THE ENORMOUS OUTER GALAXY H\textsc{ii} REGION CTB 102

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Received 2008 October 17; accepted 2009 May 27; published 2009 July 7

ABSTRACT

We present new radio recombination line observations of the previously unstudied H\textsc{ii} region CTB 102. Line parameters are extracted and physical parameters describing the gas are calculated. We estimate the distance to CTB 102 to be 4.3 kpc. Through comparisons with H\textsc{i} and 1.42 GHz radio continuum data, we estimate the size of CTB 102 to be 100–130 pc, making it one of the largest H\textsc{ii} regions known, comparable to the W4 complex. A stellar wind blown bubble model is presented as the best explanation for the observed morphology, size, and velocities.

Key words: H\textsc{ii} regions – ISM: bubbles – ISM: individual (CTB 102) – radio lines: ISM

1. INTRODUCTION

The radio bright outer Galaxy region CTB 102 (\(\ell = 93:060, b = +2:810\)) was first cataloged by the Wilson \& Bolton (1960) radio survey of the Galactic plane. The source is then mentioned in subsequent Galactic radio surveys including Kallas \& Reich (1980), where it is identified as KR 1. Using radio recombination line (RRL) observations at \(\lambda\,3\,\text{cm}\), Lockman (1989) (H\(87\alpha\), \(\sim3'\,\text{beam}\)) identified the region as a H\textsc{ii} region with a line brightness of \(T_{\text{line}} = 18 \pm 1.3\ \text{mK}\), a velocity of \(V_{\text{LSR}} = -61.0 \pm 0.8\ \text{km\,s}^{-1}\), and a full width at half maximum (FWHM) of \(\Delta V = 22.9 \pm 1.9\ \text{km\,s}^{-1}\). Radio continuum images at 1.4 GHz and \(-1'\,\text{resolution}\) from the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003), show filamentary structures extending from a bright complex source. From the appearance of the structure and a kinematic distance estimate, the region appears to be a very large H\textsc{ii} region and a major feature in the Perseus spiral arm.

Yet this major Galactic region is unstudied. Suffering heavy extinction in this direction in the Galactic plane, there is no known optical counterpart to CTB 102. The purpose of this study is to determine the basic properties of CTB 102, mainly how large in physical size it is, and how it influences its Galactic environment. In this paper, we present new RRL observations toward CTB 102. RRL observations allow direct velocity measurements, and along with continuum observations will tell us the density and temperature of any gas in the beam at or near thermodynamic equilibrium.

2. OBSERVATIONS

RRL observations toward CTB 102 were performed with the 100 m NRAO Green Bank Telescope (GBT) during six nights in 2006, July 31, August 2–4, 15, and 17. Twelve pointings were observed around the CTB 102 complex. These telescope pointings are illustrated in Figures 1 and 3. Positions and total integration times for the chosen observations are given in Table 1, the observations themselves were divided into 600 s scans. RRLs observed were H103\(\alpha\) through H110\(\alpha\). A 50 MHz bandwidth receiver was used to allow the eight recombination lines to be simultaneously observed in the high end of the C-band (\(v = 4.8–5.9\ GHz\)). Both polarizations were admitted, and the spectrum consists of 4096 channels (0.62–0.75 km s\(^{-1}\) per channel). System temperatures ranged from 19–26 K, depending mainly on the elevation of the source. Average system temperatures for each observation are given in Table 1. As a check of the system’s ability to record RRL emission, the bright “head” of CTB 102 at \(\ell = 93:115, b = +2:835\), hereafter CTB102p, was observed for 600 s at the beginning of each session.

3. DATA REDUCTION

None of the eight 50 MHz bands were seriously affected by radio frequency interference. Frequency-switched scans in each linear polarization (YY, XX) were folded individually; since frequency switching was done in-band (\(\pm12.5\ MHz\)), we doubled our effective integration time. Each 600 s scan contains 16 spectra. To assure that no line structure (e.g., very extended wings from outflows) is removed, velocities forbidden by Galactic rotation (typically \(-300\ \text{km\,s}^{-1} \leq V_{\text{LSR}} \leq -130\ \text{km\,s}^{-1}\) and \(+30\ \text{km\,s}^{-1} \leq V_{\text{LSR}} \leq +200\ \text{km\,s}^{-1}\)) define a range of baseline velocities. For each of the 16 spectra in every scan, a baseline was determined using a fourth order polynomial fitted to the range of baseline velocities. This fitted baseline was then subtracted from every spectrum in each scan. After baseline subtraction, the spectra in the individual scans are combined (for every velocity channel, intensity values are summed up and then divided by the number of scans) to create averaged spectra, one for each line and polarization. At this point in the reduction process, there are 16 spectra (H103\(\alpha\) XX, H103\(\alpha\) YY, H104\(\alpha\) XX, etc.) for every observation in Table 1.

These averaged spectra were re-gridded to a common channel width (0.67 km s\(^{-1}\)) and smoothed to a common velocity resolution (1.5015 km s\(^{-1}\)). Typically 4–10 of these averaged spectra do not show residual wavy baselines in regions of no RRL signal. The only exception is H110\(\alpha\) (polarization XX), which shows a very wide “bump” in the spectrum centered around \(-200\ \text{km\,s}^{-1}\), extending into the region of the RRL signal. This line and polarization is completely excluded from the analysis. To reduce noise, composite spectra, one for each filament, are made by combining the averaged spectra that do not show residual wavy baselines. The composite spectra typically have a noise level of \(\Delta T_{\text{rms}} \lesssim 1\ \text{mK}\) (antenna temperature).

