MOLECULAR GAS INTERACTING WITH THE TeV γ-RAY SNR G347.3$-$0.5

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Abstract

Supernova remnants (SNRs) are believed to be sites of cosmic-ray acceleration. In particular, the region where dense molecular clouds interact with the supernova remnant has been suggested to be an effective site of proton acceleration, which emits synchrotron-dominant X-rays and TeV γ-rays. Dense molecular gas toward the TeV γ/synchrotron X-ray supernova remnant may confirm the existence of cosmic-ray protons. We present new high-resolution millimeter-wave observations of molecular gas at one kiloparsec distance interacting with the TeV γ-ray SNR G347.3$-$0.5. The clouds are clearly associated with the non-thermal X-ray shell and one of the molecular clumps coincides with X-ray/gamma-ray peak, providing strong evidence for proton acceleration. We have estimated the total energy of accelerated protons to be about 10^{48} erg, which corresponds to an acceleration efficiency of about 0.001, posing an observational constraint on the proton acceleration.

1 Introduction

Supernova remnants (SNRs) are believed to be major candidates of sites of high energy cosmic-ray acceleration in our Galaxy for an energy range of $< 10^{15}$ eV. Interacting regions of interstellar molecular clouds with young supernova remnants can be a site of effective γ-ray emission due to pion decay, implying that such regions can be possible indicators of proton acceleration in supernova remnants (e.g., Aharonian et al. 1994).

G347.3$-$0.5 is one of the most important SNRs in the Galaxy in this view. G347.3$-$0.5 is known to be a non-thermal X-ray shell whose dominant synchrotron component is interpreted as the evidence of electron acceleration (Koyama et al. 1997). The TeV γ-ray emission, possibly of proton origin, was detected from the direction of the X-ray shell by Enomoto et al. (2002).

In this paper we present a detailed CO molecular survey toward the SNR G347.3$-$0.5 and discuss the association and interaction of the molecular clouds with the SNR. The new CO data lead us to reconsider the distance and provide information about the energetics of the SNR and the efficiency of proton acceleration. More comprehensive discussions about acceleration in G347.3$-$0.5 are given in Fukui et al. (2003).

2 Observations

The present CO data were taken as part of a CO survey of the galactic plane made with NANTEN 4-m radio telescope of Nagoya University located at Las Campanas Observatory in Chile. The telescope, equipped with the superconducting mixer receiver, has been used to observe about 1.1 million positions in CO emission in a galactic longitude range of 240 degrees (from l = 180° to 60°) for a galactic latitude coverage of 10–20 degrees at a 2–8 grid-spacing with a $2'.6$ beam (cf. Matsunaga et al. 2001).

We first examined the CO distribution toward G347.3$-$0.5 in the $4'$ data, and made more sensitive CO observations at a $2'$ grid covering the entire SNR. The final data were sensitive enough to detect a molecular column density greater than 8.3×10^{19} cm^{-2} if we assumed the conventional conversion relation from the CO intensity to the H_2 column density (Bertsch et al. 1993).

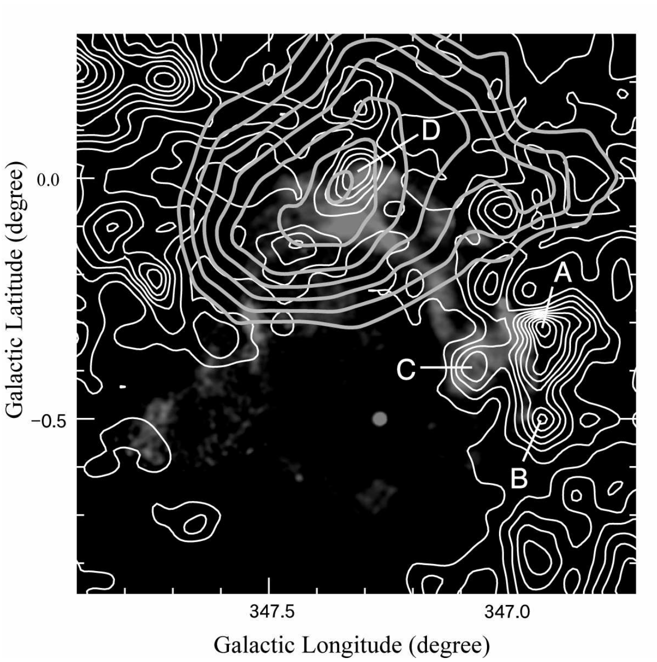

Figure 1: Overlay map of G347.3−0.5, in gray scale [*XMM-Newton* (Hiraga et al. 2004)], TeV γ-ray relative flux contours, and the intensity distribution of CO (J=1–0) in the thinner contours. The CO intensity is derived by integrating the CO spectra from -11 to -3 km s^{-1}, which is considered to be the velocity component interacting with the SNR. The lowest CO contour level and interval are 4 K km s^{-1}. The TeV contours were calculated from the distribution of the detection significance. The lowest contour level and interval of TeV γ-ray are 55% and 7%, respectively.

3 Results

Figure 1 shows the CO distribution at a velocity range from -11 to -3 km s^{-1}, corresponding to a distance of 0.5–1.6 kpc kinematically when a galactic rotation model (Brand & Blitz 1993) is adopted. The TeV γ-ray distribution superposed by gray contours exhibits a striking positional coincidence with CO (Enomoto et al. 2002), showing a peak just toward the CO peak D, among the four CO peaks designated as from A to D, seen adjacent toward one of the major X-ray peaks.

Figure 1 also shows the good associations of CO with the X-ray peaks resolved with *XMM-Newton* (Hiraga et al. 2004). These CO peaks are all located adjacent to the X-ray features, suggesting that the molecular gas is being impacted by blast waves and its surface becomes bright in X-ray emission.

