Molecular and Atomic Gas toward HESS J1745–303 in the Galactic Center: Further Support for the Hadronic Scenario

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Abstract

We compared TeV γ-rays with new $^{12}$CO $J = 2–1$ data toward HESS J1745–303 in the Galactic center, and confirmed that the molecular cloud MG358.9–0.5 toward $(l, b) = (358^\circ.9, -0.5)$ at $V_{LSR} = -100–0$ km s$^{-1}$ shows a reasonable positional agreement with the primary peak (northern part) of the γ-ray source. For the southern part of HESS J1745–303, we have seen no CO counterpart, whereas H$\text{I}$ gas in the SGPS H$\text{I}$ dataset shows a possible counterpart to the γ-ray source. This H$\text{I}$ gas may be optically thick, as supported by the H$\text{I}$ line shape similar to the optically thick $^{12}$CO. We estimate the total mass of interstellar protons including both the molecular and atomic gas to be $2 \times 10^6 M_\odot$ and the cosmic-ray proton energy to be $6 \times 10^{48}$ erg in the hadronic scenario. We discuss possible origins of the cosmic-ray protons including the nearby SNR G359.1–0.5. The SNR may be able to explain the northern γ-ray source, but the southern source seems to be too far to be energized by the SNR. As an alternative, we argue that the second-order Fermi acceleration in the inter-clump space surrounded by randomly moving high-velocity clumps may offer a possible mechanism to accelerate protons across the entire HESS source. The large turbulent motion with a velocity dispersion of $\sim 15$ km s$^{-1}$ has an energy density two orders of magnitude higher than in the solar vicinity, and is viable as the energy source.

Key words: ISM: clouds — ISM: cosmic rays — ISM: individual objects: HESS J1745–303

1. Introduction

Astronomical observations of γ-rays with space-borne and ground-based telescopes have become important tools to pursue physical processes in the Universe owing to the higher sensitivity and angular resolution than a decade ago. In particular, TeV γ-ray observations with the High-Energy Stereoscopic System (HESS) have revealed more than 50 γ-ray sources in the Galactic plane, offering new tools to uncover the highest energy phenomena in interstellar space (Aharonian et al. 2006a, 2006b).

Among the HESS sources, the extended source in the Galactic center (GC) is an outstanding object that shows a good spatial correlation with the dominant molecular feature, the central molecular zone (CMZ) (Morris & Serabyn 1996). Aharonian et al. (2006b) noted a correlation between the molecular gas and TeV γ-rays by comparing CS (Tsuboi et al. 1999) and the TeV γ-ray image; in particular, Aharonian et al. (2006b) noted that three peaks of extended γ-rays show a good spatial correlation with major molecular peaks in the CMZ, including the Sgr A, Sgr B2, and Sgr C molecular clouds (e.g., Fukui et al. 1977; Scoville et al. 1975; Liszt 1985).

The good correlation suggests that the γ-rays are produced by the hadronic process by which TeV γ-rays are emitted via the decay of neutral pions created in high-energy reactions between the cosmic-ray protons and interstellar protons.

HESS J1745–303 is another extended source on the negative longitude side of the GC at $(l, b) = (358^\circ.9, -0.5)$. This source seems to be separated from the CMZ by 1°, while it is not clear if it is connected to the CMZ. Aharonian et al. (2008) studied this source, and identified molecular gas observed at a lower resolution of 9′ as a candidate of the associated cloud, but could not find any objects that could fully match the TeV γ-rays. This molecular cloud (hereafter MG358.9–0.5) is located toward the Galactic-western edge of the shell-like distribution, which surrounds an SNR G359.1–0.5 (Uchida et al. 1992a). Aharonian et al. (2008) searched for associated objects in the literature, and listed up several candidates, including pulsars and G359.1–0.5, while the origin of the cosmic-rays remained unclear.

We present here new $^{12}$CO $J = 2–1$ observations with NANTEN2 and H$\text{I}$ data obtained with the Parkes 64-m telescope toward HESS J1745–303. We confirmed an association of the suggested molecular cloud MG358.9–0.5 with the HESS source, and identified another possible association between the HESS source and atomic gas. Section 2 gives observations and section 3 presents results. Section 4 gives a discussion and section 5 summarizes the paper.

