ABSTRACT

We report the discovery of a shell-like structure G354.4+0.0 of size \(1.6\) that shows the morphology of a shell supernova remnant (SNR). Part of the structure shows polarized emission in a NRAO VLA sky survey map. Based on 330 MHz and 1.4 GHz Giant Metrewave Radio Telescope observations and existing observations at higher frequencies, we conclude that the partial shell structure showing synchrotron emission is embedded in an extended \(\text{H}\,\text{II}\) region of size \(\sim 4\). The spectrum of the diffuse \(\text{H}\,\text{II}\) region turns over between 1.4 GHz and 330 MHz. The \(\text{H}\,\alpha\) absorption spectrum shows this object to be located more than 5 kpc from Sun. Based on its morphology, non-thermal polarized emission, and size, this object is one of the youngest SNRs discovered in the Galaxy with an estimated age of \(\sim 100–500\) yr.

Key words: \(\text{H}\,\text{II}\) regions – ISM: supernova remnants – radio continuum: general – radio lines: ISM

1. INTRODUCTION

Galactic OB star counts, pulsar birth rates, iron abundances, and estimates of supernova rates in Local Group galaxies suggest that there should be more than 1000 supernova remnants (SNRs) in our Galaxy (Tammann et al. 1994). However, only 274 SNRs have been presently cataloged (Green 2009). This lack of detection is partly due to the poor angular resolution of existing surveys, which disfavors the detection of small-diameter SNRs (Green 1991). Future surveys with upcoming facilities (Kassim et al. 2005; Bowman et al. 2013) could address this issue. The supernova rate in our Galaxy is about 2.8 per century (Li et al. 2011). Hence, in the last 400 yr, more than 10 supernova explosions have taken place in the Galaxy. However, only two of them (Cas A and G1.9+0.3) have been reported. There are only three SNRs of angular size \(\lesssim 1.5\) listed in the catalog of Green (2009). They are G1.9+0.3, G54.1+0.3, and G337.0–0.1. Among them, G1.9+0.3 has been shown to be the youngest known SNR (Reynolds et al. 2008) in the Galaxy with age of about 150 yr. The SNR G54.1+0.3 is centrally powered by a pulsar and the size of the emission region is 1.5. The actual size of the outer shell is unknown (Leahy et al. 2008) and hence the remnant age could be much more than a few hundred years. The size of G337.0–0.1 has been measured to be 5 pc (Sarma et al. 1997), suggestive that it is a candidate young SNR.

The line of sight toward the Galactic center (GC) passes the longest distance through the Galaxy and enhances the probability of detecting an SNR. Therefore, we conducted observations of a few regions close to the GC with the Giant Metrewave Radio Telescope (GMRT) at 330 MHz (Roy & Bhatnagar 2006). The main objective of these observations was to confirm the nature of certain candidate SNRs. From one of these fields, a small diameter (\(\sim 1.5\)) object, G354.46+0.07, with a partial shell morphology was identified. To confirm its nature, this field was re-observed with the GMRT at 1.4 GHz and 330 MHz. Here, we describe the confirmation of this object as a newly-discovered young SNR in the Galaxy. In Section 2, observations and data analysis procedures are described. Results and discussions are presented in Sections 3 and 4, respectively.