Since RRLs are expected to be quite wide (25–30 km s\(^{-1}\)); Lockman (1989), a spectral resolution of 1.5 km s\(^{-1}\) is unnecessary fine. A higher signal-to-noise ratio (S/N) can be achieved without loss of information by moderate smoothing of the composite spectra, although too much will add an artificial width to
spectral lines present. We conservatively choose a resolution of 3.0 km s$^{-1}$.

4. RRL RESULTS AND ANALYSIS

To our final smoothed composite spectra, Gaussians are fit to obtain spectral line parameters: line amplitude ($T_l$), central velocity ($V_{LSR}$), and FWHM ($\Delta V$). Smoothed spectra and the Gaussian fits are shown in Figure 2 and the obtained parameters are presented in Table 2. Note that antenna temperature has been divided by the beam efficiency, $\eta_b = 0.92$ for the GBT at 5 GHz, to convert to brightness temperature. The uncertainties in Table 2 are obtained in Monte Carlo fashion. To the originally obtained Gaussian fit, randomly drawn noise from a normal distribution with the same standard deviation as the previously obtained $\Delta T_{rms}$ is added. A new Gaussian is then fitted to the generated spectrum and its parameters stored. After 1000 repetitions, the standard deviation of the distributions of spectral line parameters is combined with the mean fit uncertainties to produce the total uncertainties. Figure 3 displays the observed velocities of the filaments/objects, overlaid on a CGPS 1.42 GHz continuum image.

4.1. Velocities

This study finds that the bright radio source CTB102p has a velocity of $V_{LSR} = -62.66 \pm 0.05$ km s$^{-1}$, which is 1.7 km s$^{-1}$ less than the value in Lockman (1989). The difference is probably due to the difference in pointing position, as well as the difference in telescope beam size between the studies.
Table 2: Observed Line Parameters

| Filament/ | R.A. Decl. | $\Delta T_{\text{rms}}$ | $V_{\text{LSR}}$ | $\Delta V$ | $V - V_{\text{ref}}$ |
|----------|------------|----------------|-----------------|-------------|-----------------|
| Object   | (h m s)    | (° ) | (° ) | (mK) | (km s$^{-1}$) | (km s$^{-1}$) |
| CTB102p  | 21 12 28.9 | 52 32 23 | 93.115 2.835 | 3600 | 23.7 |
| 2        | 21 01 0.25 | 50 17 | 90.725 2.955 | 30000 | 21.9 |
| 4        | 21 05 19.1 | 52 17 01 | 92.185 0.346 | 14400 | 21.3 |
| 5        | 21 05 56.4 | 51 52 | 91.950 0.312 | 15000 | 21.0 |
| 6        | 21 07 14.6 | 52 07 03 | 12.600 0.315 | 10200 | 21.1 |
| 7        | 21 10 48.6 | 51 55 | 92.495 0.205 | 3000 | 22.4 |
| 8        | 21 13 59.6 | 52 15 09 | 92.065 0.247 | 2400 | 23.0 |
| KR 6     | 21 10 01.0 | 50 22 26 | 94.400 0.260 | 2000 | 23.5 |
| NRAO 652 | 21 01 22.6 | 52 22 | 92.688 0.306 | 600 | 23.9 |

Table 3: Derived Parameters

| Filament/ | $T_D$ | $T_r$ |
|----------|-------|-------|
| Object   | (K)   | (K)   |
| CTB102p  | 7400  | 5200  |
| 2        | 4200  | 3400  |
| 4        | 21000 | 5300  |
| 5        | 9800  | 6000  |
| 6        | 14400 | 5000  |
| 7        | 11600 | 5000  |
| 8        | 10000 | 8300  |
| 9        | 13800 | 7900  |
| 10       | 8600  | 7700  |
| KR 6     | 13400 | 8100  |
| NRAO 652 | 5600  | 5800  |
| WB 43    | 15100 | 6000  |
| WB 43    | 5200  | 5500  |

Notes. Derived parameters for each filament observed. The uncertainties in $T_D$ are 1$\sigma$ uncertainties. The listed uncertainties in $T_r$ comes from considering uncertainty in the background estimate, 0.5 K. The total uncertainty in $T_r$ are for the GBT observations.

4.2. Line Widths & Electron Temperatures

The majority of FWHMs in this study fall between 20 km s$^{-1}$ and 26 km s$^{-1}$, which is typical for dense H II regions (Lockman 1989).

The line width of a RRL depends on mainly two things, thermal motion, which is described by the electron temperature ($T_e$), and microturbulence. Both of these processes produce Gaussian profile shapes, so a Doppler temperature ($T_D$), which provides an upper limit to the true electron temperature, can be adopted as follows (Rohlfs & Wilson 2004):

$$\Delta V = 0.21T_D^{1/2},$$

where $\Delta V$ is the observed FWHM in km s$^{-1}$ from Table 2, and $T_D$ is the Doppler temperature in km s$^{-1}$.

