THE DISTANCE TO SUPERNOVA REMNANT CTB 109 DEDUCED FROM ITS ENVIRONMENT

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Abstract

We conducted a study of the environment around the supernova remnant (SNR) CTB 109. We found that the SNR is part of a large complex of H\textsc{ii} regions extending over an area of 400 pc along the Galactic plane at a distance of about 3 kpc at the closer edge of the Perseus spiral arm. At this distance, CTB 109 has a diameter of about 24 pc. We demonstrated that including spiral shocks in the distance estimation is an ultimate requirement to determine reliable distances to objects located in the Perseus arm. The most likely explanation for the high concentration of H\textsc{ii} regions and SNRs is that the star formation in this part of the Perseus arm is triggered by the spiral shock.

Subject headings: circumstellar matter — H\textsc{ii} regions — ISM: clouds — ISM: kinematics and dynamics — supernova remnants

1. INTRODUCTION

The supernova remnant (SNR) CTB 109 was discovered by Gregory & Fahlman (1980) in X-rays with the Einstein satellite. It is believed that the peculiar semicircular shape of the SNR results from its interaction with a giant molecular cloud (Tatamatsu et al. 1987) that inhibits its expansion to the west. It has an unusual double-shell structure in radio, with an inner half-shell surrounded by a wider outer shell; both shells have similar radio surface brightness at 1420 MHz (see Fig. 1). CTB 109 was classified as a shell-type SNR based on its radio properties (Downes 1983). The supernova explosion left a pulsar behind that is observable in X-rays (Fahlman & Gregory 1981), but no radio emission has been detected from the pulsar, and there is no evidence for a pulsar wind nebula.

Establishing the distance to a SNR is usually quite difficult, and CTB 109 seems to offer a particular challenge. The \(\Sigma-D\) relation was used by Sofue, Takahara, & Hirabayashi (1983) and Hughes et al. (1984) to derive distances of 4.1 and 5.6 kpc, respectively. The newest approach to \(\Sigma-D\) is that of Case & Bhattacharya (1998), who use only shell-type SNRs and get a distance of 4.7 kpc. However, the \(\Sigma-D\) technique, while the oldest, is probably the most disputed method of distance determination for SNRs. There are many statistical studies which show that there is no evidence for a working \(\Sigma-D\) relation (Green 1984; Berkhuijsen 1986; Berkhuijsen 1987).

The spectroscopic distance of H\textsc{ii} regions close to CTB 109 offers an alternative approach, and Tatamatsu et al. (1990) quote values of 3.6–5.4 kpc. However, these distances are based on very old measurements, and only two nearby H\textsc{ii} regions were used in this publication. Despite the results mentioned above, all previous authors have used a distance of 4 kpc for CTB 109.

The primary motivation for the present study is to determine a more reliable distance to this SNR. We use spectroscopic distances and radial velocities of 16 nearby H\textsc{ii} regions and compare these values with those obtained for CTB 109. We also include a comparison of absorption profiles of the radio-bright H\textsc{ii} regions with foreground H\textsc{i} column densities of CTB 109 calculated from X-ray absorption and discuss the cold environment of the SNR based on high-resolution H\textsc{i} and CO measurements from the Canadian Galactic Plane Survey (CGPS).

We have also obtained 408 and 1420 MHz radio continuum data including polarization at 1420 MHz. A joint spectral index and polarization analysis of these data in conjunction with 2.7, 4.85, and 10.55 GHz measurements from the Effelsberg 100 m radio telescope will be published elsewhere (R. Kothes, B. Uyaniker, A. Yar, & W. Reich 2002, in preparation).

2. OBSERVATIONS AND DATA ANALYSIS

The CGPS is described in detail by Taylor et al. (2002). To study the environment of the SNR CTB 109, we have used parts of the CGPS that derive from observations with the Synthesis Telescope of the Dominion Radio Astrophysical Observatory (DRAO; Landecker et al. 2000) and CO observations (Heyer et al. 1998) from the Five College Radio Astronomy Observatory (FCRAO). For the DRAO data, angular resolution varies as cosec (declination) and therefore changes slowly across the final maps. Parameters for all observations used can be found in Table 1. To ensure accurate representation of the largest scales for the DRAO data, we have incorporated single-antenna observations after suitable filtering in the Fourier domain. Single-antenna H\textsc{i} data were obtained from a survey of the CGPS region made with the DRAO 26 m telescope (Higgs & Tapping 2000). The single-antenna data for the 1420 MHz radio continuum were obtained from the Effelsberg 1420 MHz Survey of the Galactic Plane (Reich, Reich, & Fürst 1997).