2. OBSERVATIONS AND DATA ANALYSIS

The field mentioned above was observed on 2007 June 17 and 18 at 1.4 GHz and 330 MHz. In the absence of a system temperature measurement at the GMRT, we have corrected for the variation of the sky temperature from calibrator to the target source following Roy & Rao (2004), keeping the automatic level control of the antennas off.\(^4\) During the 330 MHz and 1.4 GHz observations, each of the two intermediate frequencies (IFs) had a bandwidth of 4 MHz and 16 MHz, respectively. Both the IFs during the above set of observations had 128 spectral channels. At 1.4 GHz, the velocity resolution of each of the spectral channels provided a velocity resolution of 6.6 km s\(^{-1}\) and a velocity coverage of more than \(\pm 400\) km s\(^{-1}\). We used 3C48 as the primary flux density calibrator in both the frequency bands. \(\text{H}\,\alpha\) absorption toward 3C287 is known to be less than 1% (Dickey et al. 1978) and was used as the bandpass calibrator at 1.4 GHz. We used 1751–253 and 1714–252\(^5\) as phase calibrators at 1.4 GHz and 330 MHz, respectively. The 1.4 GHz data were analyzed following the standard procedures in AIPS.\(^6\) After preliminary editing and time- and frequency-based calibration, a continuum image of the object was made omitting channels showing evidence for strong absorption. This image was used to phase-only and self-calibrate the data for all the frequency channels. Before making the channel maps, the AIPS task UVLSF was used to subtract a constant term with a constant slope across the frequency channels corresponding to the continuum from the visibility data. To reduce the effect of comparatively large-scale structures in atomic hydrogen (\(\text{H}\,\text{I}\)) along the line of sight, we did high-pass filtering with a short \(\nu\) cut-off of 1 k\(\nu\), that resolves out structures with sizes \(>3\) while making the spectral line maps for detection of \(\text{H}\,\alpha\) absorption.

During analysis of the 330 MHz data, after calibration and editing, every 10 adjacent frequency channels were averaged.

\(^4\) NCRA technical report at http://ncralib1.ncra.tifr.res.in:8080/jspui/handle/2301/437
\(^5\) VLA calibrator catalog from http://www.vla.nrao.edu/astro/calib/manual/csource.html
\(^6\) http://www.aips.nrao.edu
This procedure provided a channel width of 1.25 MHz in the output data. This process significantly reduces the data volume while keeping bandwidth smearing smaller than the synthesized beam during imaging up to the half-power point of the antennas. The initial images were improved by phase-only and later by amplitude and phase self-calibration. The final image was made using multi-resolution CLEAN (Wakker & Schwarz 1988).

3. RESULTS

3.1. Continuum Images

The continuum map of this source made from 330 MHz data with a resolution of $26'' \times 11''$ is shown in Figure 1. This map is sensitive to large-scale structures up to 30' in size. The size of the object G354.4+0.0 is $\sim 1.5'$ and shows a partial shell morphology. To detect any polarized emission and thereby confirm non-thermal emission, we have searched the NRAO VLA sky survey (NVSS; Condon et al. 1998) map at the same location of the sky; the polarization vectors from the NVSS (resolution 45'') are overlaid on Figure 1. To make the polarization total intensity and angle images from the NVSS Stokes $Q$ and $U$ maps (rms noise $\sim 0.3$ mJy beam$^{-1}$), all pixels below a signal-to-noise ratio of 4.5 were blanked and a correction for the noise bias in the polarized total intensity was made using the AIPS task COMB (option POLC). We do detect significant polarized emission from near the two brightest parts of the shell-like structure with peak polarized flux densities of $\sim 2.2\pm 0.3$ mJy beam$^{-1}$ (Figure 1). The percentage polarization of the northern and southern components are $0.6\% \pm 0.1\%$ and $0.75\% \pm 0.1\%$, respectively.

The 1.4 GHz continuum map of the shell without any short $uv$ cut-off showed extended emission (size $\sim 4'$). To image the shell structure at a higher resolution and to measure its flux density, we resolved out any extended structure of size $>3'$ using a short $uv$ cut-off of 1000$\lambda$ to the data during imaging. We also avoided the frequency channels with H i absorption. The resultant image is shown in Figure 2 (left). As can be seen from Figures 1 and 2 (left), the morphology of the source is shell-like. To measure the size of this object, we took four cross-cuts across the shell at different orientations passing through the center of the shell like structure at 330 MHz. From the angular separation of the two peaks in the cross-cuts, we measured the angular size of the shell. The mean angular diameter of the shell is $\sim 94''$, or about 1.6'. The rms error on the mean angular diameter is $\sim 5''$. To measure the flux density at 330 MHz and the spectral index of the shell between 330 MHz and 1.4 GHz, this object was further...
The measured flux densities are brought to the same pixel size and center. The AIPS task BLSUM was used to measure flux densities covering the same polygon region in both maps. To compare flux densities in these two frequencies, the 1.4 GHz map was convolved to the resolution of the new 330 MHz map and brought to the same pixel size and center. This procedure minimizes flux density variations due to different sensitivities in imaging large-scale structures. We note that the flux densities of the shell and the shell at various frequencies and their physical parameters are given in Table 1. Note that the flux densities of the shell and the diffuse emission at 330 MHz were measured from the large-scale sensitive map shown in Figure 1.