The LTE electron temperature can be calculated using the line to continuum brightness ratio

$$T_e = \frac{\Delta V}{(v/v)_{\text{GHz}}} \left( \frac{1}{a(v, T_e)} \right) \left( \frac{1}{N_{\text{He}}/N_{\text{H}}} \right)^{1.15} \times 1 + N_{\text{He}}/N_{\text{H}},$$

where $a(v, T_e)$ is a factor which depends on the optical depth of the line, and $N_{\text{He}}/N_{\text{H}}$ is the ratio of the column densities of helium and hydrogen. The parameters derived for each filament/object are in Table 3. The $T_e$ is quite sensitive to the estimated background temperature, especially when the peak brightness temperature is barely above the background. Note that $T_D > T_e$ within the 1$\sigma$ uncertainty in all cases. $T_D$ provides a useful upper limit to $T_e$ in case the uncertainty in $T_e$ is large. These derived parameters for the ionized gas gives an average LTE electron temperature of $\sim 6 \times 10^3$ K. This value

Notes. Positions are J2000. Integration times and average system temperatures are for the GBT observations.

The velocity of CTB102p is hereafter referred to as $V_{\text{ref}}$. One purpose of this study is to find out the size of CTB 102, i.e., are the filaments and objects we see around CTB 102 at the same distance? The velocity gradient (for a flat rotation curve with $R_G = 8.5$ kpc and $V_G = 220$ km s$^{-1}$) in this part of the Galaxy is $\sim 10$ km s$^{-1}$ kpc$^{-1}$. Looking at the last column of Table 2, most filaments and objects have a $|V - V_{\text{ref}}| < 6$ km s$^{-1}$, so it seems likely that the CTB 102 complex and objects KR 4, KR 6, and NRAO 652 are in the same part of the Galaxy. In contrast, WB 43 ($\sim 0.8$ km s$^{-1}$) is clearly a local H II region, and in no way connected to the CTB 102 complex (Figure 2). Filament 2 is another possible unrelated object (see Section 7), its velocity ($\sim 78.4$ km s$^{-1}$) deviates the most from the velocity of CTB102p, $|V - V_{\text{ref}}| \sim 16$ km s$^{-1}$, and is $\sim 10$ km s$^{-1}$ less than any other velocity observed in this study. Computing the average absolute difference for all observations (except WB 43) yields a result of 6.6 km s$^{-1}$, but excluding filament 2 from the average, the value drops to 4.3 km s$^{-1}$. The continuum brightness temperature provides an upper limit to the true electron temperature, can be adopting as follows (Rohlfs & Wilson 2004):
falls within the typical range of electron temperatures for \( \text{H} \text{II} \) regions.

We note the FWHM of CTB102p determined in this study, \( \Delta V = 18.34 \pm 0.08 \text{ km s}^{-1} \), is 4.6 km s\(^{-1}\) less than the value for \( \Delta V \) in Lockman (1989). Again, the difference is probably due to the difference in beam size and pointing position.

5. DISTANCE

With the majority of the filaments’ velocities found to be very similar to that of the central body, the whole CTB 102 complex subtends about one to two degrees of sky. Its distance would be able to tell us how far across its influence extends across the outer disk. Here, we provide the first ever distance estimate for this \( \text{H} \text{II} \) region.

To begin with, Figure 4 shows a latitude-velocity slice in the direction \( \ell \sim 93.6 \), taken from the 26 m telescope survey of Galactic plane \( \text{H} \text{I} \) (Higgs & Tapping 2000). Extensive intermediate velocity (\( −90 \leq V_{\text{LSR}} \leq −20 \text{ km s}^{-1} \)) \( \text{H} \text{I} \) is seen extending from \( −2 \circ \leq b \leq +5 \circ \) in latitude. The \( \text{H} \text{I} \) beyond \( V_{\text{LSR}} < −20 \text{ km s}^{-1} \) appears split into three blended concentrations. The lower-latitude concentration at \( b = 0 \circ \) and \( V_{\text{LSR}} = −44 \text{ km s}^{-1} \) blended together with the concentration near \( b = +1.4 \circ \) at \( V_{\text{LSR}} = −68 \text{ km s}^{-1} \) are contemporarily taken together to form the Perseus \( \text{H} \text{I} \) arm (see Roberts 1972, for example). The outer arm is the smaller oblong \( \text{H} \text{I} \) feature up at \( b = +3.6 \circ , V_{\text{LSR}} = −82 \text{ km s}^{-1} \), which is also blended with the upper-latitude portion of the Perseus arm.

As seen in the top panel of Figure 4, the contemporary Perseus arm exhibits a very substantial tilt in latitude toward negative velocities. This is known as the “rolling” motion in this arm. As well, the splitting of the \( \text{H} \text{I} \) Perseus arm into two concentrations has been explained by a spiral shock (Roberts 1972) which is thought to precede the arm. However, an alternative explanation for the \( \ell , b , V \) structure in the \( \text{H} \text{I} \) suggests that there are actually three spiral arms beyond \( −25 \text{ km s}^{-1} \) (e.g., Vallée 2008; Kimeswenger & Weinberger 1989); the Perseus arm (centered at \( b , V_{\text{LSR}} = 0 \circ , −44 \text{ km s}^{-1} \)), the Cygnus (= outer) arm (\( +1.4 \circ , −68 \text{ km s}^{-1} \)), and the “Far” outer arm up at \( b = +3.6 \circ \). In this three-arm interpretation, the Perseus and Cygnus arms have more reasonable moderate rolling gradients (\( dV/db \sim −2 \text{ km s}^{-1} \) per degree). The Cygnus arm appears at higher latitudes than Perseus since it lies further into the upwardly warped outer Galactic disk.

