X-RAY EMISSION FROM HESS J1731–347/SNR G353.6–0.7 AND CENTRAL COMPACT SOURCE XMMS J173203–344518

W. W. Tian1,2, Z. Li3, D. A. Leahy2, J. Yang4, X. J. Yang5, R. Yamazaki6, and D. Li4

1 National Astronomical Observatories, CAS, Beijing 100012, China; tww@bao.ac.cn
2 Department of Physics & Astronomy, University of Calgary, Calgary, Alberta T2N 1N4, Canada; wtian@ucalgary.ca
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; zyl@head.cfa.harvard.edu
4 Purple Mountain Observatory, CAS, Nanjing 210008, China
5 Department of Physics, University of XiAnTian, XianTian, Hunan, China
6 Department of Physical Science, Hiroshima University, Higashi-Hiroshima 739-8526, Japan

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ABSTRACT

We present new results of the HESS J1731–347/SNR G353.6–0.7 system from XMM-Newton and Suzaku X-ray observations and Delinha CO observations. We discover extended hard X-rays coincident with the bright, extended TeV source HESS J1731–347 and the shell of the radio supernova remnant (SNR). We find that spatially resolved X-ray spectra can generally be characterized by an absorbed power-law model, with a photon index of ∼2, typical of non-thermal emission. A bright X-ray compact source, XMMS J173203–344518, is also detected near the center of the SNR. We find no evidence of a radio counterpart or an extended X-ray morphology for this source, making it unlikely to be a pulsar wind nebular (PWN). The spectrum of the source can be well fitted by an absorbed blackbody with a temperature of ∼0.5 keV plus a power-law tail with a photon index of ∼5, reminiscent of the X-ray emission of a magnetar. CO observations toward the inner part of the High Energy Stereoscopic System (HESS) source reveal a bright cloud component at ∼20 ± 4 km s⁻¹, which is likely located at the same distance of ∼3.2 kpc as the SNR. Based on the probable association between the X-ray and γ-ray emissions and likely association between the CO cloud and the SNR, we argue that the extended TeV emission originates from the interaction between the SNR shock and the adjacent CO clouds rather than from a PWN.

Key words: ISM: molecules – ISM: supernova remnants – pulsars: general – radio lines: stars – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

The concept that astrophysical shock waves are efficient accelerators of cosmic rays have widely been accepted for a long time (Blandford & Eichler 1987; Malkov & Drury 2001). Due to the supernova energetics and rates, it seems reasonable that most of the Galactic cosmic rays up to 10¹⁵ eV originate from supernova remnant (SNR) shocks accelerating particles (protons and electrons) in the interstellar medium (ISM) and circumstellar medium (CSM). An efficiency of order 10% of the mechanical energy in the shocks must go into accelerating protons and nuclei to explain the observed intensity of cosmic rays. However, the relative efficiency of acceleration of protons versus electrons as well as the maximum energies obtained are not well understood, but are all fundamental to the study of cosmic rays and their effects on the ISM.

Recently, γ-ray observations of SNRs, e.g., SN1006, RX J1713.7–3946, and Vela Junior (RX J0852.0–4622 etc.) have revealed that SNR shocks are able to accelerate particles to TeV energies (Enomo et al. 2002; Aharonian et al. 2006). The high energy particles responsible for emitting TeV photons can be either hadrons or leptons, which are produced in astrophysical accelerators, as in SNRs. Two primary TeV photon emission processes are the decay of neutral pions produced by interactions of hadronic particles (mostly protons) with ambient matter and the inverse-Compton scattering of electrons on ambient photons (mostly the microwave background radiation in the typical ISM). The particles, which undergo such energy losses, do not escape the acceleration and emission sites due to the presence of magnetic fields. However, the TeV photons escape directly, allowing us to explore the sites of these processes.