3. THE DISTANCE TO CTB 109

In light of all the distance problems around CTB 109, we have embarked on a more thorough analysis and have tried to determine a more accurate distance to this SNR. Abandoning the \(\Sigma-D\) relation, the most commonly used method to determine the distance to a SNR is to deduce the radial
velocity of associated neutral hydrogen or molecular material. A Galactic rotation model is then used to assign to the radial velocity a distance from the Sun. The molecular material associated with CTB 109 has a radial velocity of about $-51$ km s$^{-1}$ (Tatematsu et al. 1990; see also § 4.1), implying a kinematic distance of 5 kpc (using a flat rotation model with $v_0 = 220$ km s$^{-1}$ and $R_0 = 8.5$ kpc). However, the validity of the flat rotation model has been challenged for the Perseus arm. Roberts (1972) pointed out that H$\text{ii}$ regions show a high discrepancy between their kinematic and spectroscopic distances. Furthermore, O-type stars in the Perseus arm region often show interstellar absorption lines, arising, of course, in material in front of them, with velocities more negative than the radial velocity of the star itself. According to the flat rotation model, this material should be behind those stars. Roberts (1972) successfully modeled these discrepancies with the two-armed spiral shock (TASS) model.

In Table 2, we list parameters of 16 Sharpless H$\text{ii}$ regions between Galactic longitudes $104^\circ$ and $114^\circ$ taken from Brand & Blitz (1993) and references therein, an extensive study of the velocity field of the outer Galaxy. In Figure 2, the radial velocity of these H$\text{ii}$ regions is plotted as a function of their spectroscopic distances. There are two groups of H$\text{ii}$ regions separated by their velocity and distance. The
first group comprises sources with distances well below 2 kpc and radial velocities between 0 and $-20 \text{ km s}^{-1}$. These sources are located in the Orion Spur, and their spectroscopic and kinematic distances agree quite well. There is a large gap that corresponds to the interarm region between the Orion Spur and the Perseus arm. The H II regions of the second group are all located in the Perseus arm, and most are much closer than predicted by the flat rotation curve. This result fits well with Roberts’ predictions (Roberts 1972, Fig. 4). According to Roberts' model, the radial velocity in the direction of CTB 109 would drop to about $-50$ to $-55 \text{ km s}^{-1}$ at the position of the spiral shock at a distance of about 2.5 kpc. It then rises slowly until it rejoins the flat rotation curve at about 3.5 kpc. The only H II regions with velocities between $-40$ and $-60 \text{ km s}^{-1}$ whose spectroscopic distances exceed 4 kpc are the Sh 147/8/9 complex and Sh 156 (and these two distances have the biggest errors). Independent distance estimates for these two H II regions obtained from infrared measurements by Wouterloot, Walmsley, & Henkel (1988) are about 3.5 kpc for both. The distance ambiguity for Perseus arm velocities is also indicated by the presence of many H II self-absorption features (HISA) found by Gibson et al. (2000). The HISA phenomenon requires warm neutral gas behind cold absorbing gas. The emission of the background hydrogen is then absorbed by colder foreground material at the same radial velocity. This can only occur when two distances correspond to the same radial velocity: a flat rotation curve does not permit this in the outer Galaxy (e.g., Fig. 2), but the Roberts TASS model does.

We have also produced absorption profiles for the radio-bright H II regions in our list. From these, we were able to calculate accurate foreground H I column densities, also listed in Table 2. These values are comparable to those obtained by Rho & Pete (1997) toward CTB 109 from X-ray absorption. They found absorbing H I column densities between 8 and $10 \times 10^{21} \text{ cm}^{-2}$. Patel et al. (2001) derived an absorbing H I column density of $N_{\text{HI}} = 9.3 \times 10^{21} \text{ cm}^{-2}$ for the central pulsar from Chandra observations. For the radio-bright southern spot, which is absorbed by foreground material in our data, we measure an absorbing H I column density of $8.4 \pm 0.8 \times 10^{21} \text{ cm}^{-2}$.