The CO profile toward the peak C shows a velocity shift of more than 4–5 km s^{-1}. This velocity shift reaches at least 20 km s^{-1}. Such broad components in CO can be possible signature of the interaction between the SNR and the ambient molecular gas.

4 Discussion

4.1 Distance

The new identification of the molecular gas lead us reconsider of the physical properties of the SNR. First, the distance of the SNR is determined to 0.9 kpc if we adopt the mean velocity of the non-accelerated component as to be -6 km s^{-1}. The basic physical parameters are listed in Table 1. The age of $\sim$ 1000 years suggest that the SNR is then still in the free-expansion phase, not in the Sedov phase. This marks a sharp contrast with the previously favored distance of 6 kpc (e.g., Slane et al. 1999).

Second, the pion decay model becomes plausible as the origin of the TeV γ-ray emission in the case of d = 1 kpc. The TeV γ-ray distribution of the CANGAROO experiment (Tanimori et al. 2001) gives a striking positional coincidence with CO peak D. The γ-ray distribution indicates that it is not a point source but is extended by $\sim 0\overset{\circ}{.}2$. We suggest that this gives a possible evidence that the cosmic-ray protons generated in the SNR shell have interacted with the molecular gas toward peak D to produce the TeV γ-ray emission.

4.2 Acceleration efficiency

We can explain the multi-wavelength spectra by evoking pion decay due to the high-energy protons (as does Enomoto et al. 2002). The molecular mass contained toward CO peak D, whose extent is $\sim 0\overset{\circ}{.}2$ (= 3 pc), is calculated to be $\sim$ 200 solar masses. If we assume that only this CO clump is significantly irradiated by the cosmic ray protons, we can estimate the total energy of the accelerated protons to be $\sim 10^{48}$ erg by using the following relationship (Enomoto et al. 2002):

$$(E/10^{48})(M_{\rm cloud}/200)(l/3)^{-3}(d/l)^{-5} = 1.35$$

where E (erg) is the total energy of cosmic ray protons, $M_{\rm cloud}$ ($M_\odot$) the molecular cloud mass interacting with them, l (pc) the typical length of the cloud, and d (kpc) the distance, giving an estimate of the cosmic-ray generation rate via pion decay.

This energy suggests that the acceleration efficiency of the cosmic ray protons is $\sim$ 0.001 for the total energy release of a SNR, $\sim 10^{51}$ erg.

Table 1: Physical parameters of G347−0.5

Parameters	d = 1 kpc	d = 6 kpc
Radius[30′](pc)	8.7	52
Historical record	A.D. 393	$\cdots$
Age (yr)	1600	> 10,000
Evolutionary phase	Free-exp	Sedov
Ambient density (cm^{-3})	< 0.01	0.003
Shock velocity (km s^{-1})	5500	3200
Swept-up mass ($M_\odot$)	< 1	35
Total energy of the accelerated particles (erg)	$\sim 10^{48}$	$\sim 10^{50}$

The observed non-thermal X-ray spectrum requires extremely high shock velocity of > 5000 km s^{-1} within the standard framework of the radiation of ultra-relativistic electrons (Koyama et al. 1997, Uchiyama et al. 2003). This is also consistent with the present view that the SNR is still in the free-expansion phase. G347.3−0.5 is therefore considered as to be a young SNR exploded in a low-density cavity (~ 0.01 cm^{-3}), perhaps produced by the stellar wind or pre-existing supernovae, and its non-decelerated blast wave is colliding with the dense molecular gas at present.

5 Conclusion

The new CO observations with NANTEN have shown that the X-ray distribution of G347.3−0.5 shows a good spatial coincidence with the molecular gas at a distance of 1 kpc, implying the interaction between them. This is consistent with the TeV γ-ray distribution, which shows a peak just toward the CO peak, allowing us to estimate the acceleration efficiency of the cosmic-ray protons to be about 0.1% of total kinetic energy of SN, 10^{51} erg.

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References

Aharonian, F. A., Drury, L. O'C., Voelk, H. J. 1994, A&A, 285, 645

Bertsch, D. L., Dame, T. M., Fichtel, C. E., Hunter, S. D., Sreekumar, P., Stacy, J. G., Thaddeus, P. 1993, ApJ, 416, 587

Brand, J., Blitz, L. 1993, A&A, 275, 67

Enomoto, R., et al. 2002, Nature, 416, 823

Fukui, Y., Moriguchi, Y., Tamura, K., Yamamoto, Y., Tawara, Y., Mizuno, N., Onishi, T., Mizuno, A., Uchiyama, Y., Hiraga, J., Takahashi, T., Yamashita, K., Ikeuchi, R. 2003, PASJ, 55, L61

Hiraga, J., et al. 2004, submitted

Koyama, K., Kinugasa, K., Matsuzaki, K., Nishiuchi, M., Sugizaki, M., Torii, K., Yamauchi, S., Aschenbach, B. 1997, PASJ, 49, L7

Matsunaga, K., Mizuno, N., Moriguchi, Y., Onishi, T., Mizuno, A., Fukui, Y. 2001, PASJ, 53, 1003

Tanimori Y., et al. 2001, in Proc. 27th int. Cosmic Ray Conf. Vol.6, ed. M. Simon, E. Lorentz & M. Pahl, (Copernics e.V., Katlenverg-Lindau, Germany), 2465

Slane, P., Gaensler, B. M., Dame, T. M., Hughes, J. P., Plucinsky, P. P., Green, A. 1999, ApJ, 525, 357

Uchiyama, Y., Aharonian, F. A., Takahashi, T. 2003, A&A, 400, 567