figure 3 is supporting evidence that G35.6–0.4 is an SNR.

Phillips & Onello (1993) suggested a kinematic distance of 12 kpc for SNR G35.6–0.4, which is consistent with the dispersion measure (DM) distance of ~13 kpc to PSR J1857+0212. Therefore, these authors thought that the SNR G35.6–0.4/PSR J1857+0212 association was real. Although the recently estimated DM distance to PSR J1857+0212 has changed to 7.98 kpc (Han et al. 2006), the SNR changed its distance as well, to 10.5 kpc (assuming that SNR G35.6–0.4 is at the same distance as the H ii region G35.5–0.0, whose distance has been well measured; Green 2009). Thus, the SNR G35.6–0.4/PSR J1857+0212 association still seems possible according to recent studies.

Paron & Giacani (2010) noticed that the weak gamma-ray source HESS J1858+020 is located at the southern border of SNR G35.6–0.4 (see Figure 1 of their paper). They analyzed the 13CO J = 1–0 line of two molecular clouds (MCs) toward the southern border of G35.6–0.4 and suggested the association between the SNR G35.6–0.4 and the ~55 km s⁻¹ MC as the counterpart of HESS J1858+020. Torres et al. (2011) pointed out that if this association is real, i.e., that HESS J1858+020 is connected with cosmic-ray protons accelerated by SNR G35.6–0.4, it would be difficult not to produce detectable GeV emission at the same location. These results are based on the derived molecular mass in the environment and a distance of 10.5 kpc to both SNR G35.6–0.4 and the CO cloud.

It is important to obtain reliable distances to the components of the complex G35.6–0.5 in order to clarify their interrelationships (e.g., the W51 complex; Tian & Leahy 2013; Brogan et al.
In this paper, we measure the kinematic distance of the complex using 1420 MHz continuum, 21 cm H\textsc{i} spectral line, and $^{13}$CO $J = 1$–0 line data. We also discuss the relationships among its components.

2. DATA AND METHODS TO BUILD AN ABSORPTION SPECTRUM

2.1. Data

The 1420 MHz radio continuum and H\textsc{i} emission data come from the Very Large Array Galactic Plane Survey (Stil et al. 2006). The continuum images have a spatial resolution of 1′ at 1420 MHz. The H\textsc{i} spectral line images, shown with a resolution of 1′ × 1′ × 1.56 km s$^{-1}$, have an rms noise of 2 K per 0.824 km s$^{-1}$ channel. The $^{13}$CO($J = 1$–0) spectral line data are from the Galactic Ring Survey conducted with the Five College Radio Observatory 14 m telescope (Jackson et al. 2006). These data have an angular and spectral resolution of 46′ and 0.21 km s$^{-1}$, respectively.

2.2. Method for Building a Reliable Absorption Spectrum

We use the following formulae to calculate the absorption spectrum.

For the source (ON):

$$T_{\text{on}}(v) = T_B(v)(1 - e^{-\tau_c(v)}) + T_s(e^{-\tau_c(v)} - 1).$$

(1)

For the background (OFF):

$$T_{\text{off}}(v) = T_B(v)(1 - e^{-\tau_i(v)}) + T_{bg}(e^{-\tau_i(v)} - 1).$$

(2)

Then, we obtain an expression for the 21 cm absorption spectrum:

$$e^{-\tau_i(v)} = 1 - \frac{T_{\text{off}}(v) - T_{\text{on}}(v)}{T_s - T_{bg}}.$$  

(3)

The “$-1$” in the second term of Equations (1) and (2) refers to the subtracted continuum emission. $T_{\text{on}}(v)$ and $T_{\text{off}}(v)$ are the H\textsc{i} brightness temperatures of the source and the background regions at a velocity $v$. $T_s$ and $T_{bg}$ are the continuum brightness temperatures for the regions, same as $T_{\text{on}}(v)$ and $T_{\text{off}}(v)$. $T_B(v)$ is the spin temperature of the H\textsc{i} cloud.