2. Observations and Datasets

2.1. $^{12}$CO $J = 2–1$ Observations

We made observations of the $^{12}$CO $J = 2–1$ line (the rest frequency is 230.53800 GHz) using the NANTEN2 4-m telescope at Atacama, Chile, during the period from 2010 July to 2011 January. The 4m-diameter provides a half-power beam width (HPBW) of 90′. The receiver front-end was a 4K cooled SIS receiver. The spectrometer was a digital Fourier spectrometer (DFS) with a 1 GHz (corresponds to 1300 km s$^{-1}$ at 230 GHz) bandwidth and a 61 kHz (0.08 km s$^{-1}$) resolution. The velocity $V_{LSR}$ hereafter refers to the local standard of rest. The pointing accuracy was
estimated to be about 10" by observing Jupiter and Venus every two hours, and system stability was checked by observing M17SW (α = 10°20′24.4″, δ = −16°13′18″ at J2000.0 coordinates) and Ori-KL (5°32′14.5″, 5°22′28″) every hour. The standard chopper-wheel method was employed to calibrate the intensity and to correct for atmospheric attenuation. The adopted main beam efficiency, ηmb, was 0.5 as measured by observing Jupiter.

The observations were made as part of the NANTEN2 Galactic-Center Survey, which make a mosaic of 15′ × 15′ maps. Each 15′-square map was made by using an on-the-fly (OTF) mapping technique. The dump interval, the scan velocity, and the inter-scan distance were 1 s, 30 km s⁻¹, and 30′ respectively, producing a Nyquist-sampled 30′ grid map. An off-source reference scan was obtained after every two lines of on-source scan. The off-position of (l, b) = (1°133, −1°467) was checked to be free of emission with an r.m.s. noise level of 0.1 K for 61 kHz resolution. In order to remove the scanning effect, the maps were obtained by scanning in both the Galactic longitude and latitude directions, and combined using an algorithm described by Emerson and Gräve (1988). The image was smoothed with a Gaussian kernel with FWHM of 60′.

2.2. $^{12}$CO J = 1–0 Dataset

We used the $^{12}$CO J = 1–0 NANTEN Galactic Plane Survey (NGPS) dataset (Mizuno & Fukui 2004). The HPBW was 2′/6 at 115 GHz. The spectrometer was an acousto-optical spectrometer (AOS) with 2048 channels. The frequency coverage and resolution were 250 MHz and 250 kHz, corresponding to a velocity coverage of ±300 km s⁻¹ and a velocity resolution of 0.6 km s⁻¹, respectively. The observations were carried out by position switching at a 4′ grid spacing. The on-source integration time per point was 4 s and the r.m.s. noise fluctuations of the spectral data were ~0.3 K at 0.6 km s⁻¹ velocity resolution.

2.3. H i Dataset

We also used the Southern Galactic Plane Survey (SGPS) dataset (McClure-Griffiths et al. 2005). The SGPS data were gridded with a cell size of 4′ and a Gaussian smoothing kernel of 16′. The bandwidth and channel width of the spectrometer were 4.5 MHz and 3.9 kHz (950 and 0.82 km s⁻¹ at 1420 MHz), respectively. For further details, see McClure-Griffiths et al. (2005).

3. Results

3.1. CO Results

Figure 1 shows the overall $^{12}$CO distribution in the (l, b) plane and the velocity-l plane toward the CMZ with the TeV γ-ray distribution overlaid. We searched for possible counterparts in a velocity range from −300 to +300 km s⁻¹ in the $^{12}$CO J = 2–1 dataset. Figure 2(a) shows an overlay of $^{12}$CO and TeV γ-rays in an area of HESS J1745–303. The peak of MG358.9–0.5 is very coincident with the primary peak in the northern part of the TeV γ-rays, region A of Aharonian et al. (2008), as already noted by these authors. We note that our new $^{12}$CO data have a higher spatial resolution by a factor of 5 than the $^{12}$CO data used by Aharonian et al. (2008). It seems that the cloud has velocities of between −100 and around 0 km s⁻¹ toward the position a1 and −100–+40 km s⁻¹ toward the position a2 in region A (see table 1), although the full velocity range of the molecular cloud is not well determined because of contamination by the foreground emission at low velocities ($|V_{LSR}| ≤ 20$ km s⁻¹). Sample spectra toward these two positions are shown in figure 3. The southern part of the γ-ray source (regions B and C of Aharonian et al. 2008), however, does not have any counterpart in $^{12}$CO.

