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# Discovery of Interacting Molecular Gas toward the TeV Gamma-Ray Peak of the SNR G 347.3–0.5

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## Abstract

Supernova remnants (= SNR) are suggested to be sites of cosmic-ray acceleration. In particular, it has been an issue of keen interest whether cosmic ray protons are being accelerated in a SNR which emits TeV $\gamma$-rays. A crucial observational test for this is to find dense molecular gas towards the SNR, because such molecular gas can best verify the existence of cosmic-ray protons via pion decay to $\gamma$-rays. Here, we show that new high-resolution mm-wave observations of interstellar CO molecule have revealed molecular gas at 1 kpc distance interacting with the TeV $\gamma$-ray SNR G 347.3$-$0.5, and that a molecular cloud of $\sim$ 200 solar masses is clearly associated with the TeV $\gamma$-ray peak, providing strong evidence for proton acceleration. We have estimated the total energy of accelerated protons to be $\sim$ 1048 erg, which corresponds to an acceleration efficiency of $\sim$ 0.001, posing an observational constraint on the proton acceleration.

**Key words:** cosmic rays — ISM: cloud — molecules — supernova remnants

Interstellar molecular clouds are the densest interstellar media, and can be best studied in the mm-wave rotational transitions of the interstellar CO molecule because of its stable and ubiquitous nature. The present CO data at 2.6 mm wavelength were taken as part of a CO survey of the Galactic plane made with NANTEN, a 4-m mm and sub-mm telescope of Nagoya University located at Las Campanas Observatory in Chile. The telescope, equipped with the most sensitive superconducting mixer receiver, has been used to observe 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 2–4 grid-spacing with a 2.6 beam (cf. Matsunaga et al. 2001, and other papers in PASJ, Vol. 53, No. 6, 2001). This is the most extensive CO dataset obtained so far, particularly for the southern Milky Way, at an angular resolution of ten-times higher than the previous one (Dame et al. 2001).

We first examined the CO distribution toward G 347.3$-$0.5 in the $4'$ data, and found a hole of CO emission corresponding to the SNR. We then made new more sensitive CO observations at a $2'$ grid covering the entire SNR in 2003 April. The final data were sensitive enough to detect a molecular column density greater than $8.3 \times 10^{19}\,\mathrm{cm}^{-2}$ if we assumed the conventional conversion relation from the CO intensity to the $H_2$ column density (Bertsch et al. 1993).

The new CO data have revealed a remarkable association with the X-ray SNR in three respects: 1) the global coincidence of a CO hole at a degree scale with the X-ray SNR obtained by ASCA (Koyama et al. 1997; Slane et al. 1999) and ROSAT (Pfeffermann, Aschenbach 1996); 2) a detailed correspondence of the CO peaks on an arc-min scale with the X-ray data of XMM (= the X-ray Multi-mirror Mission) (J. Hiraga et al. in preparation), and 3) the existence of a velocity-shifted CO component apparently associated with one of the X-ray peaks.

Figure 1 shows the CO distribution at a velocity range from $-11$ to $-3\,\mathrm{km\,s^{-1}}$. This velocity corresponds to a distance of 0.5–1.6 kpc kinematically when a galactic rotation model (Brand, Blitz 1993) is adopted. The hole of the CO emission agrees well with the ASCA/ROSAT X-ray image, and the CO emission delineates the outer boundary of the SNR over the three quadrants, except for the southeast where the X-ray emission is weak.

Figure 2 shows a CO distribution that is the same as in figure 1. The TeV $\gamma$-ray distribution superposed by yellow contours exhibits a striking positional coincidence with CO (Tanimori et al. 2001), 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. The figure also demonstrates the good association of CO with the X-ray peaks resolved with XMM; such an association is in fact obvious in many of the other velocity channel maps of CO at $-11$–$0\,\mathrm{km\,s^{-1}}$. The four CO peaks are all located adjacent to (or towards) the X-ray features, suggesting that the dense molecular gas is being impacted by blast waves and its surface becomes bright in X-ray emission. Similar associations between CO and X-ray or optical filaments are seen in other SNRs (e.g., for the Vela SNR see Moriguchi et al. 2001).