The systemic velocity estimated for CTB 102 in \( \text{H} \text{I} \) (\( ⩾ −58 \text{ km s}^{-1} \); see Section 7) and its latitude (\( b = +2.8 \circ \)) place it somewhat in the middle of the contemporary Perseus arm, in an \( \text{H} \text{I} \) “wall” that connects the two brighter concentrations. In \( b , V \) plots (Figure 4, top), CTB 102 is situated between the two major \( \text{H} \text{I} \) concentrations, and in the three-arm picture above it is not clear in which spiral arm it resides. In \( \ell , b \) maps (Figure 4, bottom) a “mushroom-cap”-like feature centered on CTB 102’s coordinates (\( \ell = 93.2 \circ , b = +2.8 \circ , V_{\text{LSR}} = −58 \text{ km s}^{-1} \)) appears as a “blister” off of the top of the extensive \( \text{H} \text{I} \) arm at \( b = +2 \circ \). As well, in an \( \ell , V \) plot of \( 80 \circ \leq \ell \leq 110 \circ \) (Figure 4, center) this cap is seen as a finger-like extension off of the Cygnus \( \text{H} \text{I} \) arm, centered at \( V_{\text{LSR}} = −57 \text{ km s}^{-1} \) extending down to \( −47 \text{ km s}^{-1} \). It has the appearance of either an upper-latitude extension to the Perseus arm (up to \( b = +3.8 \circ \)), or a blended \( \text{H} \text{I} \) concentration (possibly the wall of an expanding bubble) extending off the Cygnus arm to more positive velocities. A distance to the Perseus arm in this direction then forms a good estimate for at least a lower-limit distance to CTB 102.

Figure 4. Three views of the large-scale \( \text{H} \text{I} \) environment near CTB 102, taken from the 36’ resolution 26 m DRAO \( \text{H} \text{I} \) survey. Top: \( T_B (b, V) \) (latitude-velocity) centered on \( \ell = 93.6 \circ \). Center: \( T_B (\ell, V) \) (longitude-velocity) centered on \( b = +2.8 \circ \). Bottom: \( T_B (b, \ell) \) (longitude-latitude) centered at \( V_{\text{LSR}} = −58 \text{ km s}^{-1} \). The position \( \ell , b , V \) of CTB 102 is marked with the star symbol in each slice. Brightness-temperature contours in each panel are at 40, 54, 65, and 80 K. CTB 102 appears associated with \( \text{H} \text{II} \) that could either be a high-latitude extension of the Perseus spiral arm (centered at \( −44 \text{ km s}^{-1} \)) pushed to negative velocities by the “rolling” motion in the arm, or part of a low-velocity extension of \( \text{H} \text{II} \) from the Cygnus spiral arm (up to \( −68 \text{ km s}^{-1} \)), either of which could be part of a very large \( \text{H} \text{II} \) bubble expanding away from its parent arm.

The velocity of CTB 102 (\( V_{\text{LSR}} \sim −58 \text{ km s}^{-1} \)) indicates a rather large kinematic distance of 6.8 kpc, assuming a flat rotation curve with \( R_0, \Omega_0 \sim 7.6 \text{ kpc}, 28 \text{ km s}^{-1} \text{ kpc}^{-1} \) (see, e.g., Kothes & Dougherty 2007). However, this assumes that the systemic \( V_{\text{LSR}} \) derives only from the projection onto the line of sight of the object’s Galactic circular motion. Being near a major spiral feature of the Galaxy, CTB 102 is likely influenced by gravitational forces from the stellar component of the arm, so its velocity is likely tainted with non-circular motions such as
those from the “rolling” motions in the arms (velocity gradients perpendicular to the plane), and streaming motions from the gravitational influence of density waves.

A new kinematic-based distance method that accounts for non-circular streaming motions due to a two-armed density wave has been developed by Foster & MacWilliams (2006). The approach is to model the Galactic H$^\text{I}$ distribution and rotation curve by fitting an empirical model of Galactic structure and density-wave motions to the observations, rather than just assuming a purely circular model. The model assumes that only two arms are present in the second quadrant, arranged as a two-armed density wave pattern. We model a direction near to $b = 0^\circ$ to ensure that velocity gradients with latitude (i.e., rolling motions, which are not accounted for in Foster & MacWilliams 2006) are not included. The “rolling” gradient of the H$^\text{I}$ Perseus arm observed toward CTB 102 is $dV/db \approx -2$ km s$^{-1}$ per degree of latitude; corrected for this latitude gradient, CTB 102’s systemic velocity is $V_{\text{LSR}} \approx -52$ km s$^{-1}$. The velocity field of the best-fitting H$^\text{I}$ model in the direction $\ell = 92.4^\circ, b = -0.2^\circ$ is shown in Figure 5. In this direction, only the Perseus arm is seen along the line of sight. The model shows the Perseus Arm gaseous density peak (associated with the spiral shock) to be 4.3 kpc distant from the Sun in this direction. The velocity field is ambiguous between $-55 \lesssim V_{\text{LSR}} \lesssim -44$ km s$^{-1}$ due to the shock, so the heliocentric distance to CTB 102 ($V_{\text{LSR}}^{\text{corr}} = -52$ km s$^{-1}$) is either 4.3 kpc or 5.8 kpc.