The absorption profiles obtained for the radio-bright southern spot of CTB 109, the two closest H II regions Sh 149 and Sh 152, and a nearby extragalactic source are plotted in Figure 3. All profiles are very similar for the local gas. The profiles of the three Galactic objects are also very similar for the Perseus arm gas, indicating that they are located at comparable distances. However, the extragalactic source has an additional component around $-45 \text{ km s}^{-1}$, which is completely missing in all of the Galactic sources (and so must arise beyond the Galactic sources). This is another indication of the existence of the TASS, because the radial velocity within the Perseus arm would be increasing with distance in the TASS model while it would be decreasing if the flat rotation curve applied. This evidence also favors the closer distance for Sh 149, since material with a radial velocity of around $-45 \text{ km s}^{-1}$, which is absorbed by the extragalactic source but not by Sh 149, should be located at around 4 kpc, according to Roberts (1972). We should note at this point that the deduction of the systemic velocity of the Galactic sources from their absorption spectra is not possible due to the peculiar behavior of the rotation curve in the Perseus arm.

CTB 109 contains a pulsar (discovered by Fahlman & Gregory 1981) and is evidently the product of the explosion of a massive star. Hence, it seems quite reasonable to associate it with the other massive stars in the vicinity, which are exciting the nearby H II regions. In light of all this new information, we propose that CTB 109 and the nearby H II regions are part of the same complex, which is located in the shock zone of the Perseus arm as described by Roberts (1972). This would imply a distance of $3.0 \pm 0.5$ kpc. The mean distance of all H II regions listed in Table 2, weighted by $1/\sigma^2$, is $3.1 \pm 0.2$ kpc, which supports the above-mentioned distance estimate. The linear size of the SNR

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**TABLE 2**

**PARAMETERS OF 16 NEARBY H II REGIONS TAKEN FROM BRAND & BLITZ (1993)**

| Name | Galactic Coordinates | Distance (kpc) | $v_{\text{LSR}}$ (km s$^{-1}$) | $N_{\text{HI}}$ ($10^{21} \text{ cm}^{-2}$) |
|------|---------------------|----------------|-----------------------------|-------------------------------------|
| Sh135 | 104.59$^a$1.37 | 1.4$ \pm $0.4 | $-20.7 \pm 0.5$ | ... |
| Sh137 | 105.15$^a$7.12 | 0.6$ \pm $0.2 | $-10.3 \pm 1.4$ | ... |
| Sh139 | 105.77$^a$0.15 | 3.3$ \pm $1.1 | $-46.5 \pm 0.5$ | ... |
| Sh140 | 106.81$^a$5.31 | 0.9$ \pm $0.1 | $-8.5 \pm 1.0$ | ... |
| Sh142 | 107.28$^a$0.90 | 3.4$ \pm $0.3 | $-41.0 \pm 0.5$ | ... |
| Sh149 | 108.34$^a$1.12 | 5.4$ \pm $1.7 | $-53.1 \pm 1.3$ | 8.4 |
| Sh152 | 108.75$^a$0.93 | 3.6$ \pm $1.1 | $-50.4 \pm 0.5$ | 8.2 |
| Sh154 | 109.17$^a$1.47 | 1.4$ \pm $0.4 | $-11.5 \pm 0.9$ | ... |
| Sh155 | 110.22$^a$2.55 | 0.7$ \pm $0.1 | $-10.0 \pm 1.5$ | ... |
| Sh156 | 110.11$^a$0.05 | 6.4$ \pm $2.0 | $-51.0 \pm 2.0$ | 8.7 |
| Sh157 | 111.28$^a$0.66 | 2.5$ \pm $0.4 | $-43.0 \pm 2.0$ | ... |
| Sh158 | 111.54$^a$0.78 | 2.8$ \pm $0.9 | $-56.1 \pm 1.1$ | ... |
| Sh159 | 111.61$^a$0.37 | 3.1$ \pm $1.2 | $-56.0 \pm 1.0$ | 11.0 |
| Sh161B | 111.89$^a$0.88 | 2.8$ \pm $0.9 | $-51.9 \pm 0.7$ | ... |
| Sh162 | 112.19$^a$0.22 | 3.5$ \pm $1.1 | $-44.7 \pm 0.5$ | 7.7 |
| Sh163 | 113.52$^a$0.57 | 2.3$ \pm $0.7 | $-44.9 \pm 3.8$ | ... |

$^a$ The errors in the H I column density values are between 10% and 20%.