The flux density of the diffuse emission decreases significantly at 330 MHz compared with 1.4 GHz; this result indicates self-absorption. For a typical extended source in the Galaxy, self-absorption at meter wavelengths is caused by the Bremsstrahlung process. No significant free–free absorption by the line of sight gas is likely at 330 MHz, as a significant optical depth of this gas is observed only at $\lesssim$100 MHz (Brogan et al. 2003). The free–free optical depth ($\tau$) is related to the observed frequency ($\nu$) by

$$\tau = \int \frac{0.2n_e^2T_e^{-1.35}(\nu/2.8)^{-2.1}}{c^2} dL,$$  
(1)

where $n_e$ is electron density, $T_e$ electron temperature, and $L$ is the path length through the diffuse H II region.

The flux density ($S$) of an object is related to its brightness temperature in the radio frequency range by

$$S = \frac{2kT_b\nu^2\Delta\Omega}{c^2},$$  
(2)

where $\Delta\Omega$ is the solid angle and $T_b$ is the brightness temperature of the diffuse emission. In the case of Bremsstrahlung emission, the brightness temperature of the emission is related to the thermal electron temperature ($T_e$) by

$$T_b = T_e \times (1 - e^{-r}).$$  
(3)

We note that the significant decrease in the flux density of the diffuse emission at 330 MHz (Table 1) indicates a significant optical depth at this frequency. However, the measured value of $T_b$ for the H II region at 330 MHz (from Table 1) is only about 500 K. As this temperature would be comparable to the Galactic background temperature at 330 MHz, a correction due to the absorption of the Galactic background radiation by the H II region needs to be made. We measured the Galactic background temperature at 330 MHz.
temperature from the Haslam et al. (1982) 408 MHz single dish map convolved to the primary beam of the GMRT at 330 MHz and scaled to the same frequency assuming a spectral index of $-2.7$ for the sky brightness temperature. The measured temperature is 700 K toward the H\textsc{ii} region. The 1$\sigma$ error on this measurement is less than 70 K. Following the discussion in Nord et al. (2006), we can write

$$T_b = T_e \times (1 - e^{-\tau}) + T_{gb} e^{-\tau} + T_{gf},$$

where $T_{gb}$ and $T_{gf}$ are the brightness temperature of the non-thermal emission behind and in front of the diffuse H\textsc{ii} region, respectively. For a direction slightly away from the H\textsc{ii} region, the Galactic plane temperature ($T_{gf}$) is

$$T_{gf} = T_{gb} + T_{gf}. $$

An interferometer is insensitive to the total large-scale temperature (or flux density) and measures the difference between the two brightness temperatures discussed above. Therefore, the observed brightness temperature of the H\textsc{ii} region is

$$T_{obs} = T_e \times (1 - e^{-\tau}) - T_{gb} \times (1 - e^{-\tau}).$$

(4)

Therefore, $T_e$ in Equation (2) needs to be replaced by $T_{obs}$ (Equation (4)), where $\tau$ is given by Equation (1). One finally obtains

$$S = 3.07 \times 10^8 \times \nu^2 \times \left[ T_{e4} - (T_{gb4} \times \nu^{-2.7}) \right] \times [1 - e^{-0.306 \times EM \times (T_{e4}^{1.8}) \times \nu^{2.1}] \times \Delta\Omega, \quad (5)$$

where $T_{e4}$ is the electron temperature in units of $10^4$ K, $T_{gb4}$ is the Galactic plane temperature at 1 GHz in units of $10^4$ K, EM is the emission measure in units of $10^6$ cm$^{-6}$ pc, and $\nu$ is in GHz. We fit Equation (5) to the observed flux densities of the diffuse H\textsc{ii} region to measure its physical properties ($T_e$, $n_e$).

