Discovery of an old supernova remnant candidate through carbon monoxide line emission

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ABSTRACT

Most old supernova remnants (SNRs) in the Milky Way have not yet been identified. Considering their high potential number and the sufficient momentum-energy transfer to the interstellar medium (ISM), they are a key part of our understanding of the overall role of SNRs in the ISM. Here, we report our discovery of an expanding molecular shell identified by CO line observations, namely G16.11−0.51. It covers a known SNR, specifically G16.0−0.5, and is larger in size (i.e., 0.56° over 0.20°). Based on its spatial and kinematic structures, weak nonthermal radio-continuum emission, and derived physical properties, we suggest that it is an old SNR. At a systemic velocity of +41.3 km s⁻¹, the best estimated kinematic distance of G16.11−0.51 is ~3.2 kpc, implying its radius of about 15.6 pc. The age of G16.11−0.51 is estimated to be greater than ~10⁵ yr, and, in a dense molecular environment, it has formed dense and thin shell layers. The kinetic energy of the expanding molecular gas of G16.11−0.51 is about 6.4 × 10⁴⁹ erg, accounting for approximately 6% of the initial SN explosion energy. Although old SNRs have essentially become cold and hard to detect, our discovery suggests that they can be found by searching for CO line emissions.

Key words. ISM: clouds – ISM: lines and bands – ISM: molecules – ISM: supernova remnants

1. Introduction

Supernova remnants (SNRs) contain a large amount of momentum, energy, and heavy elements. They sufficiently transfer these to the surrounding interstellar medium (ISM) and cool down in their late stages (e.g., >10⁵ K; Koo et al. 2020). One supernova event occurs on average every 40 ± 10 yr in the Milky Way (Tammann et al. 1994), resulting in over 2000 SNRs younger than 10⁵ yr. If we take 10⁶ yr to be the lifetime of an SNR, there would be over 20,000 SNRs in total. The number of old SNRs is much larger than that of young bright ones. Old SNRs are a key part of understanding the overall role of SNRs in the ISM, especially their impact on molecular clouds (MCs; e.g., how they regulate the formation of next-generation stars). Old SNRs that have a large potential number and large size are also likely to overlap with other sources, and they act as backgrounds to affect our understanding of other sources.

Only a limited number of SNRs have been identified in our Galaxy, that is, fewer than 400, mostly based on their radio-continuum emission (see Green 2019; Ferrand & Safi-Harb 2012). Most of these known SNRs are bright and young. It is difficult to detect old SNRs because they usually have very weak radiation; for example, they are radio faint and begin to dissolve into the ISM. Benefitting from enhanced observations in different wavelengths, new SNR candidates have been continuously discovered, for example by optical emission (Fesen et al. 2020), by X-ray emission (Becker et al. 2021; Churazov et al. 2021; Khabibullin et al. 2023), and mostly by radio-continuum emission (Anderson et al. 2017; Hurley-Walker et al. 2019a; Gao et al. 2020; Dokara et al. 2021; Ball et al. 2023, etc.). It appears that there are still a large number of potential SNRs waiting to be discovered; nevertheless, background emission would limit such detections (see, for e.g., radio-continuum emission from HESS J1912+101 confused by background diffuse emission Reich & Sun 2019), especially for weak SNRs or toward the inner Galactic region. Additionally, the large size and quantity of old SNRs can lead to a severe overlapping effect, further complicating the situation. Considering that old SNRs would form a cold, dense, and gradually momentum-conserving shell, H i 21 cm line emission has been used as a good tracer to detect such old SNRs, especially large ones at high Galactic latitude or with localized high-velocity H i features (e.g., Koo & Kang 2004; Koo et al. 2006; Kang & Koo 2007; Kang et al. 2012; Xiao & Zhu 2014, etc.). Although CO line emission can also trace dense shells associated with SNRs (e.g., for known SNRs; Chen et al. 2014; Sofue et al. 2021), no known SNR has been discovered through CO lines to date (Green 2019; Ferrand & Safi-Harb 2012). We note that, based on the analysis of CO and H i data, Su et al. (2017) suggested the SNR origin of the TeV source HESS J1912+101. Compared to H i gas, molecular gases are more dense and clumpy; hence, it is difficult to detect a large complete shell-like structure associated with an SNR. In addition, molecular lines are very likely to have serious overlapping effects too, especially toward the inner Galactic region, which can complicate their velocity features. Nevertheless, since remnants of core-collapse supernovae are thought to be located close to their parent MCs, numerous molecular shells are expected to have originated from old SNRs; for example, some CO bubbles in the W43 molecular complex were interpreted as fully evolved SNRs by Sofue (2021).
Here, we report the discovery of a new expanding CO shell, namely G16.11–0.51, which covers a known SNR, G16.0–0.5. Its spatial and kinematical structure, weak nonthermal radio-continuum emission, and derived physical properties indicate its origin from an SN explosion.