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**Fig. 2.** — Radial velocities of H II regions in the vicinity of CTB 109 as a function of their spectroscopic distances. **Solid line:** Expected behavior according to the flat rotation model with $v_c = 220 \text{ km s}^{-1}$ and $R_0 = 8.5 \text{ kpc}. **Dashed line:** Radial velocity of CTB 109.
at 3.0 kpc would be 24 pc. The existence of this group of \( \text{H II} \) regions at about the same distance suggests that star formation in the Perseus arm in this vicinity was triggered by the spiral shock.

4. THE COLD ENVIRONMENT OF CTB 109

The 1420 MHz radio continuum image of CTB 109 taken from the CGPS is shown in Figure 1. The radio emission shows two shells of radius 8' and 18'. Both shells are incomplete in the northwest, where the radio emission abruptly stops. The binary pulsar 1E 2259+586 lies near the geometric center of the larger shell. There is another bright emission structure in the south, where both shells overlap. The remnant is brightest to the northeast and southeast, with an intervening depression. A striking feature of the radio emission is the presence of several thin filaments between the shells and even some on top of them, indicating complex dynamical structures within the remnant and around it.

4.1. The Molecular Material

The molecular environment of CTB 109 was studied intensively by Tatematsu et al. (1987, 1990) on the basis of CO observations with the Nagoya 4 m radio telescope and the 45 m telescope, respectively, at the Nobeyama Radio Observatory. They described the massive molecular cloud to the west of CTB 109 and found a ridge of molecular material extending inside the SNR, showing an anticorrelation with the X-ray emission. They found no evidence of shocked CO inside or around the remnant. In Figure 4, we plot channel maps of our CO data toward CTB 109 around the systemic velocity of the SNR. We should note at this point that, in contrast to the customary Perseus arm velocity profile, in this vicinity, higher negative velocity indicates a shorter distance (see also § 3).

The massive molecular cloud to the west of the SNR is very prominent in the channel maps. This cloud blocks the shock wave from further expansion in this direction. According to Tatematsu et al. (1987), this cloud is responsible for the peculiar shape of the SNR. In the northern part, there is an extension from the cloud into the SNR, separating both radio shells. This CO ridge appears at about \(-46\) to \(-47\) km s\(^{-1}\) and vanishes at \(-52\) km s\(^{-1}\), while the main body of the cloud appears at a slightly more negative velocity, moving in gradually from the west until it disappears in the same direction at \(-54\) to \(-55\) km s\(^{-1}\). This indicates that the main body of the cloud is located closer to us than the ridge, or that the CO ridge is moving away from us relative.
to the big cloud. It also shows that the core of the massive cloud is to the west, and the SNR shock wave has been reflected by its eastern edge. The dark cloud at the tip of the ridge, which is more pronounced in the integrated map in Figure 1, causes strong absorption in the X-ray data (Tatematsu et al. 1987, 1990; Rho & Petre 1997), indicating that it lies in front of the SNR or is associated with it. The only possible radial velocity for CTB 109 would be between \( \pm 50 \) and \( \pm 52 \) km s\(^{-1}\), where both structures, the ridge and the massive cloud, are present. This also explains the weak outer radio shell beyond the CO ridge. The shock wave traveling in that direction has mostly been blocked by this ridge.

### 4.2. Neutral Hydrogen

Associated neutral hydrogen features are less pronounced than those seen in CO, but the general structure seen in the CO data is also present. The massive cloud to the west extends further to the south and is generally closer to the remnant. The ridge in the north is also visible, although it is seen slightly further south, closer to the inner SNR shell, and can be followed further around the inner shell. It appears to be smoother, which makes it difficult to detect in the channel maps (Fig. 5), but in the integrated map of Figure 1, it is quite obvious. The SNR seems to be located at a density gradient in the H\(_{\alpha}\) distribution most prominent in the three channel maps in the second row of Figure 5. This gradient goes from high densities in the west smoothly down to a hole in the H\(_{\alpha}\) distribution east of CTB 109. Figure 1 also reveals a diffuse shell of H\(_{\alpha}\) surrounding almost the whole outer radio shell of the SNR. Note that the deep depression in the area between the bright spot in the south and the northeastern part of the outer shell (in the H\(_{\alpha}\) channel maps between \(-47\) and \(-53\) km s\(^{-1}\)) cannot be caused by absorption, since the continuum emission of the outer shell in this area is not strong enough. Therefore, this relative absence of H\(_{\alpha}\) emission is due to the presence of the smooth outer shell. Absorption of the bright southern spot is also detectable in the channel maps.