A simple line of reasoning will show that $r = 5.8$ kpc is probably not the true distance to CTB 102. Supposing that it is, then for $\ell = 93^\circ$ the Galactocentric distance to CTB 102 is $R = 10.1$ kpc (for $R_0 = 8$ kpc), and in this direction the Perseus arm shock (which defines where the arm is) is 9.3 kpc from the center. By assuming the arm is a logarithmic spiral with pitch angle $12^\circ$, one finds the intersection of a 10.1 kpc radius circle with the shock at a current position of $\phi \approx 5^\circ$ (here $\phi$ is Galactocentric azimuth, defined as zero from the Galactic center to the Sun and related to longitude $\ell$ by $\sin \phi = (r/R) \sin \ell$; hence $\phi$ is positive in the 2nd quadrant of longitude). Thus the stars have since migrated some $\Delta \phi \sim 30^\circ$ beyond the arm (their formation place) to their current position $R, \phi = 10.1$ kpc, $35^\circ$. How long has it taken them to move this 30$^\circ$ angular distance? For “flat” circular rotation the angular velocity of CTB 102 is $\Omega = 220/10.1 = 21.8$ km s$^{-1}$ kpc$^{-1}$. A reasonable pattern speed for the Perseus arm is $\Omega_p = 15$ km s$^{-1}$ kpc$^{-1}$, a mean between modern estimates near 20 (e.g., Martos et al. 2004) and older estimates near 11 (e.g., Roberts 1972) for the Milky Way’s spiral pattern. Then the time it took the system to migrate $\Delta \phi$ from the arm at angular rate $\Omega - \Omega_p$ (the relative angular velocity with respect to the arm) is $t = \Delta \phi/(\Omega - \Omega_p) = 75$ Myr. If the massive stars in CTB 102 formed from the compression of the shock, then by now the only ones left would be those that live longer than 75 Myr, or stars of $\gtrsim 7 M_{\odot}$ (B5V types, for example). A cluster of hundreds of such stars would be needed to power CTB 102 ($U = 112$ pc cm$^{-2}$; see Section 6.1). It is highly unlikely that CTB 102 contains stars later than B5 only. It is more likely that CTB 102 lies near to the arm/shock, which is 4.3 kpc distant in this direction.

The uncertainty in this estimate is $\pm 20\%$, from the variation of best-fitting models of the same direction and in models fitted to several immediately adjacent directions (see Foster & MacWilliams 2006). This agrees with stellar distances of the nearby optically brilliant H$^\text{II}$ regions Sh2–124 ($\ell, b = 94.6^\circ, -1.5^\circ$, $V_{\text{LSR}} = -44$ km s$^{-1}$, $r = 3.6 \pm 0.6$ kpc) and Sh2–132 ($\ell, b = 103^\circ, -0.8^\circ$, $V_{\text{LSR}} = -49$ km s$^{-1}$, $r = 3.5 \pm 0.9$ kpc), both of which are Perseus arm objects ($^{12}\text{CO}$/H$^\text{I}$-based velocities and spectrophotometric distances to 100 sharpless objects in the second quadrant are forthcoming in Foster et al. 2009).

We note that CTB 102 and filaments may instead be kinematically associated with the Cygnus spiral arm, participating in an extensive star formation group along with H$^\text{II}$ region NRAO 655 ($V_{\text{LSR}} \approx -70$ km s$^{-1}$; Foster & Routledge 2001) and SNR 3C434.1 ($V_{\text{LSR}} \approx -80$ km s$^{-1}$; Foster et al. 2004). This would extend its distance estimate here by a factor of 1.6, since the mean stellar distance to Cygnus arm H$^\text{II}$ regions between $90^\circ \leq \ell \leq 100^\circ$ (Sh2–121, BFS 8, Sh2–128, BFS 10, and DA 568) is $r \approx 7.0$ kpc.

### 6. RADIO CONTINUUM ANALYSIS

Radio continuum measurements of H$^\text{II}$ regions can provide a lower limit on the total number of ionizing photons ($N_L$) and estimates of the average excitation parameter ($U$). Assuming a optically thin, spherical, constant-density H$^\text{II}$ region, the equations used are (Rudolph et al. 1996),

$$N_L = 7.5 \times 10^{43} S_\nu d^2 v^{0.1} T_e^{-0.45} \text{ s}^{-1},$$

$$U = 1.33 S_\nu^{1/3} d^{2/3} v^{1/30} T_e^{0.116} \text{ pc cm}^{-2},$$

where $\nu$ is the frequency in GHz, $S_\nu$ is the flux density measured at frequency $\nu$ in mJy, $d$ is the distance to the source in kpc, and $T_e$ is the electron temperature in units of $10^4$ K. Parameter values used are $\nu = 1.42$ GHz, $d = 4.3$ kpc, and $T_e = 10000$ K. Since none of the parameters are very sensitive to $T_e$, and the uncertainties in Table 3 are large, a general value of $10^4$ K is used (Rudolph et al. 1996).

The flux density for the considered region is obtained from the CGPS continuum image by using the Dominion Radio Astrophysical Observatory (DRAO) sofware imview. A polygon incorporating the region of interest is drawn by eye. The polygon’s perimeter defines the background and a twisted plane is fitted...
to estimate the background. The flux density with the estimated background subtracted is then used to compute the parameters $N_L$ and $U$. The biggest contribution to the uncertainty is where to draw the polygon around the region of interest. To estimate this uncertainty, each flux measurement is done 10 times, each time with a new polygon drawn. The average value is used to compute the estimated parameters, and the standard deviation is used to estimate the uncertainty in the flux measurement.