2. Observations

The CO line emission was observed from November 2011 to November 2013 and from February to April 2019 using the Purple Mountain Observatory (PMO) 13.7 m millimeter-wavelength telescope located in Delingha, China, as part of the Milky Way Imaging Scroll Painting (MWISP) project\(^1\). The 3 × 3 multibeam side-band separation receiver, that is, the Superconducting Spectroscopic Array Receiver (SSAR, Shan et al. 2012), was used to simultaneously observe the \(^{12}\)CO (\(J = 1–0\)) and \(^{13}\)CO (\(J = 1–0\)) and \(^{18}\)O (\(J = 1–0\)) lines. The fast Fourier transform (FFT) spectrometer with 1 GHz bandwidth and 16384 channels was used as the back end for each side band. Correspondingly, the spectral resolutions of the three CO lines were 0.17 km s\(^{-1}\) for \(^{12}\)CO (\(J = 1–0\)) and 0.16 km s\(^{-1}\) for both \(^{13}\)CO (\(J = 1–0\)) and \(^{18}\)O (\(J = 1–0\)). We mapped a 1.2° × 1.2° area via on-the-fly (OTF) observing mode. Following the standard procedure of the MWISP CO line survey, observations were performed at least twice along the Galactic longitude and latitude directions, respectively, and specialized data checks were carried out. Data with bad baselines were excluded, and thereby baseline problems were largely suppressed. However, some minor rms noise inhomogeneities were introduced, for example, in the Galactic longitude or latitude direction. The total error in pointing and inhomogeneities were introduced, for example, in the Galactic longitude or latitude direction. The total error in pointing and inhomogeneities were introduced, for example, in the Galactic longitude or latitude direction. The total error in pointing and inhomogeneities were introduced, for example, in the Galactic longitude or latitude direction. The total error in pointing and inhomogeneities were introduced, for example, in the Galactic longitude or latitude direction.

Radio-continuum emission data in four bands with frequencies ranging from 72 to 103 MHz, 103 to 134 MHz, 138 to 170 MHz, and 170 to 231 MHz were obtained from the Galactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) survey\(^2\) (Wyatt et al. 2015; Hurley-Walker et al. 2017, 2019b). Other radio-continuum emission data in six bands were obtained from The HI/OH/Recombination line survey (THOR; Beuther et al. 2016; Wang et al. 2020), and they are centered at 1.06, 1.31, 1.44, 1.69, 1.82, and 1.95 GHz and have a bandwidth of 128 MHz. Combined 1.4 GHz continuum data from the THOR and the VLA Galactic Plane Survey (VGPS, Stil et al. 2006) was applied, from which the flux retrieved is consistent with the literature (Anderson et al. 2017; Wang et al. 2020).