To build the H\textsc{i} absorption spectrum, the traditional method selects the background region ($T_{bg}^{c}$) separated from the continuum source ($T_s$). However, there is a possibility that a false absorption spectrum can be constructed due to the potential difference in the H\textsc{i} distribution along the two lines of sight. Tian et al. (2007) presented a revised method to build a 21 cm H\textsc{i} absorption spectrum against a background extended source. In their method, the background region surrounds the source region directly. This geometry minimizes the possibility of obtaining a false absorption spectrum. In addition, Tian et al. (2007) use a CO spectrum in the source direction and the H\textsc{i} absorption spectrum of other bright continuum sources nearby to understand the absorption spectrum of the target source. In this paper, the minimum standard for a reliable absorption feature is taken as $e^{-\tau_i(v)} > 1 - (3\Delta T)/(T_s - T_{bg}^{c})$ (used as 3σ), where Δ$T$ is calculated based on baselines without emission and used as an estimate of fluctuations caused by the receiver noise.

3. RESULTS AND ANALYSIS

3.1. H\textsc{i} Absorption and $^{13}$CO Emission Spectra

The left panel of Figure 1 shows the 1420 MHz continuum image of the complex with contours (20, 25, 30, and 35 K), including PNe: PN G035.5–00.4 and IRAS 18551+0159, SNR: SNR G35.6–0.4; and H\textsc{ii} regions: G35.6+0.14 (an ultracompact H\textsc{ii} region; Giveon et al. 2007), G35.6–0.5, G35.59–0.03, G35.05–0.52, and G35.14–0.76 (re-identified as an H\textsc{ii} region by Froebrich & Ioannidis 2011). The right panel of Figure 1 presents a close-up of the PNe–SNR–H\textsc{ii} region complex. The green contours delineate the radio emission from the Very Large Array Galactic Plane Survey (Stil et al. 2007) presented a revised method to build a 21 cm H\textsc{i} absorption spectrum against a background extended source. In this paper, we measure the kinematic distance of the complex using 1420 MHz continuum, 21 cm H\textsc{i} spectral line, and $^{13}$CO $J = 1$–0 line data. We also discuss the relationships among its components.
Figure 1 displays a close-up of the complex with an angular size of $\sim 13' \times 17'$. Two small bright areas are centered at $l = 35.56$, $b = -0.49$ and $l = 35.59$, $b = -0.49$, the same coordinates as the PN G035.5$-00.4$ and the H$\alpha$ region G35.6$-0.5$. For PN G035.5$-00.4$, IRAS 18551+0159, and the H$\alpha$ regions except for G35.6$-0.5$, the method described by Tian et al. (2007) and Tian & Leahy (2008) is used to extract the H$\alpha$ spectrum. The source regions are shown with white boxes in Figure 1. The background regions are the regions between the white box and the yellow box. Because the SNR G35.6$-0.4$ and the H$\alpha$ region G35.6$-0.5$ are faint and extended, we use the traditional method to construct their H$\alpha$ absorption spectra. The white box labeled 1 is selected as their source region. The average of the yellow boxes numbered from 2 to 7 is used as the background.

Figure 2 shows the H$\alpha$ emission, absorption, and CO emission spectra of PN G035.5$-00.4$ (the top panel), IRAS 18551+0159 (the middle panel), and SNR G35.6$-0.4$ and H$\alpha$ region G35.6$-0.5$ (the bottom panel). Figure 3 shows spectra of four H$\alpha$ regions: G35.05$-0.52$ (top-left), G35.14$-0.76$ (top-right), G35.47$+0.14$ (bottom-left), and G35.59$-0.03$ (bottom-right). The lack of reliable H$\alpha$ absorption at negative velocities for all sources in Figures 2 and 3 implies that all of the sources are localized in the solar circle (for SNR G35.6$-0.4$ and H$\alpha$ region G35.6$-0.5$, the $-10$ km s$^{-1}$ and the $-46$ km s$^{-1}$ absorption features are not real; see Section 3.2.3). The nearly continuous absorption features from $\sim 10$ km s$^{-1}$ to $\sim 58$ km s$^{-1}$ are seen in all sources except for G35.14$-0.76$, indicating a lower limit on the distances of these objects. G35.14$-0.76$ only shows continuous absorption features up to $\sim 35$ km s$^{-1}$.