The High Energy Stereoscopic System (HESS), with its excellent sensitivity and spatial resolution in the standard of γ-ray astronomy, greatly stimulates studies of very high energy astrophysics in recent years. A multi-wavelength approach has proven to be robust in shedding light on the nature of TeV sources. Among well-identified radio/X-ray counterparts of about 30 Galactic TeV sources, young shell-type SNRs and pulsar wind nebulae are thought to be two major γ-ray generators (Bamba et al. 2003; Katagiri et al. 2005; Aharonian et al. 2006; Uchiyama et al. 2007; Chang et al. 2008; Camilo et al. 2009). Other candidates have also been proposed as counterparts of some unidentified TeV sources, e.g., old SNRs (Yamazaki et al. 2006; Fang & Zhang 2008), hypernova and γ-ray burst remnants (Ioka & Meszaros 2009), giant molecular clouds (GMCs; Butt et al. 2008; Bamba et al. 2009), and young stellar clusters (Aharonian et al. 2007). Recently, the extended TeV source HESS J1731–347 is found to almost entirely overlap an old radio/X-ray SNR candidate G353.6–0.7 (Aharonian et al. 2008; Tian et al. 2008, hereafter T08). The association between HESS J1731–347 and G353.6–0.7, as suggested by T08, makes this system a favorable laboratory for studying the generation of γ-rays in evolved SNRs. T08 considered the case of hadronic particle acceleration in an SNR shock encountering a dense molecular cloud, based on the theoretical model of Yamazaki et al. (2006), but conclusion remained to be drawn due to limitation of the data explored in their paper, i.e., low counting statistics of the ROSAT observation and the lack of high-resolution 12CO maps. In this paper, we report new results obtained from XMM-
Newton and Suzaku X-ray observations and CO spectral-line data from Delinha 13.7 m radio telescope, and examine the theoretical model.

2. X-RAY AND RADIO OBSERVATIONS

2.1. XMM-Newton and Suzaku Data

HESS J1731–347 was observed by XMM-Newton on 2007 March 21 (ObsID 0405680201; PI: G. Puehlhofer), with a 25 ks exposure. We reduced the data obtained from the European Photon Imaging Camera (EPIC), using the XMM-Newton Science Analysis System (SAS), version 8.0. We selected EPIC-MOS and EPIC-pn events with patterns 0–12 and 0–4, respectively. An examination of the light curve indicated that the observation was contaminated by background flares. Cleaning of the high particle background results in an effective exposure of 15.9, 11.8, and 6.2 ks for the MOS1, MOS2, and pn detectors, respectively. Moreover, the observation was also contaminated by stray light, presumably from a bright source, 1RXS J173157.7–335007 (Voges et al. 1999), located at ~50′ off-axis to the north and outside the field of view (FoV). Consequently, a substantial portion of the upper (northern) FoV of the MOS1 and pn detectors was contaminated (contamination in the MOS2 FoV is apparently minimal) and thus masked out from subsequent analysis. We produced counts and exposure maps for the three detectors, in the 0.8–1.5, 1.5–2.2, and 2.2–7 keV bands. The low energy cutoff is justified by the relatively high foreground absorption near the Galactic plane. We then merged the counts and exposure maps, accounting for the difference in the effective area among the three detectors. We also produced corresponding background maps, using the Filter Wheel Closed data that characterizes the quiescent particle background.

HESS J1731–347 was observed by Suzaku on 2007 February 23 (ObsID 401099010; PI: G. Puehlhofer), with both X-ray Imaging Spectrometers (XIS; Koyama et al. 2007) and hard X-ray detector (Takahashi et al. 2007). The net exposure time is about 33 ks. In this work, we focus on the XIS Front-Illuminated (FI) CCDs that have very high efficiency and low background especially around 5 keV. Since the XIS2 has been inoperable since 2002 November, only data from XIS0 are used here. We used cleaned version 2.0 data (reduction by HEADAS software version 6.5). The Suzaku FoV is 18′ × 18 arcmin², centered at a bright compact source [17h32m10s, –34°46′]. The Suzaku spectra were extracted from a circular-source region with off-source annulus background region in the same observation so that possible contamination by SNR emission is reduced to minimum. In order to increase the statistics, the spectra from XIS0 and XIS3 were jointly fitted for subsequent analysis.