Figure 3 shows a CO profile in which we recognized a shift in velocity by more than 4–5 $\mathrm{km\,s^{-1}}$ as well as the distribution of this velocity-shifted gas localized toward CO peak C. In the CO profile the velocity-shifted gas is shown in yellow, and the non-accelerated component at a velocity

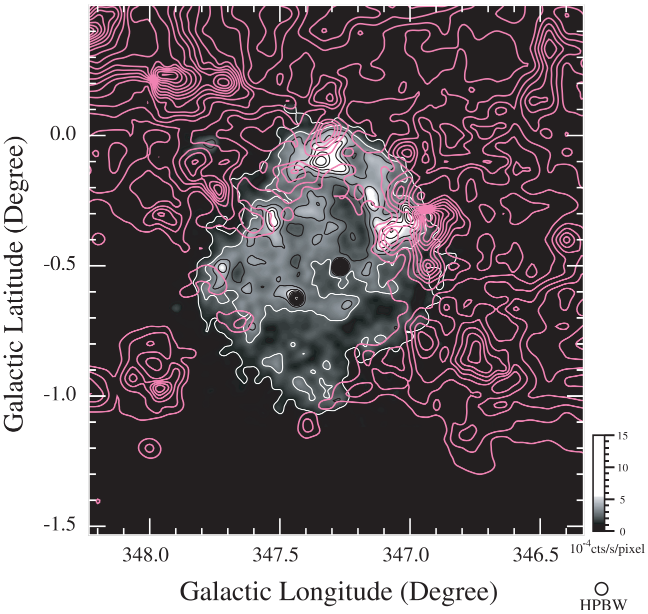


**Fig. 1.** Overlay map in Galactic coordinates showing a supernova remnant (SNR), G 347.3−0.5, in gray scale [ROSAT PSPC X-ray Survey (Slane et al. 1999); from ROSAT archive database] and the intensity distribution of CO ($J$ = 1–0) emission in purple contours. The intensity is derived by integrating the CO spectra from −11 to $-3\,\mathrm{km\,s^{-1}}$, which is considered to be a velocity component interacting with the SNR. The lowest contour level and interval of CO are $4\,\mathrm{K\,km\,s^{-1}}$.

greater than $-11\,\mathrm{km\,s^{-1}}$ in red. This velocity shift reaches at least $20\,\mathrm{km\,s^{-1}}$. Similar broad components in CO were found in other SNRs and taken to be an unmistakable signature of the interaction between the SNR and the ambient molecular gas (e.g., IC 443; White et al. 1987, W 28; Arikawa et al. 1999). The momentum of the accelerated gas, $\sim 1000\,M_\odot\,\mathrm{km\,s^{-1}}$, is in fact consistent with that of the blast waves estimated from the physical quantities given in table 1.

The consequence of the new identification of the molecular gas is profound. First, the distance to the SNR is determined to 0.9 kpc, if we adopt the mean velocity of the non-accelerated component as $-6\,\mathrm{km\,s^{-1}}$. This forces us to revise the basic physical parameters, as listed in table 1, where we adopt 1 kpc as the nominal distance. First of all, the age is small, on the order of 1000 years, making an assignment to one of the historical supernovae AD 393 (proposed by Wang et al. 1997) most plausible. The SNR is then still in the free-expansion phase, but not in the Sedov phase. This marks a sharp contrast with the previously favoured distance, 6 kpc, where an association with a CO cloud at $-90\,\mathrm{km\,s^{-1}}$ was claimed based on a coarse CO map at $30'$ resolution. The present CO data at these velocities confirm this cloud, but it lacks a detailed spatial correlation at the present resolution, making it unlikely to be associated with the SNR. It was also claimed that the unusually low nucleon column density toward $l = 347^\circ$ favours a large distance for the X-ray absorption (Slane et al. 1999). It is true that this direction corresponds to a hole of the interstellar matter created by a supershell, GS 347.3+0.0−21, at a distance of $\sim 3$ kpc (Matsunaga et al. 2001). Nonetheless, the NANTEN CO data and the Parkes H I data indicate that the local molecular and atomic gas at around $6\,\mathrm{km\,s^{-1}}$ has a column density large enough to explain the X-ray absorption (e.g., see figure 3b in Matsunaga et al. 2001, and Cleary et al. 1979 for H I). Second, the pion decay model becomes plausible as the origin of the TeV $\gamma$-ray emission in the case of $d = 1$ kpc. The TeV $\gamma$-ray distribution of the CANGAROO experiment (Tanimori et al. 2001) gives a striking positional coincidence with CO peak D, as already shown in figure 2. The $\gamma$-ray distribution indicates that it is not a point source but is extended by $\sim 0\overset{\circ}{.}2$, while the $\gamma$-ray sensitivity decreases significantly beyond $0\overset{\circ}{.}5$ of the intensity maximum. We conclude that this gives convincing evidence that the cosmic-ray protons generated in the SNR shell have interacted with the molecular gas towards peak D to produce the TeV $\gamma$-ray emission. The multi-wavelength spectra, especially the steep spectra at a few TeV range, can be explained only by the pion decay due to the high-energy protons accelerated in the blast waves (Enomoto et al. 2002), as is consistent with the present conclusion. This comparison also implies that the acceleration of the cosmic ray protons is taking place in a localized area of the hard X-ray peak in the SNR at $(l, b) \sim (347\overset{\circ}{.}3, 0\overset{\circ}{.}0)$, since we would otherwise expect more spatially extended $\gamma$-ray emission covering the present molecular distribution. The EGRET source 3EG J1714−3857 at $(l, b) \sim (348\overset{\circ}{.}0, -0\overset{\circ}{.}1)$ (Hartman et al. 1999), on the other hand, appears not in contact with the SNR if its association to the $-90\,\mathrm{km\,s^{-1}}$ cloud is correct. The molecular mass contained towards 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 $10^{48}$ erg by using the following relationship (Enomoto et al. 2002): $(E/10^{48})(M_\mathrm{cloud}/200)(l/3)^{-3}(d/l)^{-5} = 1.35$, where $E$ (erg) is the total energy of cosmic ray protons, $M_\mathrm{cloud}(M_\odot)$ 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 an SNR, $\sim 10^{51}$ erg, posing an observational constraint on the acceleration mechanism.