3. Results

We show the pseudo-tricolor image of integrated intensities of three CO isotope lines of G16.11–0.51 over a wide velocity range in Fig. 1. Multiple shell structures are clearly seen around a circular region with a radius of about 0.28°, and they are distributed from the north to the southwest and in the east. G16.11–0.51 overlaps with a known SNR, G16.0–0.5, but it is much larger in size. The molecular shell associated with G16.0–0.5 in its southern region is also visible, which was also detected in previous work (Beaumont et al. 2011). As shown in the position-velocity maps along horizontal and vertical strips across G16.11–0.51 (Fig. 1), the molecular shells are expanding at a velocity of about 10 km s\(^{-1}\). Some molecular clumps correlated with the expanding shells are also strongly disturbed, indicated by line broadening features of about 20 km s\(^{-1}\) (see, e.g., those indicated by three red arrows in the right panel of Fig. 1). We note that the line broadening features are significant and not due to scanning effects (artifacts caused by baseline variations). Two of these molecular clumps are located within and on the edge of the G16.0–0.5 region. However, the blueshifted velocity of these molecular clumps is consistent with the blueshifted velocity direction of the expanding shell at their locations. The quiescent molecular gas at \(\sim +43\) km s\(^{-1}\) around the expanding shell structures is rarefied. Molecular gases at \(\sim +57\) km s\(^{-1}\) inside G16.11–0.51 are all disturbed or associated with the expanding shells. There is a small amount of quiescent molecular gas at \(\sim +57\) km s\(^{-1}\) outside G16.11–0.51. However, this small amount of molecular gas may have a peculiar velocity compared to the Galactic rotation curve, but the major \(\sim +43\) km s\(^{-1}\) component is unlikely. The expanding shell structures and broadened line emission are probably associated with the quiescent molecular gas at \(\sim +43\) km s\(^{-1}\). The \(\sim +43\) and \(\sim +57\) km s\(^{-1}\) MCs may be adjacent to each other, and at the same distance, however, it is uncertain.

The kinematic properties of molecular gases and the corresponding spatial distribution can be illustrated by the velocity dispersion map. As shown in the \(^{12}\)CO velocity dispersion map (left panel, Fig. 2), disturbed molecular gases are present in the northeastern shell of G16.11–0.51 and in a molecular clump located around the southeastern boundary. There is also some diffuse and disturbed molecular gas distributed around the northeastern boundary of G16.11–0.51, where there is a weak radio-continuum shell. Known H II regions are introduced from the WISE catalog of Galactic H II regions (Anderson et al. 2014), which is one of the most complete catalogs of H II regions in the Galaxy (see the right panel of Fig. 2). We note that the systemic velocity of some H II regions is not within the selected velocity range. The disturbed molecular gases along the G16.11–0.51 boundary do not originate from known H II regions. For SNR G16.0–0.5, disturbed gas in the associated molecular shell is well correlated with the southeastern radio continuum shell of the remnant. The \(^{13}\)CO line emission is optically thinner than the \(^{12}\)CO line emission, which can trace inner and denser molecular gas. The \(^{13}\)CO velocity dispersion map (right panel, Fig. 2) shows the distribution of dense disturbed molecular gas. By comparison, no dense disturbed gas associated with G16.0–0.5 is seen. For G16.11–0.51, dense disturbed gas distributed in a thin layer is seen inside its northeastern molecular shell. Besides this, in its southeastern clump, dense disturbed gas is distributed only in the thin inner layer facing the center of G16.11–0.51. It indicates that the disturbed gas in the southeastern clump is mainly distributed on its surface and transmitted toward the outside of G16.11–0.51. Further study of these disturbed molecular gases in future work is needed for a better understanding of them. For MCs outside the G16.11–0.51 region, some disturbed gases are associated with H II regions, such as those in the northwest, northeast, and southeast.

\(^1\) http://english.dlh.pmo.cas.cn/ic/
\(^2\) http://www.radioast.nsdc.cn/mwisr.php
\(^3\) http://www.iran.fr/IRAMFR/GILDAS
\(^4\) https://www.mwatelescope.org/gleam
G16.11−0.51 presents a partial radio continuum shell along its northeastern boundary (see Fig. 2). There is significant radio-continuum emission outside G16.11−0.51 in the northeast, which is associated with H II regions (see the right panel of Fig. 2). However, radio-continuum emissions from G16.11−0.51 and the H II regions surround different centers. We measured the flux densities of G16.11−0.51 in different bands, with the background level subtracted. We first smoothed all the radio-continuum data in different bands to a common resolution as the lowest resolution GLEAM 72–103 MHz data. An annular region half the beam size of the GLEAM 72–103 MHz data away from the source region, with an area similar to the source region, was used to subtract the background emission. The flux densities of H II regions, THOR radio continuum sources, and the SNR G16.0−0.5 region, all enlarged by half the beam size, were removed from the calculation (see regions in the right panel of Fig. 2). The same regions are applied for all GLEAM, THOR, and THOR+VGPS bands. The radio-continuum emission of G16.11−0.51 is weak; hence, the individual measured flux densities are not so significant. The overall radio-continuum spectrum can be fit by the power-law function (see Fig. 3). The best-fit spectral indices obtained using the GLEAM-only and GLEAM+(THOR+VGPS) data are consistent and steep (i.e., $\alpha = -0.8 \pm 0.3 (S_r \propto \nu^\alpha)$). No radio-continuum emission is detected by the THOR-only data, which is likely to suffer from serious missing flux problems in the interferometric observations for such a large source. These indicate that the radio-continuum emission is nonthermal and not from H II regions. The extrapolated 1 GHz surface brightness of G16.11−0.51 is estimated as $\Sigma_1 \text{GHz} \sim 3 \times 10^{-21} \text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$.