For PN G035.5$-00.4$, the highest H$\alpha$ absorption velocity appears at $\sim 68$ km s$^{-1}$. However, the $68$ km s$^{-1}$ absorption feature disappears in the absorption spectrum averaged over four adjacent channels. Therefore, it is more reasonable to take $\sim 58$ km s$^{-1}$ as the highest absorption velocity, which suggests a lower limit distance to PN G035.5$-00.4$. The $^{13}$CO emission spectrum toward PN G035.5$-00.4$ shows a clear peak at $\sim 82$ km s$^{-1}$ without any associated H$\alpha$ absorption. This fact hints that the CO cloud is behind PN G035.5$-00.4$. IRAS 18551+0159 shows its highest absorption feature at $\sim 66$ km s$^{-1}$. For SNR G35.6$-0.4$ and H$\alpha$ region G35.6$-0.5$, the highest absorption velocity is at $\sim 61$ km s$^{-1}$. Like PN G035.5$-00.4$, there is no absorption at $\sim 82$ km s$^{-1}$, which is also confirmed by the channel maps (see Figure 4). We detect absorption at the tangent point velocity of $\sim 106$ km s$^{-1}$ for G35.59$-0.03$ and G35.05$-0.52$. This result implies that both of these objects are beyond the tangent point and farther than the complex.

### 3.2. Distances

In this section, all kinematic distances are calculated based on a circular Galactic rotation curve model with the IAU-adopted value $V_0 = 220$ km s$^{-1}$ and $R_0 = 8.5$ kpc. A 7 km s$^{-1}$ random motion (Belfort & Crovisier 1984) is employed to derive the distance uncertainty.

#### 3.2.1. Four H$\alpha$ Regions

RRLs at $51.4 \pm 2.3$ km s$^{-1}$ and $51.2 \pm 1.9$ km s$^{-1}$ have been found toward the H$\alpha$ regions G35.59$-0.03$ and G35.05$-0.52$, respectively (Lockman 1989; Kim & Koo 2001). The velocities correspond to a near side distance of $3.4 \pm 0.4$ kpc and a far side distance of $10.4 \pm 0.4$ kpc. Because continuous H$\alpha$ absorption features are seen from $51$ km s$^{-1}$ to the tangent point velocity, both H$\alpha$ regions are at $10.4 \pm 0.4$ kpc.

Watson et al. (2003) detected an RRL at $80.9 \pm 0.5$ km s$^{-1}$ toward G35.47$+0.14$, which implies a near side distance of $5.3 \pm 0.7$ kpc and a far side distance of $8.6 \pm 0.7$ kpc. In the absorption spectrum toward G35.47$+0.14$, the highest absorption velocity is about $88$ km s$^{-1}$ (see the lower-left panel of Figure 3). There are no H$\alpha$ absorption features near the tangent point velocity, although we find a $^{13}$CO emission peak at $\sim 101$ km s$^{-1}$. Therefore, the near side distance of $5.3 \pm 0.7$ kpc is a proper estimate to G35.47$+0.14$. The absorption features between $80.9$ km s$^{-1}$ and $88$ km s$^{-1}$ are likely caused by the random motion of H$\alpha$ clouds.

For G35.14$-0.76$, the highest H$\alpha$ absorption velocity is $\sim 35$ km s$^{-1}$, at which velocity there is also a $^{13}$CO emission peak. Compared with absorption spectra of three other H$\alpha$
regions, which show absorption features from 30 km s\(^{-1}\) to 50 km s\(^{-1}\), a distance of 2.4 ± 0.5 kpc is sensible for G35.14−0.76 (i.e., the near side distance of the 35 km s\(^{-1}\) absorption feature).

3.2.2. Planetary Nebulae: IRAS 18551+0159 and PN G035.5−00.4

The highest absorption velocity of ∼66 km s\(^{-1}\) in the spectrum of IRAS 18551+0159 suggests a lower limit distance of 4.3 ± 0.5 kpc to IRAS 18551+0159. In Figure 4, many H\(\iota\) self-absorption features at about 82 km s\(^{-1}\) are found around the complex, consistent with the 13CO emission at 82 km s\(^{-1}\) (red contour). The appearance of H\(\iota\) self-absorption features reveals that there are cold H\(\iota\) clouds at about 5.4 kpc (the near side distance of 82 km s\(^{-1}\)). IRAS 18551+0159 is likely closer than 5.4 ± 0.7 kpc because we do not find any absorption features at 82 km s\(^{-1}\) where there is a 13CO emission peak at 82 km s\(^{-1}\). Comparison with the background source G35.59−0.03, which is not beyond the tangent point distance of 6.9 kpc and displays continuous absorption features from ∼70 km s\(^{-1}\) to ∼88 km s\(^{-1}\), we suggest a near distance of 4.3 ± 0.5 kpc for IRAS 18551+0159.