MG358.9–0.5 shows $^{12}$CO line profiles peaked at high velocity ($\sim −50$ km s⁻¹) with broad line-widths ($\sim 30−50$ km s⁻¹, FWHM) and absorption at −60 km s⁻¹ by the 3 kpc-arm component, as previously mentioned by Uchida et al. (1992a). Thus, the cloud is not a local feature, but in the GC perhaps near the CMZ. Figure 1 shows a strong hint that the cloud is physically linked to the CMZ from its continuity to the CMZ both in both space and velocity, whereas such a connection is not recognized in the CS image, which does not cover b below −0°25.

The molecular cloud mass within a HESS 4σ significance contour is estimated to be $1.6 \times 10^6 M_{\odot}$ by adopting a distance of 8.5 kpc and a conversion factor between the
H$_2$ column density and the $^{12}$CO integrated intensity in the GC, $X(^{12}\text{CO}_{1-0}) = N($H$_2$)/$W(^{12}\text{CO}_{1-0}) = 7 \times 10^{19}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Torii et al. 2010). Here, we used the $J = 1-0$ integrated intensity instead of $J = 2-1$, because the $N($H$_2$)/$W(^{12}\text{CO}_{2-1})$ conversion factor is not well established. The $^{12}$CO $J = 1-0$ integrated intensities of MG358.9–0.5 in a velocity range from $-100$ to $-15$ km s$^{-1}$ are $\sim 100$–500 K km s$^{-1}$ and roughly proportional to those of $J = 2-1$ with an intensity ratio of $W(^{12}\text{CO}_{2-1})/W(^{12}\text{CO}_{1-0}) \sim 0.7$. The average H$_2$ density is estimated to be $2 \times 10^{22}$ cm$^{-2}$, as derived by dividing the mean H$_2$ column density $2 \times 10^{22}$ cm$^{-2}$ by the projected size of the molecular cloud, 40 pc.

### H I Results

Figure 2(b) shows the H I distribution compiled from the H I dataset (McClure-Griffiths et al. 2005) in the same region. Although the angular resolution, 16’, is not high enough, the H I distribution shows a possible counterpart to the TeV $\gamma$-rays. Figure 3 shows H I and $^{12}$CO line profiles toward four positions: a1, a2, b, and c (table 1).

In order to test if the H I emission is similar to the $^{12}$CO emission, we subtracted the H I profiles toward the four positions and the reference H I profiles; the reference H I profiles for each were taken at the same $b$ separated by $\sim 0.5$ on both sides ($l = 358^\circ 2$ and $359^\circ 4$). The results shown in figure 3 indicate that these subtracted H I profiles show fairly similar shapes and intensities to those of the $^{12}$CO profiles toward MG358.9–0.5 in their peak velocity and linewidth. The similarity leads us to suggest that the H I emission is from H I gas physically connected to MG358.9–0.5, but without $^{12}$CO emission. We note that the absorption of the radio continuum emission is not important in this direction (e.g., Yusef-Zadeh et al. 2004).

The H I emission in the negative velocity range consists of three features: the 3-kpc arm at $V_{\text{LSR}} = -60$ km s$^{-1}$ (van Woerden et al. 1957), the $V_{\text{LSR}} = -100$–75 km s$^{-1}$...
feature and the $V_{LSR} \leq -100$ km s$^{-1}$ feature. The 3-kpc arm is located in front of and outside the GC, and is not seen in the $^{12}$CO emission in figure 3. The $V_{LSR} \leq -100$ km s$^{-1}$ feature is likely distributed within 1 kpc of the GC (Rougoor & Oort 1960). The $100-75$ km s$^{-1}$ feature is perhaps located within the inner few 100 pc, similar to the CMZ, and is physically related to the $^{12}$CO counterpart of HESS J1745–303, MG358.9–0.5. The contamination by the 3-kpc arm masks the H I emission above $-75$ km s$^{-1}$, while the $^{12}$CO emission at position a2 (figure 3(2)) suggests that the velocity of the H I counterpart may be extended to $-45$ km s$^{-1}$.