4. Discussion
We extracted CO spectra in the G16.11−0.51 region, which is defined as a circular region 1.2 times larger than that shown in Fig. 2. We also excluded the SNR G16.0−0.5 region, which is a circular region 1.2 times larger than that shown in Fig. 2. The extracted $^{12}$CO and $^{13}$CO spectra are shown in Fig. 4. According to the number of their peaks, the $^{12}$CO spectrum is fit by six
Table 1. Fit and derived parameters for two related velocity components in G16.11−0.51.

<table>
<thead>
<tr>
<th>Component</th>
<th>Line</th>
<th>Peak $T_{mb}$ (K)</th>
<th>Center $V_{LSR}$ (a) (km s$^{-1}$)</th>
<th>FWHM (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>$^{12}$CO ($J = 1-0$)</td>
<td>4.79 ± 0.03</td>
<td>+43.31 ± 0.07</td>
<td>12.4 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>$^{13}$CO ($J = 1-0$)</td>
<td>1.027 ± 0.007</td>
<td>+41.25 ± 0.09</td>
<td>12.0 ± 0.3</td>
</tr>
<tr>
<td>Shifted</td>
<td>$^{12}$CO ($J = 1-0$)</td>
<td>1.30 ± 0.03</td>
<td>+58.0 ± 0.2</td>
<td>8.8 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>$^{13}$CO ($J = 1-0$)</td>
<td>0.198 ± 0.008</td>
<td>+57.4 ± 0.2</td>
<td>7.8 ± 0.5</td>
</tr>
</tbody>
</table>

### Derived physical parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>$T_{ex}$ (b) (K)</th>
<th>$\theta^{(1)}$CO (b)</th>
<th>$N$(H$_2$) (c) (10$^{21}$ cm$^{-2}$)</th>
<th>$M$ (c) (10$^4$ $M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>8.1</td>
<td>0.27</td>
<td>11 (11)</td>
<td>14$d_{3/2}^2$ (17$d_{3/2}^2$)</td>
</tr>
<tr>
<td>Shifted</td>
<td>4.3</td>
<td>0.19</td>
<td>1.9 (2.2)</td>
<td>2.5$d_{3/2}^2$ (3.2$d_{3/2}^2$)</td>
</tr>
</tbody>
</table>

Notes. (a)$V_{LSR}$ is the velocity with respect to the local standard of rest. (b)Using the assumption of local thermal equilibrium (LTE). See the details of the calculation method in Zhou et al. (2016). (c)Derived from $^{12}$CO column density by assuming the $^{12}$CO abundance of 1.4×10$^{-4}$ (Ripple et al. 2013). For comparison, we also show the values in parentheses, which are estimated by using the conversion factor $N$(H$_2$)/$W$(12CO) ≃ 1.8 × 10$^{20}$ cm$^{-2}$ K$^{-1}$ km s$^{-1}$ (Dame et al. 2001). $d_{3/2}$ stands for $d/(3.2$ kpc), where $d$ is the distance to G16.11−0.51 in kiloparsecs.