The observed hard X-ray spectrum is noted to be due to an non-thermal emission (Uchiyama et al. 2003), as first shown by Koyama et al. (1997) and that it requires an extremely high shock velocity of more than $5000\,\mathrm{km\,s^{-1}}$ within the standard framework of the radiation of ultra-relativistic electrons. This is again consistent with the present view that the SNR is still in the free-expansion phase. The higher shock velocity of G 347.3−0.5, caused by the lower ambient density and massive ejecta, results in the hard X-ray spectrum. G 347.3−0.5 is therefore considered to be a young SNR exploded in a low-density cavity ($\sim 0.01\,\mathrm{cm^{-3}}$), 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. This is in contrast to the case of SN 1006, another TeV-$\gamma$ SNR, where the spectrum can be explained in terms of the inverse-Compton scattering of the 2.7 K cosmic microwave background (Koyama et al. 1995). The lack of molecular gas in SN 1006 may have favoured the inverse-Compton process instead of the pion decay to produce $\gamma$-ray, providing a possible

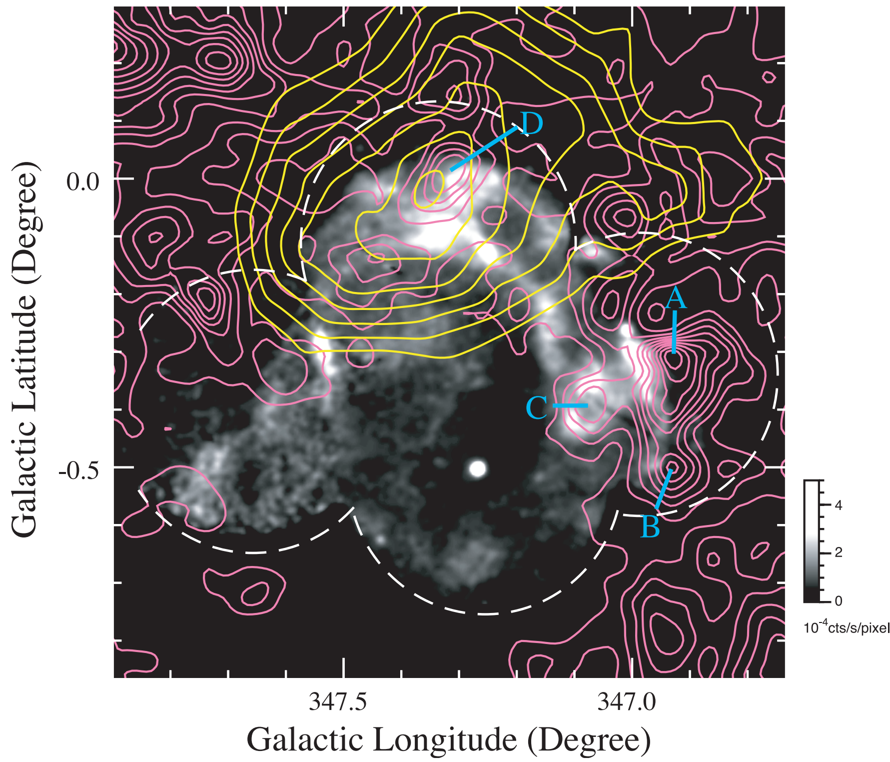


**Fig. 2.** Close-up view of G 347.3−0.5 with an XMM X-ray (Hiraga et al. in preparation) image, TeV $\gamma$-ray relative flux contours, and CO intensity. The CO contours are the same as in figure 1. The TeV contours were calculated from the distribution of the detection significance. The lowest contour level and interval of TeV $\gamma$-ray are 55% and 7%, respectively.