The H I column density can be calculated by the following relation if the line is optically thin:

$$N(HI) = 1.823 \times 10^{18} \int T_B(v)dv \text{ (cm}^{-2}) \text{.}$$

(1)

where $T_B(v)$ is the brightness temperature in units of $K$. The H I integrated intensities of 160–270 K km s$^{-1}$, which are given by assuming single-Gaussian profiles with FWHM line-widths of 30–50 km s$^{-1}$ and a peak intensity of 5 K, correspond to a H I column density of $(3-5) \times 10^{20}$ cm$^{-2}$ when the line is optically thin, as is usually assumed. The average H I density is then estimated to be 3–5 cm$^{-3}$ for a line-of-sight length of 30 pc.

An alternative is that the H I line may be optically thick, because the H I line profile seems to be fairly similar to that of the optically thick $^{12}$CO line (figure 3). If so, the H I emission is from dense atomic gas with lower temperature close to that of the $^{12}$CO cloud, as suggested by the peak temperature of H I, similar to $^{12}$CO; we are not able to estimate the H I density, but can constrain the average density to be $\leq 100$ cm$^{-3}$ by assuming that the H I is less dense to emit $^{12}$CO. Adopting a spin temperature of $T_\sigma \sim 30-60$ K, which is comparable to the kinetic temperature of the molecular gas in the CMZ (e.g., Güsten et al. 1981; Morris & Serabyn 1996; Martin et al. 2004), we estimate the H I column density to be $N(HI) \gtrsim (0.5-1) \times 10^{22}$ cm$^{-2}$ for a H I peak optical depth, $\tau$, greater than $\sim 3$ and a linewidth of $\sim 30$ km s$^{-1}$ by using the following relation:

$$N(HI) = \frac{32\pi v^2 k T_\sigma}{3c^3 n_H} \tau \Delta V$$

$$= 1.823 \times 10^{18} \tau \left( \frac{T_\sigma}{K} \right) \left( \frac{\Delta V}{km\,s^{-1}} \right) \text{ (cm}^{-2}) \text{.}$$

(2)

where $c$ is the light velocity, $h$ the Planck constant, $k$ the Boltzmann constant, $\nu = 1420$ MHz the rest frequency and $A_{ul} = 2.85 \times 10^{-15}$ s$^{-1}$ Einstein’s $A$ coefficient. We then obtain $n(HI) \gtrsim (0.5-1) \times 10^{2}$ cm$^{-3}$ by dividing the column density by the typical size of the $\gamma$-rays, $\sim 30$ pc. Considering the upper limit for the average density, we infer that the density of the optically thick H I gas linked to MG358.9–0.5 is around 100 cm$^{-3}$.

4. Discussion

The origin of the $\gamma$-rays in HESS J1745–303 has been discussed in the literature. Aharonian et al. (2008) reported that there is no significant spectral variability across HESS J1745–303, and suggested a single origin of the TeV $\gamma$-rays. It is to be noted that the HESS detection is at the 5$\sigma$ level toward the southern part of HESS J1745–303, and the distribution of the spectral index is yet to be confirmed by higher sensitivity. The authors also showed that the $\gamma$-ray source has no extended X-ray source in the XMM-Newton data. Bamba et al. (2009) confirmed the lack of a non-thermal X-ray counterpart, and argued that the leptonic model requires a weak magnetic field strength, $B \lesssim 6 \mu G$ in a $n = 0.1$ cm$^{-3}$ model and $B \lesssim 10^2 \mu G$ in a $n = 5 \times 10^3$ cm$^{-3}$ model, to explain the observed upper limit of the X-ray flux in the 2–10 keV band, $2.1 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. It has, on the other hand, been shown that the field strength is at least $50 \mu G$ over 400 pc in the CMZ where the average gas density is $10^2-10^3$ cm$^{-3}$ (Crocker et al. 2010). Such strong magnetic field seems to be inconsistent with the absence of X-rays. This suggests that the hadronic scenario is favorable in HESS J1745–303. The positional coincidence with the unidentified EGRET source 3EG J1744–3011 (Hartman et al. 1999), also known as the AGILE first-catalog source 1AGL J1746–3017 (Pittori et al. 2007).
PSR B1742 high-energy cosmic-ray proton injector. Among them, pulsars ion of HESS J1745/NUL and T and 2009), again supports the hadronic scenario, which usually predicts bright GeV γ-rays, though positional accuracy of the EGRET/AGILE source is not sufficiently high.