2.2. CO Data

We observe the G353.6–0.7/HESS J1731–347 system by employing the 13.7 m Delinha millimeter telescope at the Purple Mountain Observatory in 2008 March. The telescope has an angular resolution of 55″ at the observing frequencies. Simultaneously, the three $J = 1$–0 CO isotopic lines (i.e., $^{12}$CO, $^{13}$CO, and $^{18}$CO) were observed by using a cryogenic superconducting SIS receiver and a multi-line back-end spectroscopic system (Zuo et al. 2004), but only the $^{12}$CO was bright enough for significant detection. The system provides a velocity coverage from $V_{LSR} = -150$ to 60 km s⁻¹ and velocity resolution of 0.37 km s⁻¹ in $^{12}$CO. Three target spots (see Figure 1(b)), each with a size of 5′ × 5′, were selected over the G353.6–0.7 area, which includes the center position at the TeV γ-ray peak (S1: [R.A. = 17:32:00, decl. = –34:42:00]), and the ROSAT X-ray peak sites (S2: [173220, –345400], S3: [173250, –344600]), respectively. These regions were mapped with a grid size of 1′ × 1′. Each point was integrated up to 6 minutes, resulting an average rms noise level in the spectra to be 0.2–0.3 K. Spectral-line data were processed by the CLASS package of GILDAS software developed by IRAM.

Figure 1. Smoothed XMM-Newton 0.8–7 keV intensity (gray scale) images overlaid with contours of the VLA radio continuum emission (a) and HESS γ-ray emission (b). The gray scale is logarithmically coded between $(0.5–250) \times 10^{-4}$ counts s⁻¹ arcmin⁻². (a) The region enclosed by the two dotted circles outlines the ring-like feature, while the small ellipse/circle outlines the bright knots (K1, K2, and K3) and the compact source (CS). (b) The circles show the regions where the CO spectra are extracted from.
3. RESULTS

3.1. X-ray Emission

3.1.1. X-ray Morphology

Figure 1 shows the overall X-ray morphology revealed by XMM-Newton, along with the radio continuum emission of G353.6–0.7 (Figure 1(a)) and the γ-ray emission of HESS J1731–347 (Figure 1(b)). The radio SNR has a shell-like morphology and an extent of ∼30' in diameter, largely overlapping the extended HESS source. On the eastern half of the SNR, X-ray emission coincident with the radio emission was detected in an early ROSAT observation (T08). This is confirmed by the present XMM-Newton observation, although the lower (southern) part of the radio shell falls outside the XMM-Newton FoV. It is also evident that X-ray emission is present along the western half of the radio shell, which was not detected in the ROSAT observation albeit its larger FoV. This can be understood, as the emission is detected only in the 2.2–7 keV band that is almost entirely beyond the ROSAT energy coverage.

A number of X-ray substructures are revealed under the moderate spatial resolution of XMM-Newton. In particular, a prominent filament is present within the shell, passing through the brightest (inner) part of the HESS source (Figure 1(b)) and partially coincident with radio continuum emission (Figure 1(a)). With comparable widths of ∼2', the filament and the eastern X-ray shell together define a ring-like feature (enclosed by the two dotted circles in Figure 1(a); hereafter referred to as the ring), along which there are several bright knots (highlighted by the small ellipses in Figure 1(a)). Several plumes are present northwest of the ring, where the radio shell apparently breaks. From their projected positions, it is not clear whether the plumes are the natural extent of the shell or the filament. Furthermore, there is a bright compact source centered at (R.A., decl.) = (17h32m03s, −34°45′18″), showing no counterpart on the radio image. This source is named XMMS J173203–344518 hereafter.

The ring is not necessarily a coherent feature. Nevertheless, subsequent analysis is focused on the X-ray emission along the ring, as it occupies the central portion of the XMM-Newton FoV that is not subject to the stray light contamination. Figure 2 shows the azimuthal distribution of the X-ray emission along the ring. Individual peaks, e.g., at position angles of ∼120°, 190°, and 230°, arise from the bright knots (hereafter referred to as K1, K2, and K3). The ring appears harder on its western half (i.e., the filament, in an angular range of 0°–180°) than on its eastern half (i.e., the shell).