6.1. CTB 102 Central Region

A representative polygon around the region of interest is shown in Figure 6, top. The flux density is measured 10 times with results ranging between 28.9 and 36.9 Jy. After subtraction of the flux density from the foreground source WB 43, the average value and 1σ uncertainty in the flux density is $31.3 \pm 2.5$ Jy, which gives a value of $N_L = (4.5 \pm 1.8) \times 10^{49}$ s$^{-1}$ and $U = 112 \pm 15$ pc cm$^{-2}$. Almost all the uncertainty in these values comes from the uncertainty in the distance. Comparing the values ($\log N_L = 49.7$) to Panagia (1973) suggests an ionizing flux and excitation parameter corresponding to a O5 V star. Comparing to Vacca et al. (1996) suggests an O4 V star. However, the 30 K contour in Figure 6 shows the brightest parts of CTB 102 being along an arc stretching from CTB102p toward filament 7 (i.e., toward smaller Galactic longitude and latitude). Given this continuum flux distribution, it is more likely that the ionizing flux comes from several stars. In summary, the estimates together with the morphology of the 1.42 GHz continuum emission, suggest that the CTB 102 complex is powered by at least several late-type O stars, maybe even an early-type O star (since $N_L$ is a lower limit).

6.2. Filament 10

Filament 10 looks strikingly circular in the 1.42 GHz continuum image (see Figure 6, bottom) with an angular diameter of $\sim 5\arcmin$, yielding a physical size of $\sim 6$ pc at a distance of 4.3 kpc. The intensity profile, with a rapid falloff at the edge, strongly suggests the region is ionization bound. As such this filament would not contribute ionizing photons to the larger complex. Drawing a circular polygon around filament 10 (average background $T_B \simeq 11.1$ K) yields $0.46 \pm 0.03$ Jy for the flux density (same method for uncertainty estimate as for the whole complex), giving $N_L = (6.6 \pm 2.6) \times 10^{47}$ s$^{-1}$ ($\log N_L = 47.8$) and $U = 28 \pm 4$ pc cm$^{-2}$. Comparisons suggest an O9.5 V (Panagia 1973) or an B0.5 V (Vacca et al. 1996) star ionizing the region. For this filament, a single star or a compact cluster of early-type B stars are ionizing the probably homogeneous interstellar medium (ISM), given the circular radio continuum profile.

7. DISCUSSION

This study was partly motivated by the appearance of the CTB 102 region in the 1.42 GHz continuum mosaic (Figure 1). Looking at Figure 3, one can make out the outline of a cone-shaped bubble. The radio brightness is concentrated along a ridge following an arc with a maximum at CTB102p. The arc goes toward filaments (in turn) 7, 6, 5, 4 and continues toward greater Galactic latitude, with faint filamentary structures around $b = +4^\circ$ eventually bending back toward greater Galactic longitude and then down. Within the arc, there appears to be a “cleared out” region extending from the central region of CTB 102 toward greater Galactic latitude and smaller Galactic longitude. The observed velocities for the filaments along this arc all fall within $\lesssim 11$ km s$^{-1}$ of the velocity of CTB102p, indicating that they at least are in the same part of the Galaxy. Taking the velocities and the 1.42 GHz continuum image together, it is likely that the CTB 102 complex includes filaments 7, 6, 5, and 4. Filament 2 is probably not part of the region, since its velocity deviates by 16 km s$^{-1}$, and no obvious association with the other filaments is seen in the radio continuum data. As will be discussed below, our model shows that filament 2 could not be powered by CTB 102.

With the inclusion of these filaments, the angular size of the CTB 102 H II region is $\sim 80\arcmin$, which corresponds to a physical size of $\sim 100$ pc at a distance of 4.3 kpc. Inclusion of filaments 8, 9, and 10, all within $\lesssim 6$ km s$^{-1}$ of CTB102p with apparent connections to CTB 102 in the 1.42 GHz image, increases the angular size of the H II to $\sim 100\arcmin$ or $\sim 130$ pc at 4.3 kpc. The objects KR 4, KR 6, and NRAO 652 have no obvious connection to the region in the radio data, and are probably H II regions which happen to be in the same part of the Galaxy as CTB 102.

If the assumption of the filaments being part of the structure is indeed correct, what sort of process would create such a big
H\textsc{ii} region? The typical sound speed in a H\textsc{ii} region is on the order of 10 km s\(^{-1}\), which is also the typical velocity associated with blister regions and champagne flows (Tenorio-Tagle 1982). This velocity corresponds to \(\sim 10 \text{ pc}/(10^6 \text{ yr})\). The velocity is consistent with the observed velocities in Table 2. However, to reach a radius of 50–65 pc \((2R = \sim 100 \text{ or } \sim 130 \text{ pc})\) would require a timescale of 5 to 6.5 million years (assuming constant expansion velocity). This timescale is longer than the main-sequence lifetime of an O5 V star, \(3.7 \times 10^6\) years (Schaller et al. 1992), but comparing CGPS 408 MHz and 1.42 GHz show no sign of a supernova in the CTB 102 region. Also, CTB 102 does not appear like a blister in the 1.42 GHz continuum image.