The absorption spectrum of PN G035.5−00.4 averaged over two adjacent velocity channels is shown in Figure 2. The spectrum reveals that the highest absorption velocity is ∼68 km s\(^{-1}\). However, this feature disappears in the absorption spectrum averaged over four adjacent velocity channels (we do not show the spectrum in this paper). The feature also cannot be found when we use the average of regions 2 to 7 (see the right panel of Figure 1) as the background region to construct the absorption spectrum. Therefore, the 68 km s\(^{-1}\) feature is likely caused by small scale fluctuations of H\(\iota\) clouds. It is more reasonable to adopt 58 km s\(^{-1}\) as the highest absorption velocity. The 13CO emission peak shown at the same velocity confirms the reality of the absorption. This fact suggests a lower limit distance of 3.8 ± 0.4 kpc to PN G035.5−00.4. The lack of H\(\iota\) absorption at 82 km s\(^{-1}\) where there is a 13CO emission peak suggests an upper limit distance of 5.4 ± 0.7 kpc to PN G035.5−00.4.

3.2.3. SNR G35.6−0.4 and H\(\iota\) Region G35.6−0.5

The bottom panel of Figure 2 displays the absorption spectra of SNR G35.6−0.4 and the H\(\iota\) region G35.6−0.5. Two absorption features at velocities of ∼−10 km s\(^{-1}\) and ∼−46 km s\(^{-1}\) correspond to distances of ∼14.7 kpc and ∼19.2 kpc, respectively. No absorption features are found from 70 km s\(^{-1}\) to 100 km s\(^{-1}\) where H\(\iota\) self-absorption features are found around the complex. If the SNR lies behind those cold clouds, H\(\iota\) absorption should be seen just like in the cases of other background sources such as G35.59−0.03, G35.47+0.14, and G35.05−0.52. However, no absorption features are found in either of the ∼82 km s\(^{-1}\) channel maps or the H\(\iota\) absorption spectrum (see Figure 4). Therefore, large-scale H\(\iota\) variations across the ON–OFF region are likely responsible for the ∼10 km s\(^{-1}\) and ∼46 km s\(^{-1}\) absorption features.

Paron & Giacani (2010) found ∼55 km s\(^{-1}\) 13CO emission from the MC on the southern border of SNR G35.6−0.4. The emission line is asymmetric and has a slight broadening (see their Figure 2). They suggested that these features are the result
Figure 4. Upper panel: H\textsc{i} channel maps at 81.81 km s\(^{-1}\) (left) and 83.46 km s\(^{-1}\) (right) with overlays of 1420 MHz continuum contours from Figure 1 (green) and \(^{13}\)CO \(J = 1-0\) emission contours with a level of 0.3 K per channel (red). Middle and lower panels: H\textsc{i} (histogram) and \(^{13}\)CO \(J = 1-0\) emission (dotted lies) at four regions around the complex.

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

of the interaction between the SNR and the MC. Then, the MC and SNR G35.6–0.4 should be at the same distance, i.e., 3.6 ± 0.4 kpc at the near side or 10.2 ± 0.4 kpc at the far side. The absorption spectrum in the bottom panel of Figure 2 shows absorption features up to ∼61 km s\(^{-1}\), which suggests that a near-side distance of 3.6 ± 0.4 kpc is plausible.

Lockman (1989) observed a narrow RRL (with a width of 28.9 ± 3.6 km s\(^{-1}\)) at 56.0 ± 2.6 km s\(^{-1}\) toward G35.6–0.5.
while Phillips & Onello (1993) found a broad RRL (with a width of $39 \pm 5$ km s$^{-1}$) at $54 \pm 1$ km s$^{-1}$ in the same direction. These authors believed that the RRL originated from the H$\Pi$ region G35.6$-0.5$. Paron et al. (2011) found clear polycyclic aromatic hydrocarbon emission at 8 $\mu$m, which suggests that G35.6$-0.5$ is likely an extended H$\Pi$ region. The RRL peak antenna temperature ($T_{\text{A}}$) of Phillips & Onello (1993) was $91 \pm 5$ mK, which implies a relative signal-to-noise ratio of 18.2. In Lockman (1989), $T_{\text{A}}$ is equal to 24 $\pm$ 2.3 mK and the calculated relative signal-to-noise ratio is 10.4.