3.1.2. X-ray Spectra

We will focus on the XMM-Newton data because the Suzaku XIS has a smaller FoV and a lower spatial resolution (∼1.8 arcmin) than that of the XMM-Newton. We extract spectra, based on the MOS1, MOS2, and pn data, from various regions along the ring, including the three knots, the eastern half of the ring (K2 and K3 excluded), and the western half of the ring (i.e., the filament, K1 excluded). As the SNR fills almost the entire FoV, an ideal selection of local background is not possible. We choose to adopt a background spectrum from a 2.5' radius concentric circle within the ring, where the intensity appears to be among the lowest values across the FoV. Given the high intensities along the ring, our background adoption is not expected to introduce significant bias to the spectral fit. An absorbed power-law model is found to be an acceptable characterization for almost all the spectra, resulting in absorption column densities of ∼10^{22} cm^{-2} and photon index of ∼2, typical of non-thermal emission. The only exception is the spectrum of the eastern ring (i.e., the shell), for which the power-law model, with a steeper photon index of ∼2.7, is not a satisfactory fit. Fitting the ER spectra with a thermal or thermal+PL model does not lead to a better fit, hence we present the PL model fit for consistency with other spectra. The MOS2 spectrum of the plumes northwest to the ring (Figure 1(a); the MOS1 and pn data at this region are contaminated by stray light) can also be fitted by a power law with the index of about 2.2, but subject to large uncertainty due to the limited counts. The fit results are summarized in Table 1. Selected spectra and the best-fit models are shown in Figure 3. All the spectra are binned to achieve a signal-to-noise ratio greater than 4 (and a minimum of 30 counts per bin), ranging from about 50 to 350 bins.

We also extract spectra for XMMS J173203–344518 from both the XMM-Newton and Suzaku XIS data. The simple pure absorbed power-law model gives a steep photon index, i.e., ∼5.1 for the XMM-Newton spectra and ∼4.7 for the Suzaku spectra. However, the compact source spectra from both the XMM-Newton and Suzaku are better fitted by a combined model (i.e., blackbody plus power law or two blackbodies). When the XMM-Newton and Suzaku data were fitted independently, the temperatures were found to be consistent with being equal (∼0.5 keV). To better constrain spectral parameters we jointly fit the XMM-Newton and Suzaku spectra. For this joint fit, the column density and temperature were set equal for the XMM-Newton and Suzaku spectra (the power-law photon index is tied for both spectra also); all other parameters were independent. Both the blackbody plus power-law fit ($\chi^2$/d.o.f. = 252/260) and the two blackbodies fit ($\chi^2$/d.o.f. = 249/260) are good fits. We show the spectra and the blackbody plus powler-law best-fit model in the bottom panels of Figure 3. The fit parameters...
Figure 3. Spectra (black: EPIC-pn or Suzaku XIS (right panel of the bottom row); red: EPIC-MOS1; green: EPIC-MOS2) extracted from the western ring (left panel of the first row), the eastern ring (right panel of the first row), the compact source (bottom row), and the best-fit models (see the text). The XMM-Newton spectra are binned to achieve a signal-to-noise ratio greater than 4 and a minimum of 30 counts per bin, while the Suzaku spectrum is binned with a minimum of 100 counts. (A color version of this figure is available in the online journal.)

Table 1

| Parameter            | K1    | K2    | K3    | ER    | WR    |
|----------------------|-------|-------|-------|-------|-------|
| $\chi^2$/d.o.f.      | 29/22 | 147/109 | 79/77 | 88/54 | 155/165 |
| $N_H$ (10$^{22}$ cm$^{-2}$) | $1.44^{+0.55}_{-0.26}$ | $1.21^{+0.15}_{-0.12}$ | $0.86^{+0.11}_{-0.11}$ | $1.06^{+0.19}_{-0.17}$ | $1.85^{+0.20}_{-0.16}$ |
| Photon index         | $1.98^{+0.44}_{-0.22}$ | $2.15^{+0.14}_{-0.13}$ | $2.25^{+0.15}_{-0.15}$ | $2.72^{+0.29}_{-0.26}$ | $2.39^{+0.16}_{-0.13}$ |
| Norm (PL; 10$^{-4}$) | $1.1^{+0.9}_{-0.3}$ | $5.3^{+1.1}_{-0.8}$ | $4.3^{+0.9}_{-0.7}$ | $12^{+3}_{-5}$ | $25^{+4}_{-6}$ |
| Flux$_{2-10}$ keV (10$^{-13}$ erg s$^{-1}$ cm$^{-2}$) | 2.8 | 11.0 | 7.8 | 11.5 | 36.3 |

Notes. Regions of spectral interest: K1, K2, and K3: three bright knots; ER: the eastern half of the ring excluding K2 and K3; WR: the western half of the ring excluding K1; see details in the text. Quoted uncertainties are at 90% confidence level. An absorbed power-law model is used to fit all spectra.

are given in Table 2. The compact source shows intrinsic flux in the Suzaku observation a little higher than in the XMM-Newton observation. We discuss the nature of this source in Section 4.