Rather, an alternative interpretation is the whole CTB 102 complex with its filaments is a combination of an H\textsc{ii} region with a bubble/chimney structure. A stellar wind from massive O star(s) creates a bubble in the ISM. Toward a region of the Galaxy with lower density (higher Galactic latitude) the expanding bubble has its top “blown off,” creating the possible chimney. Toward regions with higher densities, the expanding stellar wind bubble sweep up a shell of the ISM. The shell and left over neutral material is exposed to ultraviolet radiation from the O star(s), gets ionized and forms the H\textsc{ii} region.

What would be expected if this interpretation is correct? The H\textsc{i} structure would show a cavity in H\textsc{i}. In this picture, the expanding bubble sweeps up a shell of neutral material.

Figure 7. CGPS H\textsc{i} line images, averaged over three velocity channels to a width of 2.5 km s\(^{-1}\), centered on the velocities shown in each frame. The white contours correspond to 1.42 GHz continuum brightness temperature levels of 15 and 30 K. The white circles indicate the positions of the GBT pointings for filaments 4, 5, 6, and 7 (from Figure 1).
shell would be ionized from the inside of the bubble and if viewed through the edge, the increased path length would cause the shell to appear as neutral and ionized filaments. These H\textsc{i} and H\textsc{ii} filaments would have observed velocities which do not deviate too much from each other and from the velocity of the central region. Also, the ionized filaments would be expected to be located on the “inside” of the neutral filaments.

Support for the idea comes from viewing the H\textsc{i} structure in the region. Figure 7 shows the averaged velocity slices (of width 2.5 km s\(^{-1}\)) of the CGPS H\textsc{i} line data, overlaid with contours (15 and 30 K) indicating where the 1.42 GHz continuum flux is located in relation to the H\textsc{i}. A cleared out region is most easily seen in the final three velocity frames (−60.8 to −65.8 km s\(^{-1}\)), extending from the central region of CTB 102 toward the Galactic north. This cavity in H\textsc{i} disappears beyond ~−72 km s\(^{-1}\). The Galaxy contains gas out to ~−100 km s\(^{-1}\) in this direction (see Figure 4, center). The H\textsc{i} emission is mostly concentrated along an arc extending from north of CTB 102, wrapping around the “edges” of the H\textsc{ii} region and extending further up next to filaments 7, 6, and 4. These H\textsc{i} filaments (seen in the final three velocity frames, −60.8 to −65.8 km s\(^{-1}\)) are located on the “outside” of the corresponding H\textsc{ii} filaments and they correspond roughly in velocity to the RRL results in Table 2. In the first velocity frame, −53.4 km s\(^{-1}\), a filament of H\textsc{i} is spatially coincident with filament 5 (observed \(V_{LSR} = −51.9\) km s\(^{-1}\)).

Figure 8 shows a MSX A-band image (8.3 \(\mu\)m) toward CTB 102. The contour corresponds to an averaged CGPS H\textsc{i} brightness temperature level of 70 K from the −55.9 km s\(^{-1}\) velocity frame in Figure 7. The MSX A-band traces poly cyclic aromatic hydrocarbon (PAH) emission from neutral material being bombarded with ultraviolet photons. Figure 8 clearly shows the morphological association between structures seen in the H\textsc{i} arc discussed above, neutral material in a UV radiation field and the 1.42 GHz continuum emission. This is best demonstrated by the 8.3 \(\mu\)m emission tracing a thin filamentary H\textsc{i} structure which extends from the main H\textsc{i} arc toward CTB102p (i.e., toward greater Galactic longitude and latitude). This thin filament runs parallel to the bright arc seen in the 1.42 GHz continuum image (traced by the 30 K contour in Figure 6), something which would be expected if the interpretation of a neutral shell being ionized from slightly above the bright arc is correct.

Can ionizing photons reach the filaments? To reach the inside of the proposed swept up shell at filament 6, ionizing photons have to travel an angular distance of ~50' from CTB102p, corresponding to ~60 pc at 4.3 kpc. In the bubble scenario, the inside of the bubble is filled with stellar wind, a hot, low-density plasma. Absorption in such a plasma is negligible, and the purely geometrically diluted radiation field could easily maintain a high ionization fraction in the ionized inside of the swept up shell. The same is true for the other filaments we consider part of the shell structure. For filament 2, at a distance of ~180 pc from CTB102p (~140'), a purely geometrically diluted radiation field could maintain a high ionization fraction if the stellar wind bubble extended all the way out to filament 2. The proposed bubble does not extend that far (see below), and inserting any realistic ISM between the proposed bubble and filament 2 causes significant absorption in the ISM, thus leaving no photons from CTB 102 to ionize filament 2.

A simple analytical model of the development of a stellar wind bubble was given by Castor et al. (1975). Using the formulation in Kwok (2007), the radius (\(R\)), shell expansion velocity (\(\dot{R}\)), and shell fractional thickness (\(\Delta R/R\)) of such a region are given by

\[
R = 28 \left( \frac{\dot{E}/10^{36} \text{ erg s}^{-1}}{\mu n_0/1 \text{ cm}^{-3}} \right)^{\frac{1}{2}} (t/10^6 \text{ yr})^{\frac{3}{2}},
\]

\[
\dot{R} = 16 \left( \frac{\dot{E}/10^{36} \text{ erg s}^{-1}}{\mu n_0/1 \text{ cm}^{-3}} \right)^{\frac{1}{2}} (t/10^6 \text{ yr})^{-\frac{1}{2}} \text{ km s}^{-1},
\]

\[
\frac{\Delta R}{R} = \frac{1}{3} \left( \frac{a_0}{R} \right)^2,
\]

where \(\dot{E}\) is the energy loss rate from the star, \(\mu\) is the mean molecular weight of the medium the shell is expanding into (\(\mu = 1.4\) for neutral ISM, \(\mu = 0.62\) for a fully ionized ISM), \(n_0\) is the ISM density and \(a_0\) is the sound speed inside the bubble.