At 843 MHz and 4.8 GHz, the contribution of the shell could not be separated from the diffuse emission. Therefore, the estimation of the flux densities of the diffuse emission at these two frequencies depends on the actual flux density of the shell emission, which in turn depends on its location with respect to the diffuse H\textsc{ii} region. Therefore, we consider below three possible configuration of the shell with respect to the H\textsc{ii} region, thereby allowing us to constrain the spectral index of the shell.

### Table 1

| Source Name | Angular Size ($\degree$) | $S_{330}$ (Jy) | $S_{843}$ (Jy) | $S_{1400}$ (Jy) | $S_{4800}$ (Jy) | $\alpha_{1000}$ | $\tau_{330}$ | $T_e$ (K) | $n_e$ (cm$^{-3}$) |
|-------------|--------------------------|---------------|---------------|---------------|---------------|----------------|-------------|----------|-----------------|
| G354.4+0.0 shell | ~4 | 1.6 $\pm$ 1 | 0.9$^b$ $\pm$ 0.1 | 0.9$^b$ | 0.7 $\pm$ 0.1 | 0.4$^b$ | $-0.2 \pm 0.1$ | ... | ... |
| H\textsc{ii} region | ~4 | 2.4 $\pm$ 0.2 | 3.3$^b$ $\pm$ 0.3 | 3.5 $\pm$ 0.3 | 3.3$^b$ $\pm$ 0.2 | $-0.1 \pm 0.1$ | 0.4 | 2300 | $\pm 350$ |

**Notes.** In the table, $S_{330}$, $S_{843}$, $S_{1400}$, and $S_{4800}$ denote the flux densities at 330, 843, 1400, and 4800 MHz, respectively. $\alpha_{1000}$ is the observed spectral index between 1.4 GHz and 843 MHz (H\textsc{ii} region) or 1.4 GHz and 330 MHz (shell). $\tau_{330}$ is the optical depth at 330 MHz.

$^a$ $-1.1 \pm 0.1$ Jy with emission from the eastern part of shell.

$^b$ Estimated assuming the shell is at the center of the diffuse H\textsc{ii} region.

$^c$ Estimated assuming the G354.4+0.0 shell is in front of the diffuse emission.

$^d$ Estimated assuming the G354.4+0.0 shell is behind the diffuse emission.

### Figure 3

![Figure 3](image_url)

**Figure 3.** Fit of Equation (5) ($f(x)$) to the flux densities of the diffuse H\textsc{ii} region at different frequencies (cross signs), assuming that the shell is at the center of the diffuse emission. Also plotted are the flux densities of the G354.4+0.0 shell (with solid squares) scaled by a factor of four. Its flux densities at 843 MHz and 4.8 GHz are only estimates and are shown with no error bar.

### 3.2.1. The G354.4+0.0 Shell at the Center of the Diffuse H\textsc{ii} Region

From the plot of the flux densities of the shell and the diffuse emission (Figure 3), we note the slopes of their flux densities between 1.4 GHz and 330 MHz are very different. This result indicates that the shell-type object and the diffuse emitting region are two different objects. When the shell is at the center of the H\textsc{ii} region, its emission undergoes absorption by the diffuse H\textsc{ii} region at 330 MHz and the intrinsic spectral of the shell is steeper than the observed one, as given by Table 1. By assuming the diffuse emission to be optically thin ($\tau \ll 1$) at 843 MHz and above, and an intrinsic spectral index of $-0.5$ for the shell (typical for a shell-type SNR; Green 2009), we estimate its flux densities at 843 MHz and 4.8 GHz from its measured flux density at 1.4 GHz. The estimated flux densities are then subtracted from the total measured flux densities of the complex at the above two frequencies to obtain the flux densities of the diffuse emission.