3.2. CO Spectra

The three CO spectra (S1: J173200–344200; S2: J173220–345400; S3: J173250–344600) all show several bright cloud components (Figure 4). Given a near kinematic distance of $\sim3.2$ kpc for G353.6–0.7, as inferred from the highest H$_1$ absorption feature at a velocity of $\sim-20 \pm 4$ km s$^{-1}$ (T08), these CO spectra reveal increasing H$_2$ column density ($\sim2$, 3, and $6 \times 10^{19}$ cm$^{-2}$ for S2, S3, and S1, respectively; see discussion section) toward the Galactic plane. A bright cloud component at $-20 \pm 4$ km s$^{-1}$ appears in the direction of S1 (i.e., near the intensity peak of the HESS source). This cloud is likely
Figure 4. CO spectra from the TeV source peak (S1: the left panel of the first row) and the X-ray peak sites (S3: right of the first row; S2: the bottom row).

Table 2

| Parameter | BBa | PLb | BB+PLa | BB+PLb | BB+BBa | BB+BBb |
|-----------|-----|-----|--------|--------|---------|--------|
| $\chi^2$/d.o.f. | 120/78 | 118/78 | 76/78 | 82/78 | 252/260 | 249/260 |
| $N_0$ (10$^2$ cm$^{-2}$) | 1.36 ± 0.06 | 3.20 ± 0.09 | 2.56 ± 0.24 | 1.53 ± 0.08 | 2.80$^{+0.26}_{-0.26}$ | 1.96$^{+0.27}_{-0.22}$ |
| Photon index | 4.69 ± 0.08 | 4.40 ± 0.32 | 4.84$^{+0.48}_{-0.48}$ | 2.41$^{+1.41}_{-0.93}$$^{+2.38}_{-0.96}$ |
| Norm (PL;10$^{-2}$) | 5.27 ± 0.56 | 1.91 ± 0.91 | c2.41$^{+1.41}_{-0.93}$$^{+2.38}_{-0.96}$ |
| Temp$_1$ (keV) | 0.52 ± 0.01 | 0.48 ± 0.03 | 0.47 ± 0.02 | 0.50$^{+0.02}_{-0.02}$ | c3.6$^{+2.3}_{-2.2}$$^{+4.8}_{-2.8}$ |
| Norm$_1$ (BB) | 9.51 ± 0.87 | 9.21 ± 3.35 | 14.92 ± 2.51 | c6.0$^{+2.0}_{-1.6}$$^{+2.9}_{-2.3}$ | 0.57$^{+0.06}_{-0.03}$ |
| Temp$_2$ (keV) | 2.37±0.49 | 1.37 ± 1.66 | 168$^{+184}_{-184}$f | 76$^{+87}_{-87}$f |
| Flux | 62 | 313 | 168 | 71 |

Notes. The fitting models: BB, blackbody; PL, power law. The spectral extraction area has a radius of ∼3 arcmin in Suzaku image larger than that (40 arcsec) in XMM-Newton image; quoted uncertainties are at 90% confidence level.

a Spectra obtained from the Suzaku.
b Spectra obtained from the joint XMM-Newton and Suzaku.
c Fitting parameters to the XMM-Newton.
d Fitting parameters to the Suzaku.
e 1–10 keV (10$^{-13}$ erg s$^{-1}$ cm$^{-2}$) intrinsic flux from the XMM-Newton.
f 1–10 keV (10$^{-13}$ erg s$^{-1}$ cm$^{-2}$) intrinsic flux from the Suzaku.