### 5. DISCUSSION

#### 5.1. CTB 109 as Part of a Large Complex

The distribution of H\(_{\alpha}\) regions and SNRs in the vicinity of CTB 109 is displayed in Figure 6 in relation to the Perseus arm locations from Roberts (1972) and Taylor & Cordes
(1993). Apparently, the kinematic distance for CTB 109 derived from the flat rotation curve would place the SNR in the interarm region behind the Perseus arm. Even the 4 kpc distance assumed by various earlier authors would be outside the spiral arm. Since the SNR is associated with dense molecular and atomic material, an interarm location would be very unlikely.

In the area shown in Figure 6, there are two concentrations of sources within the Perseus arm. The first is around CTB 109 and the supernova remnant Cas A, and the second is around the Tycho SNR. There is a third concentration at higher longitudes around the W3/4/5 complex and the supernova remnant HB 3 (not shown here). Obviously, while traveling through the Perseus arm, the spiral shock triggered star formation in high-density regions, where we now find these concentrations of young stellar objects, indicated by the compact H\(\text{ii}\) regions and supernova remnants which are the result of the explosion of massive young stars as well.

5.2. Neutral Material in the Vicinity of CTB 109

CTB 109 is located at a density gradient which goes west to a gap in the emission in the east of the SNR. Apparently, the progenitor star was formed at the edge of a dense molecular cloud, while the star in Sh 152 was formed in its center. To the west, the shock wave expanded into the dense cloud, which decelerated it very quickly. To the east, however, the shock wave is expanding into a moderately dense medium. The structure of the surrounding H\(\text{i}\) indicates that the SNR is not expanding inside a stellar wind bubble, because we would expect such a structure to have a more pronounced outer boundary. It is more likely that the missing emission from the interior is the result of taking away the neutral hydrogen by ionizing it with the expanding shock wave. This would imply a progenitor star of type B2/3, since more massive stars would have a strong stellar wind.

Between the outer and inner shell in the north, we find the ridge of cold material separating both structures. The fact that the H\(\text{i}\) is smoother and mostly concentrated outside the thin, dense molecular ridge indicates an interaction with the SNR in which the surface of the molecular structure was dissociated or even evaporated by the expanding shock wave. The lack of X-ray emission coinciding with the ridge indicates that the ridge is located on the near side of the rem-
nant and is absorbing the X-ray emission that originates behind it.

The outer radio shell shows two very prominent features. These are the bright knot to the south and the bright part of the northeastern shell. Both features are located within bright parts of the surrounding H i (see Fig. 1), indicating that these parts of the remnant are expanding into a higher density medium than the part between them where the emission of the radio shell is weakest and the surrounding H i seems to have almost a gap. This suggests a close relation between the radio brightness of the SNR’s expanding shell and the density of the medium it is expanding into, which is, of course, expected.

6. SUMMARY

We have presented new radio continuum data for the SNR CTB 109 together with H i and CO observations of the surrounding medium. Our data show that the radio continuum emission from the remnant is closely related to the surrounding cold material. Analysis of the H i and CO dynamics, and comparison of the results with parameters of nearby H ii regions, has led us to the conclusion that the SNR is located at a distance of 3 ± 0.5 kpc, as opposed to larger distances previously published in the literature. It also implies that the SNR, together with several H ii regions, is part of a large complex created by the spiral shock present in the Perseus arm. We have shown that inclusion of the spiral shock is necessary to produce reliable kinematic distances in this part of the Galaxy, and we have demonstrated that, in seeking the distance to a supernova remnant, it is important to take a broader view of the environment. The wide-field, high-resolution data of the CGPS, revealing multiple components of the interstellar medium, are ideal for a study of this type.

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Fig. 6.—H ii regions (open circles) and SNRs (open stars) in the vicinity of CTB 109. Dashed lines: Perseus arm as defined by Roberts (1972). Dotted line: Location of the maximum electron density in the Perseus arm as determined by Taylor & Cordes (1993). The names of the individual SNRs are noted. For Sh 156 and the Sh 147/8/9 complex, the distances from Wouterloot et al. (1988) are used, and for all other H ii regions, the spectroscopic distances listed in Brand & Blitz (1993). The distances for the SNRs Cas A and Tycho were taken from Reed et al. (1995) and Chevalier et al. (1980), respectively.