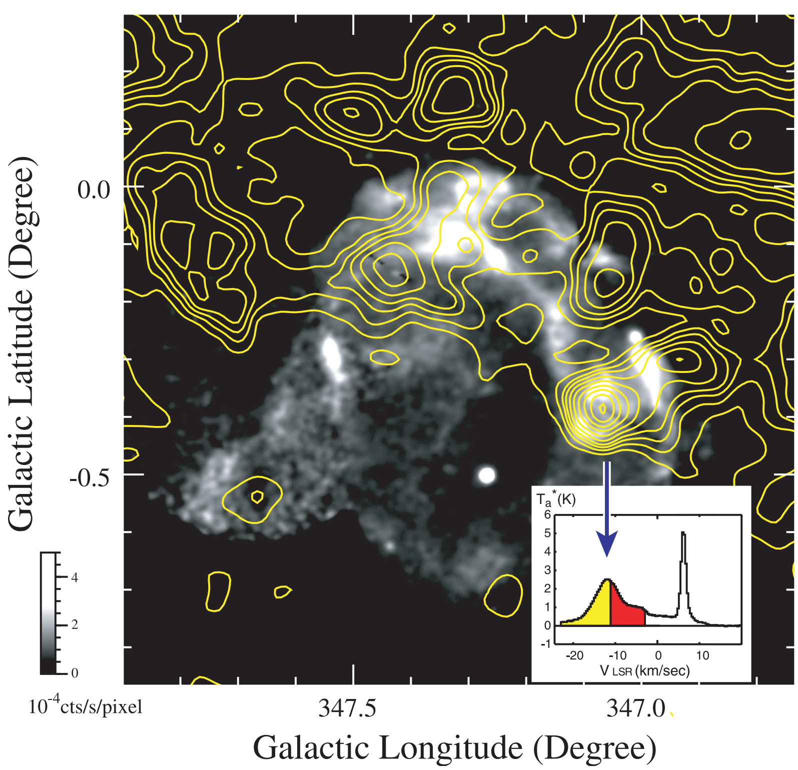


**Fig. 3.** Distribution of high-velocity, wing, component of molecular gas associated with the SNR in yellow contours overlaid with an XMM X-ray image. The CO intensity was derived by integrating the CO spectra from $-14$ to $-11\,\mathrm{km\,s^{-1}}$. The contour levels of CO are 2, 4, 6, 8, 11, 15, 20, 25, 30, and $35\,\mathrm{K\,km\,s^{-1}}$. The spectrum shown in this figure is an averaged spectrum where the high-velocity component is significant, i.e., around $l \sim 347.^{\circ}05$ and $b \sim -0.^{\circ}40$.

**Table 1.** Physical parameters of G 347−0.5.

| Parameters | $d = 1\,\mathrm{kpc}$ | $d = 6\,\mathrm{kpc}$ |
|---|---|---|
| Radius[30′](pc) | 8.7 | 52 |
| Histrical record | A.D. 393 | ··· |
| Age (yr) | 1600 | $> 10000$ |
| Evolutionary phase | Free-expansion | Sedov |
| Ambient density ($\mathrm{cm}^{-3}$) | $< 0.01$ | 0.003 |
| Shock velocity ($\mathrm{km\,s}^{-1}$) | 5500 | 3200 |
| Swept-up mass ($M_{\odot}$) | $< 1$ | 35 |
| Total energy of the accerelated particles (erg) | $\sim 10^{48}$ | $\sim 10^{50}$ |

Note. The historical record is from the proposal by Wang et al. (1997). We assumed 20000 years of age for the ambient density, shock velocity, shock temperature, swept-up mass, and E.I. in the case of $d = 6\,\mathrm{kpc}$.

explanation for the difference of the two SNRs.

To summarize, the new CO observations with NANTEN have shown that G 347.3−0.5 is strongly interacting with the molecular gas at a distance of 1 kpc, but not with a distant cloud as previously favoured. This is consistent with the TeV $\gamma$-ray distribution, which shows a peak just towards the CO peak, allowing us to estimate the acceleration efficiency of the cosmic-ray protons for the first time. The NANTEN CO dataset should be a very powerful tool in analysing various extremely high-energy $\gamma$-ray sources to be observed with the GLAST and the other instruments coming soon. Future higher-quality multi-wavelength data, including sub-mm, H I, X-ray, and $\gamma$-ray, are also highly desirable. Above all, higher energy X-ray imaging will be able to provide a synchrotron cut-off energy, giving crucial constraints on the cosmic-ray acceleration.

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