4. DISCUSSION AND CONCLUSION

4.1. Nature of XMMS J173203–344518

A number of Galactic TeV objects are suggested to be PWNe (Kargaltsev & Pavlov 2008; Gaensler & Slane 2006). In view of the proximity between XMMS J173203–344518 and the in front of the SNR and extends to the nearby bright H II region G353.42–0.37 to produce the deep H I absorption feature at −20 ± 4 km s$^{-1}$ seen in the H I absorption spectrum from G353.42–0.37. Therefore, it is plausible that the extended CO cloud is associated with the remnant and locates at the same distance of ∼3.2 kpc as the H II region.
projected centers of HESS J1731–347 and SNR G353.6–0.7, it is worth considering a PWN origin for the γ-ray emission. In Section 3, we described that the spectra of XMMS J173203–344518 can be approximated by a power-law model with a photon index of 4 and 5, which is much steeper than the typical values of PWNe (∼1.5–2.1; Li et al. 2008). Neither is this index reminiscent of background active galactic nuclei or Galactic X-ray binaries, whose spectra, when fitted with a power-law model, show typical photon index of ∼1.5–2. In addition, XMMS J173203–344518 has no radio counterpart and no extended morphology. The above facts strongly argue against a possible PWN origin for the HESS source.

The source’s spectra show a harder X-ray tail in the Suzaku observation than in the XMM-Newton observation (Figure 3), so the source is a little brighter in the Suzaku image than in the XMM-Newton. We have excluded the possible contamination by the SNR emission, so the flux variability seems to be real (the Suzaku observation is 26 days later than the XMM-Newton’s). This X-ray variability is possibly consistent with that of a cataclysmic variable (CV; e.g., Pretorius & Knigge 2007). We have examined the intra-observation (tens of ks in duration) light curves of the source but found no evidence for a flux variation, although we note that CVs do show X-ray variability on longer timescales. XMMS J173203–344518 does not appear in the CV’s catalog.

On the other hand, it is not implausible that XMMS J173203–344518 is the central compact object (CCO) associated with SNR G353.6–0.7. Typically found in young SNRs, CCOs are characterized by blackbody-like soft X-ray emission with temperatures of 0.2–0.5 keV (Pavlov et al. 2004). It is suggested that CCOs are neutron stars born in supernova explosions with properties different from those of classical rotation-powered pulsars (Gotthelf et al. 2005; Li 2007). XMMS J173203–344518 shows a blackbody temperature (∼0.5 keV) higher than most CCOs. We think that it is possibly a magnetar (i.e., anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs)), because magnetars have soft spectra, a typical blackbody temperature of ∼0.5 keV and a typical luminosity of 10^{34}–10^{36} erg s^{−1} (Mereghetti 2008; also see a magnetar catalog\(^{10}\)). Given a distance of ∼3.2 kpc, if XMMS J173203–344518 is associated with the SNR, it will have a 1–10 keV luminosity of ∼10^{34} erg s^{−1}. This perhaps means it is like AXPs more than SGRs, because SGRs usually have luminosities higher than AXPs, and this source so far shows no repeated soft γ-ray emission. We examine the XMM-Newton and Suzaku light curves of XMMS J173203–344518 and find no evidence for pulsations at frequencies between 0.05 and 1 Hz, a range typical of magnetars. Although magnetars often show a hard X-ray (tens of keV) tail that can be fitted by a shallow power-law model, no counterpart of XMMS J173203–344518 is found in the INTEGRAL/ISGRI map (in the energy range of 20–40 keV) and INTEGRAL/JEMX map (3–15 keV). In addition, we notice that there is a little higher column density in the direction of XMMS J173203–344518 than from other regions of SNR G353.6–0.7 (see Table 1). This may be caused by a local dense cloud. Future X-ray observations are needed to test the magnetar scenario for XMMS J173203–344518.