Gaussian functions, and the $^{13}$CO spectrum is fit by four Gaussian functions. As shown in Sect. 3, G16.11−0.51 is associated with the MC at a systemic velocity of +41.3 km s$^{-1}$. Molecular gas at +57.4 km s$^{-1}$ within the G16.11−0.51 region is mainly driven by G16.11−0.51 from the +41.3 km s$^{-1}$ MC. The different velocities between the expanding shell of G16.11−0.51 and its parent MC indicate that the medium surrounding G16.11−0.51 has a density gradient in the line of sight. The schematic diagram of the formation of the expanding shell of G16.11−0.51 is shown in the appendix. The fit and derived parameters for the +41.3 and +57.4 km s$^{-1}$ components are listed in Table 1. The kinematic distances of the +41.3 km s$^{-1}$ MC are estimated as 3.2 ± 0.4 and 4.0 ± 0.3 kpc, based on a full distance-probability density function$^5$ (Reid et al. 2016, 2019). The +41.3 km s$^{-1}$ MC is more likely to be at 3.2 kpc, which has a probability of 0.53. The momentum and kinetic energy of the expanding molecular gas of G16.11−0.51 are estimated to be $4 \times 10^4 d_{3/2}^2$ $M_\odot$ km s$^{-1}$ and $6.4 \times 10^9 d_{3/2}^2$ erg, respectively. We note that, although a far kinematic distance of the +41.3 km s$^{-1}$ MC can be estimated to be ~12 kpc, the corresponding kinetic energy of the molecular gas would be too large (i.e., $9 \times 10^{50}$ erg), even comparable to the typical SN explosion energy value. If the expanding shell is produced by the stellar wind of the OB star, even if all the stellar wind energy is transferred to the shell, even if...
a star with a mass greater than that of an O9 V type star is required (e.g., Abbott 1982). However, we searched the SIMBAD astronomical database (Wenger et al. 2000) within a 1.2 times enlarged region of G16.11−0.51 and found no O-type stars. Only a few B-type stars are found in the region, and they are located at distances of less than ~1.2 kpc, and, hence, they are not related to G16.11−0.51. The expanding shell with thin and dense layers, and its physical properties, indicates an SN origin for G16.11−0.51, which is further supported by the associated nonthermal radio-continuum emission.

If G16.11−0.51 is at a distance of 3.2 kpc, its radius is 15.6 pc. The weak radio-continuum emission as well as the presence of dense shell structures indicate that SNR G16.11−0.51 is in the radiative stage. Since the molecular shells are basically distributed on a circle on the plane of the sky, some simple models of the evolution of SNRs in a homogeneous medium can be applied as approximations to provide some references. Assuming that the SNR evolved in a homogeneous ISM, its age can be estimated as $t = 2r_j/(7v_i) \sim 2.7 \times 10^5$ yr (McKee \& Ostriker 1977) and the explosion energy as $E_{SN} = 6.8 \times 10^{34} n_0^{16} v_i^{10} (k \text{ km s}^{-1})^{2.3} (r_j/1 \text{ pc})^{16} \sim 2 \times 10^{51}$ erg, where the ambient hydrogen density $n_0$ is estimated to be ~63 cm$^{-3}$, the shock velocity $v_i$ as $v_{\text{wind}} = 16.1$ km s$^{-1}$, the radius of the SNR $r_j$ 15.6 pc, and the metallicity parameter $Z_m = Z/Z_\odot$ is set to be 1 (Cioffi et al. 1988). The ambient density is estimated by assuming that the mass of the expanding molecular shell was initially uniformly distributed throughout its internal volume. The explosion energy obtained is big in comparison to the typical value (i.e., $10^{50}$ erg). As the SNR evolves in a nonuniform medium, there is a leakage of the SNR energy in less dense directions, and therefore the explosion energy is even underestimated. Considering that the SNR is likely to have evolved in a bubble blown by the stellar wind of its progenitor, with the contribution of the stellar wind to the accumulation of the ISM, less SN explosion energy will be required. In the wind-blow bubble scenario, we estimate the explosion energy and age using the model of Chen et al. (2003). Assuming $A = r_j/r_s = 0.9$ with $(\eta, \beta) = (1, 0)$, its explosion energy can be estimated as $E_{SN} = 1.05 \rho_0^{0.5} R_1^{-1} F_\rho(4)(A)^{-2} \sim 10^{51} d_{32}^2$ erg and the age as $t = 1.02 \rho_0^{0.5} R_1^{-1} F_\rho(4)(A) \sim 10^5 d_{32}^2$ yr, where

\begin{align*}
S(Jy) & \sim 0.1 - 10.0 \\
\text{Frequency (MHz)} & \sim 100 - 1000
\end{align*}

\begin{align*}
S(Jy) & \sim 0 - 40.0 \\
\text{Frequency (MHz)} & \sim 500 - 2000
\end{align*}