Aharonian et al. (2008) argued for the hadronic process, that the 12CO cloud MG358.9–0.5 is responsible for the northern part of HESS J1745–303, whereas the ISM corresponding to the southern part of HESS J1745–303 remained unidentified. We argue that the 12CO cloud has a dense H I envelope with no 12CO emission, and that the H I envelope is responsible for γ-ray production by cosmic-ray protons; it is likely that the H I envelope has a moderately high density, like ~100 cm⁻³ and T_e of 30–60 K, significantly less than ~100 K (see subsection 3.2). We recall that the Galactic γ-ray emission requires an unseen component either in 12CO or warm H I, as indicated by an analysis of EGRET data (Grenier et al. 2005). The “dark gas” component in 12CO or H I in a Galactic scale is also recognized in the visual/infrared extinction (e.g., Dobashi 2011) and in dust emission obtained by the Planck satellite (Ade et al. 2011). In the TeV-γ-ray SNR RXJ1713.7–3946, it has been shown that cold H I gas observed as self-absorption dips matches well with the TeV γ-ray shell, suggesting that such H I having density of ~100 cm⁻³ with no 12CO emission works as target protons in the hadronic interaction (Fukui et al. 2012). Considering these results, we suggest that the H I cloud with no 12CO emission is a good candidate for the TeV γ-rays in the southern part, and that the TeV γ-ray emission of HESS J1745–303 is likely due to accelerated protons interacting with the molecular/atomic clouds in the GC region.

Figure 4 indicates the positions of nearby candidates for the high-energy cosmic-ray proton injector. Among them, pulsars PSR B1742–30 and J1747–2958 and a SNR G359.0–0.9 are at heliocentric-distances of 2.08, 2.49, and 6 kpc, respectively (Manchester et al. 2005; Bamba et al. 2000) and, thus, unrelated to HESS J1745–303, whereas G359.1–0.5 is likely to be at a distance of the GC (e.g., Uchida et al. 1992b). We discuss whether or not G359.1–0.5 is responsible for the cosmic-ray protons that produce the γ-rays in HESS J1745–303. Adopting a distance of 8.5 kpc, the total energy of cosmic-ray protons required to generate the observed TeV γ-ray flux can be estimated by the following relation (e.g., Aharonian et al. 2006c, 2007):

\[
W_p \simeq t_{pp\to p^0} \cdot L_\gamma \simeq 3.9 \times 10^{50} \left( \frac{\bar{n}_p}{1 \, \text{cm}^{-3}} \right)^{-1} \left( \frac{\nu_\gamma}{10^{-11} \, \text{erg cm}^{-2} \, \text{s}^{-1}} \right) \text{erg},
\]

where \( t_{pp\to p^0} \simeq 4.5 \times 10^{15} \left( \bar{n}_p/1 \, \text{cm}^{-3} \right)^{-1} \) s is the characteristic cooling time of protons through the \( p^0 \) production channel, \( L_\gamma = 4\pi (8.5 \, \text{kpc})^2 \nu_\gamma \) the γ-ray luminosity, \( \bar{n}_p \) the mean proton density of the target ISM, and \( \nu_\gamma \) the γ-ray energy flux. Table 2 summarizes \( \nu_\gamma \) in an energy range of 0.3–40 TeV, and the estimated \( W_p \) in the corresponding energy range of approximately 3–400 TeV for regions A, B, and C, and a region covering the entire HESS J1745–303 (named “Full” in Aharonian et al. 2008).