4.2. X-ray and γ-ray Emission Mechanisms

Based on a statistics of five young SNRs, Bamba et al. (2005) suggested the typical photon index of ∼2.1–3.7 for non-thermal SNRs. It is interesting that the hard X-ray emission of the ring in the HESS J1731–347/SNR G353.6–0.7 has a similar photon index of ∼2.2. But the SNR is old due to its extended (∼30 arcmin in diameter) and faint radio emission (T08) so it should have a different high-energy mechanism. Old SNRs have quite different characteristics for the expected broadband energy spectrum of accelerated electrons and protons than young SNRs (Yamazaki et al. 2006). As an SNR ages, the acceleration time increases, allowing higher maximum energy of accelerated particles. However, the losses also increase with time. The net result is that the electron spectrum is loss-limited when the SNR is older than ∼10^{3} yr, but the proton spectrum only becomes loss-limited when the SNR is older than ∼10^{5} yr. Therefore, in an old SNR, the γ- and X-ray emissions are expected to be dominated respectively by decay of neutral pions and by synchrotron radiation of secondary electrons from charged pion decay, respectively. These pions all result from collisions of primary protons and the ISM. One diagnostic is the ratio of TeV to X-ray synchrotron fluxes. If the protons are accelerated at the shock running into a GMC, for example, the ratio should then be ≤10, consistent with the value obtained for HESS J1834–087 (Tian et al. 2007). In contrast, if the cloud is only illuminated by the particles, the predicted ratio should then be greater than 100, due to the lack of magnetic field enhancement which would occur in the shock case (hence greatly enhancing the X-ray synchrotron emission).

Based on the best-fit models (Table 1), the 2–10 keV unabsorbed flux from the ring (including the three knots) is found to be ∼6.9 × 10^{−12} erg cm^{−2} s^{−1}. The γ-ray flux is \(F_{\gamma}(1–10 \text{ TeV}) \approx 1.7 \times 10^{−11}\) erg cm^{−2} s^{−1} in the 1–10 TeV band, so the ratio \(R = F_{\gamma}/F_{X} \approx 2.5\). A slightly lower value of \(R\) is expected if the X-ray emission from the heavily absorbed western shell is also considered.

For an old SNR (∼10^{4} yrs for SNR G353.6–0.7), a theoretical model shows that the flux in the 1–10 TeV band is a few times higher than that in 2–10 keV band if the TeV emission is from pion decays, the X-rays are from synchrotron emissions of secondary electron (in the case of a shocked GMC of Yamazaki et al. 2006). Synchrotron emissions from secondary electrons are about three orders of magnitude higher than that from primary electrons. Thermal X-ray emission is not considered in this model. However, there is little thermal emission originating from an old SNR.

The new Fermi Large Area Telescope survey released a strong γ-ray source table in the range of 100 MeV–100 GeV (Abdo et al. 2009). There is no strong GeV source within HESS J1731–347. For a case that TeV γ-ray and X-ray emissions originate from a shocked GMC, the GeV emission flux is about two orders of magnitude lower than that the TeV flux (Figure 5 of Yamazaki et al. 2006) which is much low comparing with other cases (Figures 2–6 of Yamazaki et al. 2006), consistent with the explanation above.

New CO observations support such an SNR scenario: an extended CO cloud at ∼20 km s^{−1} is associated with the SNR. From the spectrum of S1, we estimate an approximate H2 column density of ∼4 × 10^{21} cm^{−2} within the cloud, taking the X factor of ∼2.5 × 10^{20} cm^{−2} K^{−1} km^{−1}s (Solomon & Barrett 1991). Assuming the molecular cloud completely covers the SNR (at least over the extended HESS source region), then it has a mass of \(M_{H2} = N_{H2} \Omega d^{2}(2m_{H}/M_{\odot}) \approx 5 \times 10^{4} M_{\odot}\). This is a GMC. S1 is located at the peak area of the TeV source, and has a higher local H2 column density than S2 and S3. This is consistent with the model of a shocked GMC. The evidence of increasing column density from lower-latitude region to
higher-latitude region of the SNR revealed by the CO spectra gives a plausible reason on the X-rays distribution. The ROSAT X-ray image of SNR G353.6–0.7 in the soft band (0.1–2.4 keV) appears only within the lower-latitude half of the radio remnant where the $N_H$ is less than $10^{22}$ cm$^{-2}$ (e.g., S3 and S2) because absorption blocks soft X-rays but not hard X-rays from the upper half where the $N_H$ is larger than $10^{22}$ cm$^{-2}$. From the viewing angle of observers, this gives a physical image that the GMC covers the SNR, so the TeV emissions cover the X-ray and radio emission regions. The coincidence of the X-ray morphology with both the radio and TeV $\gamma$-ray morphologies suggests that they are physically associated.

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*Note Added in Proof.* Upon the submission of our manuscript, we became aware of the recent work by Acero et al. (2009) on the HESS J1731–347/SNR G353.6–0.7 system with independent approaches.

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