If we know the distance to the H\textsc{ii} region, $T_{gb}$ could be estimated from our measured temperature of $T_{gf} = 700$ K toward G354.4+0.0. Here, we assume that the shell structure and the diffuse H\textsc{ii} region are located nearly at the distance of the GC, but on the near side of the GC (discussed in detail.
in Section 3.3). Due to the expected high density of massive stars in the GC region, it is likely that most of the Galactic non-thermal emission is generated in the region. Therefore, we assume $T_{gb} = T_{gt}$, and scale the value of $T_{gt}$ as a function of frequency ($T_{gt} = 35 \times \nu^{-2.7}$). The flux densities of the diffuse emission as a function of frequency are well fit by Equation (5) (see Figure 3), with a reduced $\chi^2$ of 0.7. From the fitted parameters, the emission measure and the electron temperature of the H ii region are $1.7 \pm 0.09 \times 10^4$ cm$^{-6}$ pc and 2300 $\pm$ 350 K, respectively. Assuming the source to be spherical and located at the distance of the GC (8 kpc), the path length through the source (4') is about 9 pc. Consequently, the electron density in the diffuse emitting region is estimated to be $44 \pm 1$ cm$^{-3}$. This gas will have a $\tau$ of about 0.4 at 330 MHz.

Given the relative location of the shell with respect to the diffuse emission, the emission from the shell would undergo free–free absorption with $\tau$ being half of that of the ionized gas and $\sim$20% of its emission would be absorbed at 330 MHz. Moreover, its brightness temperature and consequent flux density would be underestimated in Table 1 due to high background. Moreover, its brightness temperature and consequent flux density of large-scale diffuse Galactic emission (Equation (4)). Given the angular cross-section used (4.4 arcmin$^2$) to measure the flux density, the optical depth toward the shell at 330 MHz is significantly with changes in the flux densities of the shell (quite small with respect to the H ii region) at 843 MHz and 4.8 GHz. The optical depth toward the shell at 330 MHz is about 0.4 (Section 3.2.1). Based on its 1.4 GHz flux density and underestimation of its flux density at 330 MHz due to large-scale Galactic plane emission, as discussed earlier, its spectral index is estimated to be $-0.6$. By using its flux density at 1.4 GHz and the spectral index, we estimate its flux densities at 4.8 GHz and 843 MHz, which are then subtracted from the corresponding total flux densities of the complex to obtain the flux densities of the diffuse H ii region at the two frequencies (Table 1). A fit of Equation (5) to the set of flux densities showed that the emission measure and the electron temperature remained the same as in Section 3.2.1 within their errors.

3.2.3. The G354.4+0.0 Shell behind the Diffuse H ii Region

If the SNR is located behind the H ii region, the absorption of the shell emission would be more than the case when it was assumed to be at the center of the H ii region. At 843 MHz and 4.8 GHz, only the total flux densities of the complex are available, and the flux densities of the diffuse H ii region were computed by subtracting the flux density of the shell with an assumed spectral index of $-0.5$. In the present case, we assume that the properties of the diffuse H ii region do not change significantly with changes in the flux densities of the shell (quite small with respect to the H ii region) at 843 MHz and 4.8 GHz. The optical depth toward the shell at 330 MHz is about 0.4 (Section 3.2.1). Based on its 1.4 GHz flux density and underestimation of its flux density at 330 MHz due to large-scale Galactic plane emission, as discussed earlier, its spectral index is estimated to be $-0.6$. By using its flux density at 1.4 GHz and the spectral index, we estimate its flux densities at 4.8 GHz and 843 MHz, which are then subtracted from the corresponding total flux densities of the complex to obtain the flux densities of the diffuse H ii region at the two frequencies (Table 1). A fit of Equation (5) to the set of flux densities showed that the emission measure and the electron temperature remained the same as in Section 3.2.1 within their errors.