Phillips & Onello (1993) found that the full width at half maximum of the RRL is nearly two times greater than the expected value from thermal broadening for a $10^4$ K H$\Pi$ region. This fact implies enhanced turbulence caused by a non-thermal source. Therefore, SNR G35.6$-0.5$ may originate not from the H$\Pi$ region G35.6$-0.5$ but from the PN G035.5$-0.4$, since PN G035.5$-0.4$ is very close to G35.6$-0.5$. Spectroscopic observations with high angular and spectral resolution are needed to address this question. If the RRL partly comes from the H$\Pi$ region G35.6$-0.5$, this fact would hint that the source is located at a distance of $3.6 \pm 0.4$ kpc.

Table 1 summarizes the velocities of the H$\text{I}$ absorption and the CO emission features and the distances to the studied objects.

| Name | G35.59$-0.03$ | G35.05$-0.52$ | G35.47$+0.14$ | G35.14$-0.76$ | IRAS 18551$+0159$ | PN G035.5$-0.00.4$ | G35.6$-0.5$ | SNR G35.6$-0.4$ |
|------|--------------|--------------|--------------|---------------|-----------------|-----------------|-----------|-------------|
| MAV  | $\sim106$    | $\sim106$    | $\sim88$    | $\sim35$     | $\sim66$       | $\sim58$       | $\sim61$  | $\sim61$   |
| RRLV | $51.4 \pm 2.3$ | $51.2 \pm 1.9$ | $80.9 \pm 0.5$ | $\sim55 \pm 3.6^{b}$ | $\sim55 \pm 3.6^{b}$ | $\sim55$ | $\sim55$ | $\sim55$  |
| CNO | $\sim82$    | $\sim35$    | $\sim82$    | $\sim82$     | $\sim82$       | $\sim82$       | $\sim82$  | $\sim82$   |
| FCO  | $\sim101$   | $\sim44$    | $\sim44$    | $\sim44$     | $\sim44$       | $\sim44$       | $\sim44$  | $\sim44$   |
| Distance | $10.4 \pm 0.4$ | $10.4 \pm 0.4$ | $5.3 \pm 0.7$ | $2.4 \pm 0.5$ | $4.3 \pm 0.5$ | $3.8 \pm 0.4 \sim 5.4 \pm 0.7$ | $3.6 \pm 0.4^{c}$ | $3.6 \pm 0.4^{c}$ |

Notes. MAV: maximum absorption velocity, RRLV: RRL velocity, CNO: velocity of nearby CO emission feature, FCO: velocity of far CO emission feature. The unit of velocity is km s$^{-1}$. The unit of distance is kpc.

$^{a}$ The SNR G35.6$-0.4$ overlaps with the H$\Pi$ region G35.6$-0.5$, so we cannot distinguish the highest absorption velocity (61 km s$^{-1}$) feature from their mixed spectrum, i.e., one of the two sources’ MAVs might be less than 61 km s$^{-1}$.

$^{b}$ PN G035.5$-0.00.4$ and G35.6$-0.5$ are covered in the same RRL observation beam. It is unknown which one is responsible for the RRL.

$^{c}$ Based on the assumption that part of the RRL comes from G35.6$-0.5$.

4. DISCUSSION

4.1. H$\Pi$ Region G35.47$+0.14$ and G35.14$-0.76$

Kolpak et al. (2002) identified G35.47$+0.14$ as an extragalactic continuum source whose absorption spectrum shows H$\text{I}$ absorption at negative velocities less than $-10$ km s$^{-1}$. However, G35.47$+0.14$’s spectrum in the lower-left panel of Figure 4 shows absorption neither at the tangent point velocity nor at the negative velocity. Considering the detected RRL at $80.9 \pm 0.5$ km s$^{-1}$, G35.47$+0.14$ is likely at a distance of $5.3 \pm 0.7$ kpc. In addition, 6 cm continuum observations (Urquhart et al. 2009), mid-infrared observations (Giveon et al. 2007), and H$\text{I}$ self-absorption (Anderson & Bania 2009) also support the fact that G35.47$+0.14$ is a Galactic object.