**Fig. 3.** Flux densities of G16.11−0.51 obtained from the GLEAM data only (left) and the GLEAM+THOR+(THOR+VGPS) data (right). The flux density obtained from the THOR+VGPS 1.4 GHz continuum data is presented by a blue star in the right panel. The flux densities are extracted from the G16.11−0.51 region indicated in Fig. 2. An annular region half the beam size of the GLEAM 72–103 MHz data away from the source region, with an area similar to the source region, is used to subtract the background emission. The flux densities of H II regions, THOR radio continuum sources, and the SNR G16.0−0.5 region, all enlarged by half the beam size, are removed from the calculation (see regions in the right panel of Fig. 2). The axes in the left panel are logarithmic, while the ones in the right panel are linear. Internal and external flux density scale errors are applied as 2% and 8% for the GLEAM data in left and right panels, respectively (Hurley-Walker et al. 2017). The flux density uncertainty of the THOR and THOR+VGPS data is determined by measuring the variation of the emission free region (see Anderson et al. 2017 for reference). The fit power-law spectra are shown by solid lines. The best-fit spectral indices are $-0.8 \pm 0.3$ and $-0.77 \pm 0.04$ for the GLEAM and GLEAM+THOR+VGPS data, respectively. The upper limits of the flux densities from the THOR only data are shown for comparison but are not used in fitting.

\begin{align*}
\text{Residuals} & \sim -0.5 - 0.5 \\
V_{\text{LSR}} (\text{km s}^{-1}) & \sim 20 - 80
\end{align*}

**Fig. 4.** $^{12}$CO ($J = 1−0$) (blue) and $^{13}$CO ($J = 1−0$) (green) spectra extracted from 1.2 times enlarged G16.11−0.51 region with 1.2 times enlarged SNR G16.0−0.5 region subtracted, together with their best-fit Gaussian model and residuals. The $^{12}$CO components peak at +19.3, +29.5, +43.3, +58.0, +68.1, and +76.0 km s$^{-1}$, and the $^{13}$CO components peak at +19.5, +30.2, +41.3, and +57.4 km s$^{-1}$. Individual Gaussian models of the $\sim +43$ and $\sim +57$ km s$^{-1}$ components are shown by black and red dotted lines, respectively. For levels of the residuals are shown by blue and green dotted lines for $^{12}$CO and $^{13}$CO, respectively. The $^{13}$CO ($J = 1−0$) spectrum and its fitting result and residuals are multiplied by a factor of 2 for better visibility.
$r_j$ is the radius of the progenitor’s wind-blown bubble, $\rho_0$ is the density of the wall of the bubble, the dimensionless term $F^R(\lambda)$ is estimated to be $-0.444$, and $F^R(\lambda)$ is estimated to be $0.206$ (see Eqs. (26), (29), (31), and (35) in Chen et al. (2003)). For $\lambda = r_j/r_0 = 0.9$, the radius of the wind-blown bubble is $r_j \sim 14$ pc. The assumption of $\eta = 1$ means that the SNR enters the radiative phase directly after hitting the cavity wall, which is reasonable for $r_j \geq 3.8$ pc (see Sect. 2.1 in Chen et al. 2003), and the assumption of $\beta = 0$ means that the density inside the cavity is much smaller than that of the cavity wall. The density of the wall of the wind-blown bubble is estimated by assuming that the mass of the expanding molecular shell was initially evenly distributed in a spherical shell with inner and outer radii of $r_j$ and $r_s$, respectively (i.e., $n_0 \sim 233$ cm$^{-3}$). According to the radius of the wind-blown bubble, the progenitor’s initial mass can be estimated to be $\sim 19 M_\odot$ by applying the linear relationship between the size of a massive star’s main-sequence bubble in a molecular environment and its initial mass (Chen et al. 2013). In the wind-blown bubble scenario, a relatively reasonable explosion energy can be obtained. We note that the uniform wind-blown bubble model is still a rough approximation. Since the radius of the SNR on the plane of the sky is smaller than the average radius (see the appendix for more information), the age obtained (i.e., $\sim 10^7$ yr) is only a lower limit. Further analysis in future work is needed to obtain more appropriate models based on specific molecular gas distributions (e.g., numerical models).