3.3. Distance from H i Absorption

To measure the distance to the shell-type object G354.4+0.0, we plot in Figure 4 the H i spectrum toward this object. Strong absorption is seen near 0 km s$^{-1}$ that is believed to be caused by local gas rotating almost perpendicular to our line of sight seen near the direction of the GC. H i absorption is also seen near $-40$ and $-80$ km s$^{-1}$. The line of sight velocity of the 3 kpc arm at the longitude of this SNR is about $-80$ km s$^{-1}$ (Cohen & Davies 1976). The presence of absorption by this feature shows that the distance of G354.4+0.0 from the Sun is at least 5 kpc. We also examined the H i absorption spectrum of a few sources in the field and the spectrum of the brightest small diameter source (peak flux density 0.49 Jy beam$^{-1}$) with R.A. = $17^h31^m20^s.7$, decl. = $-33^\circ53'25''$ (J2000) is shown in Figure 5. We will henceforth call this object source A. Compared to Figure 4, this

![Image](46x56.png)  
**Figure 4.** H i absorption spectrum toward G354.4+0.0. The velocity resolution 6.7 km s$^{-1}$.

![Image](46x56.png)  
**Figure 5.** H i absorption spectrum toward the field H ii region A (see text for details).
object shows a much wider absorption profile between +15 and −40 km s⁻¹, suggesting that source A is much further away than G354.4+0.0. The flux density of source A is found to decrease by more than a factor of four between 1.4 GHz and 330 MHz, indicating that source A is a compact H II region. It is likely that source A is located on the other side of the Galaxy. Based on the above arguments, it is likely that G354.4+0.0 is located at a distance between 5 kpc and the GC distance of 8 kpc.

4. DISCUSSION

From the above, the morphology of object G354.4+0.0 is found to be a partial shell. It shows polarized emission, and after corrections for the sky background temperature, the spectrum of the shell is found to be steep. This result holds irrespective of whether it is at the center, in front of, or behind the H II region. The polarized emission, along with the inferred steep spectrum, is indicative of synchrotron emission from the shell. Therefore, based on its shell-type morphology and its synchrotron emission, the shell-type source G354.4+0.0 is classified as a newly discovered SNR. It is also expected to emit in X-rays, but no counterpart is known in that band. The surface brightness of the shell at 1 GHz is about \(6 \times 10^{-20} \text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}\), comparable to the youngest SNR G1.9+0.3 (Green & Gull 1984). The orientation of magnetic fields in young SNRs is typically radial (Milne 1987). Therefore, the polarization vectors representing the electric field direction in Figure 1 should be cross-radial or tangential to the shell in the absence of any Faraday rotation. We note the resolution of the NVSS (45") is not much smaller than the size of the shell. This fact causes smearing of any change of the polarization vectors with change in position on the shell. From Figure 1, we note the polarization vectors in the northern part of the shell lie along the shell, while only a fraction of the polarized vectors in the southern part lie along the shell. Assuming that the magnetic field strength in the diffuse H II region is typical of the interstellar medium (ISM) value of \(~10 \mu \text{G}\) and the SNR at the center of the H II region, given the electron density and the path length through the ionized gas, any polarized emission from the SNR would undergo Faraday rotation by \(~60\) rad at the observed wavelength of the NVSS. Faraday rotation toward the northern part need to be \(n \pi r\) rad (where \(n\) is an integer) to explain the observations. It is possible that the Faraday rotation toward the southern part of the shell is slightly different from that of the northern part of shell, and that this result causes a change in the direction of the observed polarization vectors from the tangential direction of the shell. Future polarization observations at three or more frequencies with high angular resolution will be able to measure Faraday rotation accurately and could show whether the shell lies inside of or in front of the H II region.