Froebrich & Ioannidis (2011) studied G35.14$-0.76$ and found that the central star is of spectral type O9 or B0 and that its mass is about $20 M_\odot$. They suggested that G35.14$-0.76$ is a misclassified PN and should be re-classified as an H$\Pi$ region. The Two Micron All Sky Survey $K$-band extinction to G35.14$-0.76$ is 0.78 mag, which indicates a distance of $2.5$ kpc to G35.14$-0.76$. This distance is consistent with the kinematic distance of $2.4 \pm 0.5$ kpc. Han et al. (2011) detected a H$2$CO feature at $33.7 \pm 0.2$ km s$^{-1}$, nearly at the same velocity as the highest H$\text{I}$ absorption velocity, $-35$ km s$^{-1}$. Therefore, $2.4 \pm 0.5$ kpc is a robust distance estimate to the H$\Pi$ region G35.14$-0.76$.

4.2. IRAS 18551$+0159$ and PN G035.5$-0.00.4$

IRAS 18551$+0159$ has been observed by the *Midcourse Space Experiment* (MSX) satellite (Egan et al. 2003). Its $8.28 \mu$m flux density is $1.47$ Jy. According to the mid-infrared distance scale (Ortiz et al. 2011)

$$\log D = -0.1736 \log F_{8.28\mu m} - 0.3899 \log \theta + 0.7960,$$

where the calculated statistical distance to IRAS 18551$+0159$ is $5.0$ kpc. Considering the large error in the statistical method, this distance is consistent with the kinematic distance, $4.3 \pm 0.5$ kpc. Eder et al. (1988) detected OH emission (1612 MHz) from IRAS 18551$+0159$, which reveals that its age is less than $\sim 1000$ yr (Gómez 2007). Jiménez-Esteban et al. (2005) found IRAS 18551$+0159$ to be extremely red with no optical counterpart. This result indicates that IRAS 19551$+0159$ may have recently departed from the AGB. Assuming a distance of $4.3 \pm 0.5$ kpc, the size of IRAS 18551$+0159$ is about $0.06$ pc. The small size supports the hypothesis that IRAS 18551$+0159$ left the AGB phase recently.

For PN G035.5$-0.00.4$, the distance estimate (from $3.8 \pm 0.4$ kpc to $5.4 \pm 0.7$ kpc) is similar to the statistical distance, $4.6$ kpc (Ortiz et al. 2011). The new distance restriction suggests a normal linear size of about $0.2 \sim 0.3$ pc for PN G035.5$-0.00.4$. Cohen et al. (2007) studied PN G035.5$-0.00.4$ based on *Spitzer*/IRAC data and found that its morphology changes from asymmetric with an enhanced brightness of the southern limb in the three shortest bands (3.6, 4.5, and $5.8 \mu$m) to a large circular appearance at $8 \mu$m. This character can be explained by a substantial photodissociation region that envelops the entire ionized zone. Although the kinematic distance measurements do not rule out the possibility of an association with SNR G35.6$-0.4$ or the H$\Pi$ region G35.6$-0.5$, the perfect circle pattern implies no significant interaction between PN G035.5$-0.00.4$ and SNR G35.6$-0.4$ or the H$\Pi$ region G35.6$-0.5$.

Anderson et al. (2012) derived a robust color criterion to distinguish between H$\Pi$ regions and PNe. They found nearly 98% of H$\Pi$ regions in their sample have $12 \mu$m and $8 \mu$m flux density ratios less than 0.3. According to the data from *MSX* (Egan et al. 2003), this ratio is 2.4 and 3.4 for IRAS 18551$+0159$.
and PN G035.5−00.4, respectively. The values support both IRAS 18551+0159 and PN G035.5−00.4 being real PNe.