The radio-continuum emission from G16.11−0.51 is weak, and its diameter (≈31 pc) and the radio-continuum surface brightness ($\Sigma_{\text{G16.11}} \sim 3 \times 10^{-21}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$) conform to the $\Sigma$-D relation (Pavlović et al. 2018). In general, as the SNRs become older, their radio continuum emissions become weaker; for example, the SNRs discovered by H I observations with an age of around one million years is with $\Sigma_{\text{G16.11}} \leq 7 \times 10^{-23}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$ (Koo et al. 2006; Xiao & Zhu 2014). Nevertheless, when the SNR shock encounters dense clouds, the radio-continuum emission can be enhanced due to the compressed magnetic fields and the accelerated preexisting cosmic-ray electron (Blandford & Cowie 1982; Draine & McKee 1993). It seems to be efficient for SNRs encountering clouds while still having quite a high Mach number (Pavlović et al. 2018). No radio-continuum emission is detected around the density of the wall of the bubble, the dimensionless term $\beta$ is reasonable for $r_j \sim 14$ pc, and $\eta = 1$ is assumed (see Sect. 2.1 in Chen et al. 2003).

The radio-continuum emission from G16.11−0.5 is weak, and its diameter (≈31 pc) and the radio-continuum surface brightness ($\Sigma_{\text{G16.11}} \sim 3 \times 10^{-21}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$) conform to the $\Sigma$-D relation (Pavlović et al. 2018). In general, as the SNRs become older, their radio continuum emissions become weaker; for example, the SNRs discovered by H I observations with an age of around one million years is with $\Sigma_{\text{G16.11}} \leq 7 \times 10^{-23}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$ (Koo et al. 2006; Xiao & Zhu 2014). Nevertheless, when the SNR shock encounters dense clouds, the radio-continuum emission can be enhanced due to the compressed magnetic fields and the accelerated preexisting cosmic-ray electron (Blandford & Cowie 1982; Draine & McKee 1993). It seems to be efficient for SNRs encountering clouds while still having quite a high Mach number (Pavlović et al. 2018). No radio-continuum emission is detected around the density of the wall of the bubble, the dimensionless term $\beta$ is reasonable for $r_j \sim 14$ pc, and $\eta = 1$ is assumed (see Sect. 2.1 in Chen et al. 2003).

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References


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Appendix A: Schematic diagram

We present a schematic diagram in Figure A.1 to illustrate the formation of the expanding shell of G16.11−0.51. As shown in the schematic diagram, when an SNR breaks out of its parent MC, its shockwave would sweep up different amounts of molecular gas in different directions with different decelerations, resulting in an offset bubble structure. Such a structure will be further enhanced by the radial density gradient of the MC. According to the distribution of the velocity component in the line of sight of different parts of the shell, a similar structure will be present in the position-velocity map as shown in Figure 1.

Blowout morphology has been observed in many SNRs, such as 3C 400.2, RCW 103, and G352.7−0.1, which can be explained by the model in which the supernova explosion producing the remnant occurs in the medium with a density gradient or inside and near the border of a dense cloud (Ambrocio-Cruz et al. 2006; Toledo-Roy et al. 2014; Lu et al. 2021). Figure A.2 shows the distribution of 12CO ($J = 1−0$) emission in the velocity range of +34 to +82 km s$^{-1}$ with an interval of 3 km s$^{-1}$.

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**Fig. A.1.** Schematic view of formation of expanding shell of G16.11−0.51. The red star denotes the location of the initial SN explosion. The approximate location of SNR G16.0−0.5 is also marked with a red circle. The arrows indicate the velocities in different parts of the shell. According to the distribution of the velocity component in the line of sight of different sections of the shell, a similar structure will be present in the position-velocity map as shown in Figure 1.
Fig. A.2. \(^{12}\text{CO} (J = 1–0)\) intensity maps integrated over each 3 km s\(^{-1}\). The black dashed circles are the same as in Figure 1. Central velocities are indicated in each panel. The minimum value of each map is 3\(\sigma\).