4.1. Evolutionary Phase of the SNR and Its Age

If the SNR is located outside the H II region, it is then expanding in the typical ISM. Given the assumed distance and the angular size of the remnant, it will be in the free expansion stage. Hence, the structure of the shock front and the corresponding shock acceleration of energetic particles would not depend significantly on the structure of the ISM into which it is expanding. Therefore, the synchrotron emission from the shell should roughly be circularly symmetric. However, the shell appears fragmented toward the east, and only some parts of it are seen in Figure 1. This outcome is possible if the shell is no longer in the free expansion stage. Given the angular size and the distance to the SNR (~8 kpc), its linear diameter is about 3.7 pc. If it is within the dense H II region, given its \(n_e\), the SNR has swept up about 20 \(M_\odot\) of material from the surrounding ISM during its expansion. The kinetic energy of ejecta from a supernova explosion lies in the range of \(~10^{51}–10^{52}\) erg (Woosley & Bloom 2006). Depending on the type of explosion, the ejecta mass varies from \(~0.4 M_\odot\) (type Ia; Stritzinger et al. 2006) to ~20 \(M_\odot\) (core collapse; Taddia et al. 2012). As the mass of the swept up material in this case is comparable to or more than the typical ejected mass from supernova explosion, there will be an appreciable slowdown of its expansion. This phase of expansion is known as the adiabatic phase (Weiler & Sramek 1988), and, given the morphology discussed above, the SNR is likely expanding in an environment denser than the ISM. Assuming energy conservation between the supernova ejecta and the swept up material and given the range of initial ejecta mass, the age of the SNR can be estimated from the numerical integration of \(dr/\sqrt{r}\), considering that its slowdown is due to expansion in the dense environment. The range of ages possible for this remnant is ~100–500 yr. We note that the \(T_e\) of 2300 K determined in Section 3.2 is low for a typical H II region; more common values are 5000–10,000 K. However, a warm ionized medium (WIM) with a temperature of 3000 K has been reported (Dobler et al. 2009) and an unstable WIM can reach temperatures much lower (Dong & Draine 2011). Moreover, averaging the flux densities within the angular size of the source with the likely spatial variation of the electron density leads to an understimation of the source temperature (Rubin 1969). Even if we assume \(T_e\) is a factor of three higher (7000 K), as the estimated value of \(n_e\) is mainly dependent on higher radio frequency emission (\(\geq 1\) GHz), and \(n_e\) will only increase by a factor of 1.2. This result does not significantly change the evolutionary phase of the SNR.

If a pulsar was created during the supernova explosion, given their typical velocities of a few hundred km s⁻¹ (Motch et al. 2009), it would be seen within \(~10^\circ\) of the center of the remnant. However, no pulsar is known within several arcminutes of the object. This result could be caused by (1) a type-Ia explosion that does not leave behind any neutron star, (2) lack of a beaming of any pulsar in the region toward us, or (3) lack of a sensitive survey with suitable dispersion of the pulses at the right dispersion measure (DM) (the diffuse H II region itself would contribute a DM of about 400 cm⁻³ pc).

4.2. Surface Brightness and Expansion of G354.4+0.0 in the Dense Medium

When an SNR expands inside a dense ISM, it is expected to be brighter. For example, in M82, where emission measures of foreground gas toward the SNRs in that galaxy are about four orders of magnitude higher than that of the medium around the G354.4+0.0 shell (McDonald et al. 2002), the typical surface brightness of SNRs of the diameter of G354.4+0.0 are a few hundred times more (Urošević et al. 2005). In our Galaxy, such a brightening has also been observed for SNRs interacting with molecular clouds (Pavlović et al. 2013). However, the particle density in the diffuse H II region is much less than that of typical molecular clouds and that fact may explain why this SNR is not that bright. Moreover, there is more than an order of magnitude spread of surface brightness from what is predicted by the surface brightness–diameter relation of SNRs (Pavlović et al. 2013). The surface brightness of G354.4+0.0 compares well with that of CTB 33 (G337.0–0.1) in our Galaxy expanding in a dense environment (Pavlović et al. 2013).
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