4.3. SNR G35.6−0.4

With a distance of 3.6 ± 0.4 kpc, the average size and age of SNR G35.6−0.4 would be revised to about 15 pc in diameter and 2300 yr, respectively. The new age would imply that SNR G35.6−0.4 is in an early evolutionary stage. Phillips & Onello (1993) suggested that SNR G35.6−0.4 is associated with PSR J1857+0212 because both objects have similar distances. However, the new kinematic distance to SNR G35.6−0.4 (3.6 ± 0.4 kpc) is much less than the DM distance of 7.98 kpc to PSR J1857+0212. Furthermore, Clifton et al. (1988) measured the H1 absorption spectrum of PSR J1857+0212. The spectrum displays absorption features up to the tangent point velocity (see their Figure 4 for details), which indicates a lower limit distance of 6.9 ± 1.3 kpc to PSR J1857+0212. This fact suggests PSR J1857+0212 could be at least 3 kpc behind SNR G35.6−0.4. Morris et al. (2002) discovered another pulsar PSR J1857+0210 near the center of SNR G35.6−0.4. However, PSR G1857+0212 has a DM distance of 15.4 kpc. An association between the pulsar and SNR G35.6−0.4 seems impossible. Moreover, both pulsars have large characteristic ages, which also disfavor the association (the characteristic ages of PSR J1857+0212 and PSR J1857+0210 are about 160,000 and 712,000 yr, respectively). Although the characteristic age is not the real age, which is usually unknown, it is a good estimator of the age when the braking index is ~3 and the initial pulsar spin-down period is much shorter than the current one.

Both pulsars have a relatively low spin-down power, i.e., $2.2 \times 10^{34}$ erg s$^{-1}$ for PSR J1857+0212. Even at the distance we estimated for G35.6−0.4 (i.e., assuming that its DM distance is underestimated by more than a factor of two), $E/4\pi D^2$ would be $1.3 \times 10^{37}$ erg s$^{-1}$ kpc$^{-2}$. At typical efficiencies for radiation in the gamma-ray band, pulsar wind nebulae driven by these pulsars would be undetectable by the current generation of instruments (see, e.g., Martín et al. 2012). We can safely consider that none of the pulsars significantly contributes to the TeV source detected by HESS.

Does the weak gamma-ray source HESS J1858+020 originate from the interaction between SNR G35.6−0.4 and the ∼55 km s$^{-1}$ MC? Paron & Giacani (2010) and Torres et al. (2011) gave somewhat different opinions on the question. Paron & Giacani (2010) believed SNR G35.6−0.4 is interacting with the cloud at ∼55 km s$^{-1}$ crossing the SNR shell. They found the cloud shows some possible kinematical evidence of shocked gas in the $^{13}$CO $J = 1 − 0$ emission spectrum: asymmetry and a slight spectral line broadening (see their Figure 2). Assuming the clouds’ distance of 10.5 kpc, the same as the SNR, they estimated its mass and density to be $\sim 5 \times 10^{5}$ $M_\odot$ and $\sim 500$ cm$^{-3}$, respectively, which seem enough to explain the observed gamma-ray flux. Paron et al. (2011) excluded the possibility that HESS J1858+020 originates from molecular outflows of a young stellar object. Therefore, the SNR G35.6−0.4/∼55 km s$^{-1}$ MC becomes the most probable counterpart to HESS J1858+020.

Torres et al. (2011) have considered a possible association between G35.6−0.4 and HESS J1858+020 to be doubtful because of the lack of a GeV counterpart. Indeed, they have analyzed two years of Fermi-LAT data of the region of interest and considered whether it was possible that the closest LAT source, 1FGL J1857.1+0212c, could be spatially related to HESS J1858+020. They concluded that it was not, at least with the dataset at hand. However, upper limits were imposed. Thus, the cosmic-ray interaction between protons accelerated in the SNR and material in the cloud should be such to allow the production of TeV emission in HESS J1858+020 without producing a GeV counterpart. This physics may in principle be possible for particular combinations of diffusion coefficients and MC/SNR distances (low mass in the cloud and slow diffusion timescales). In fact, this very scenario has been claimed for other sources, such as SNR W28 (e.g., Li & Chen 2010).

Torres et al.’s (2011) calculation was based on a distance to the SNR/MC complex of 10.5 kpc and a molecular mass of several thousand solar masses. Accepting the new distance estimate for the remnant, of 3.6 ± 0.4 kpc, suggests that much less mass is available for cosmic-ray interactions, of the order of $600 M_\odot$. Assuming these parameters, we have reconsidered the model put forward by Torres et al. (2011) and the results are as follows. For details regarding the numerical model itself, we refer the reader to Rodriguez Marrero et al. (2008) and Torres et al. (2008, 2010).