Region A is close to G359.1–0.5, while regions B and C are 0.5 far away from it. The solid angle of region A, as viewed from the center of G359.1–0.5, is about an order of magnitude larger than those of regions B and C. The number flux of the cosmic-ray protons from the SNR should depend on the distance to the target clouds, whereas the difference among the observed TeV γ-ray flux is not so significant. Therefore, the observed γ-ray flux from HESS J1745–303 does not support that the cosmic-ray protons that originate from the SNR shell.
Alternatively, we suggest that a more spatially distributed origin of cosmic-ray protons over the whole γ-ray source could be working to explain the origin of HESS J1745–303. It is suggested that particle acceleration throughout the inter-cloud medium is responsible for the cosmic rays in the CMZ (e.g., Melia & Fatuzzo 2011). The dense gas clumps are moving at a high velocity dispersion of 15 km s\(^{-1}\), typical to the CMZ and in the other GC molecular clouds (e.g., Morris & Serabyn 1996; Fukui et al. 2006). The present work showed that the beam-filling factor of the \(^{12}\)CO and dense H\(_{2}\) emitting clumps is 0.1–0.3, indicating that there exits low-density inter-clump space. The average density of the \(^{12}\)CO and H\(_{2}\) clumps is on the order of 100 cm\(^{-3}\), not much different from each other within a factor of a few (see section 3), and that of the inter-clump medium is likely to be less than 10 cm\(^{-3}\). We argue that the second-order Fermi acceleration is taking place in the low-density inter-clump space, which is common between the \(^{12}\)CO and H\(_{2}\) clumps, and that the accelerated cosmic-ray protons interact with the clumps to produce hadronic γ-rays via neutral pion decay. The γ-rays may therefore have a similar spectral index over the entire sources, as suggested by Aharonian et al. (2006a), since both the \(^{12}\)CO and dense H\(_{2}\) gas share similar inter-clump properties. We note that the energy density of the large turbulent motion in the GC is about 100-times higher than in the solar vicinity, and is a reasonable source for particle acceleration. We note that the three major peaks of TeV γ-rays in the CMZ coincide with the molecular peaks with enhanced velocity dispersion (see figure 1), as is consistent with second-order Fermi acceleration. Amano et al. (2011) studied second-order Fermi acceleration in the CMZ based on acceleration/energy-loss time scales, and showed that the second-order Fermi acceleration is able to accelerate protons up to ~100TeV range at density of less than 10 cm\(^{-3}\). It is important to pursue this possibility further in order to better understand the γ-rays in the GC by exploring more the role of the second-order Fermi acceleration in the central few 100 pc.

5. Summary

We have used the new \(^{12}\)CO \(J = 2\rightarrow 1\) data and the SGPS H\(_{2}\) data to search for counterparts of the extended TeV γ-ray source HESS J1745–303 in the GC. We suggest that the hadronic scenario is more favorable than the leptonic scenario because the fairly large magnetic field of more than 50 μG is unfavorable to cosmic-ray electrons to produce γ-rays. The molecular cloud MG358.9–0.5 shows a reasonable positional agreement with the northern part of HESS J1745–303, as already noted by Aharonian et al. (2008). For the southern part of TeV γ-rays, we see no \(^{12}\)CO counterpart, whereas the H\(_{2}\) gas with kinematics similar to the molecular cloud is a possible counterpart. We confirmed that the H\(_{2}\) gas is not local features, but in the GC, perhaps near to the CMZ, as supported by their continuity to the CMZ both in space and velocity. We considered possible origins of the cosmic-ray protons, and found that the SNR G359.1–0.5 is not likely to be the source of cosmic-ray protons in the hadronic scenario because the estimated total energy of cosmic-ray protons required to produce the observed TeV γ-ray flux is more than what can be supplied by the SNR. We argue that a spatially extended injection of cosmic-ray protons is more plausible, and suggest that the second-order Fermi acceleration offers another possible mechanism to accelerate cosmic-ray protons. The turbulent motion with a velocity span of 30–100 km s\(^{-1}\), commonly seen in the CMZ including MG358.9–0.5, can offer a sufficiently large energy supply in this picture.

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