The physical size of the SNR shell and the projected separation to the MC are also resized due to the revised distance to the SNR/MC complex, as seen above. This fact means that the accelerated particles diffuse to much shorter distances than what was considered before. The maximum of the particle flux, for a given energy $E_p$ at a given time $t$, is reached at a distance $R = \sqrt{6/\pi}D(E_p)$ (see, e.g., Aharonian & Atoyan 1996). This distance is equal to a projected distance of $\sim 10$ pc for energies of $E_p \sim 5$ TeV and a diffusion coefficient of $D(E_p) = D_0(E_p / 10 \text{GeV})^\delta$, with $D_0 = 10^{38}$ cm$^2$ s$^{-1}$ and $\delta = 0.5$. The bulk of the particles with energies lower than 5 TeV have still not reached the target mass. This result is exact for an impulsive source, when the age of the source is much longer than the time over which the particles are injected.

Due to its smaller age, the source is probably better approximated as a continuous injection point, since the short age is comparable to the time of release of the particles. The injection luminosity is such that the total energy input in the lifetime of the SNR is $10^{50}$ erg, hence equal to $1.38 \times 10^{39}$ erg s$^{-1}$. We choose the slope of the injection spectrum to match the one in Torres et al. (2011), with $p = 2.0$. The only parameters that are left free for a fit are then the actual separation of the accelerator from the target (which would probably not exceed the projected separation by more than a factor of few) and the actual mass of the target that interacts with the cosmic-ray population. Note that in Torres et al. (2011), distances from the injection point in

| $D_{10}$ cm$^2$ s$^{-1}$ | $R_{SNR/MC}$ (pc) | Mass ($M_\odot$) |
|------------------------|-----------------|----------------|
| $10^{26}$              | 10              | 150            |
| $10^{26}$              | 15              | 500            |
| $10^{26}$              | 20              | 1000           |
| $10^{26}$              | 25              | 1500           |
| $10^{27}$              | 10              | 500            |
| $10^{27}$              | 15              | 800            |
| $10^{27}$              | 20              | 1500           |
| $10^{27}$              | 25              | 2000           |
| $10^{28}$              | 10              | 3000           |
| $10^{28}$              | 15              | 5000           |
| $10^{28}$              | 20              | 7000           |
| $10^{28}$              | 25              | 8000           |
Figure 5. Point-like injection models for the gamma-ray spectrum of SNR G35.6−0.4. The parameters used in this figure correspond to those given in Table 2 and the distance to the SNR/MC complex proposed in this work. The solid, dashed, dotted, and dot-dashed curves represent models with increasing values of separation radius, as given in Table 2. The left panels show the differential proton flux compared to the cosmic-ray sea (solid red line). The right panels show model spectral energy distributions, compared with HESS observations (Aharonian et al. 2008) and Fermi-LAT upper limits (Torres et al. 2011). From left to right, the assumed normalization of the diffusion coefficient is \( D_{\text{10}} = 10^{26.27,28} \text{ cm}^2 \text{ s}^{-1} \).

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

Figure 5 shows the prediction from models with the same parameters specified in Table 2. The cosmic-ray sea contribution is dominant at the lowest energies (in the Fermi-LAT regime). However, due to the small mass of the target cloud, the contribution to the flux from the emission related to the cosmic-ray sea is minimal, below the range of fluxes shown in the figures.

The results of Figure 5 and Table 2 show that the new distance and MC estimate do not rule out the possibility of a connection between G35.6−0.4 and HESS J1858+020. Actually, a connection is currently more favored than in the...
case of the 10.5 kpc distance, since low values of the diffusion coefficient required before are no longer needed to maintain the GeV luminosity below the observational sensitivity. We note, however, that for a diffusion coefficient of the order of Galactic average, i.e., $D_{10} = 10^{28} \text{ cm}^2 \text{ s}^{-1}$, we need a large separation between the accelerator and the target, with a mass of the latter that largely exceeds the estimates given here by one order of magnitude. Therefore, we still expect a suppressed diffusion coefficient in the environment in the case of a physical association. We also note that the SNR diameter is of the order of 15 pc, so assuming a 10 pc radius from the injection point is a bare minimum for a realistic model; slightly higher separations would be preferred.

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