We estimate \(\dot{E}\) using a typical mass loss rate of \(M = 10^{-6} M_\odot \text{ yr}^{-1}\) and a stellar wind velocity of \(V = 2000\) km s\(^{-1}\).

The sound speed is \(a_0 = 10\) km s\(^{-1}\) and the ISM density is \(n_0 = 1\) cm\(^{-3}\) (mean ISM density, from Basu et al. 1999). If \(\mu = 1.4\) it would take \(3.8 \times 10^6\) years to reach the position of filament 6 from CTB102p (60 pc), by that time the expansion velocity of the shell will be 9 km s\(^{-1}\). The other extreme, if \(\mu = 0.62\), a radius of 60 pc would be reached in \(2.8 \times 10^6\) years, with a expansion velocity at that time of 12 km s\(^{-1}\). The expansion velocity for both scenarios is fairly insensitive to large \(t\), and reaches order of magnitude ~10 km s\(^{-1}\) after roughly 2.5 million years. The estimated thickness of the proposed shell from the 1.42 GHz continuum image and the H\textsc{i} line data is ~6', corresponding to a fractional thickness of ~12%. The time it takes the model shell to reach such a fractional thickness is \(0.9 \times 10^6\) years if (if \(\mu = 1.4\) or 1.3 \(\times 10^6\) years (if \(\mu = 0.62\)). If instead \(n_0 = 10\) cm\(^{-3}\) (the rest of the parameters remain the same), time to reach 60 pc increases by a factor of ~4. This suggests that if this mechanism is responsible for the observed filaments, the ISM in the direction of decreasing Galactic latitude cannot be more than a few particles per cubic centimeter, or the timescale exceeds the main-sequence life time of the probable star(s).
In the basic model for the expanding swept-up shell, the shell density would be (Kwok 2007),

$$\rho_s = \left( \frac{R}{R_0} \right)^2 \rho_0 \text{ cm}^{-3}. \quad (8)$$

Estimates of the column density test this picture where the observed filaments are due to our line of sight through the edge of the shell. The maximum path length $s$ looking through the edge of a uniform density spherical shell of radius $R$ and thickness $\Delta R$ would be

$$s = 2R \sqrt{2(\Delta R/R) + (\Delta R/R)^2}. \quad (9)$$

Estimating the column density toward the filaments is done by integrating the CGPS H\textsc{i} line data. The single channel (width 0.82 km s$^{-1}$) rms noise is 3.3 K, corresponding to a single channel rms noise in the column density of $4.9 \times 10^{18}$ cm$^{-2}$. For filament 6, $R = 60$ pc and $\Delta R/R = 0.12$, which gives $s \approx 60$ pc. This is on the order of the radius of the proposed bubble in this direction, so this is probably an upper limit in path length through the edge of any shell associated with CTB 102. The column density through filament 6 is $\sim 10^{21}$ cm$^{-2}$ (making the rms noise negligible). The uniform density needed in a shell to produce such a column density is $\sim 5$ cm$^{-3}$. In the model, the time required to reach this shell density (with $n_0 = 1$ cm$^{-3}$) is 0.6 $\times$ 10$^6$ years. Given the large uncertainties of the parameters involved, in $R$ (from the distance uncertainty), $\Delta R$ (uncertainty in telling where the filaments start and end), and column density (mainly determining the background), the uncertainty in the shell density can be as large as $\sim 60\%$. Within such a large uncertainty, the model can account for observed column densities within a time frame set by the main-sequence lifetime of a massive star. However, it cannot be ruled out that the observed filaments are higher density regions in the ISM that happen to be exposed to ionizing photons from the star(s) powering the H\textsc{ii} region. Even if that is the case, the medium between the filaments and the powering source would most likely be low-density material with a high ionization fraction to allow for enough photons to reach the filaments. Such a medium is consistent with the H\textsc{i} line data and the 1.42 GHz continuum image.

The Castor et al. (1975) model is very basic and does not take into account multiple stellar winds nor non-uniform ISM, but the estimates indicate that the bubble model is a plausible explanation of the size of CTB 102, allowing for observed size, velocities and fractional shell thickness in a timescale of $1-2 \times 10^6$ years. That is less than the main-sequence lifetime of the star(s) that is probably powering the region. For the same reason, it is unlikely that the proposed bubble would reach all the way out to filament 2. The overall morphology of CTB 102 indicates that the proposed H\textsc{ii} region/bubble/chimney is a major feature in the Perseus Galactic arm, powerful enough to disrupt the ISM and clear out a $\sim 100-130$ pc region. The appearance of CTB 102 in the H\textsc{i} with a cleared out region makes the CTB 102 complex comparable in size to the W4 superbubble in the Perseus arm (Normandeau et al. 1996). The W4 superbubble is modeled by Basu et al. (1999) as expanding in a stratified atmosphere. An association of nine O-type stars (IC 1805) is probably the reason for the cavity in H\textsc{i} and the ionization structure of the W4 H\textsc{ii} region. CTB 102 shares similarities with W4 in large scale H\textsc{i} distribution and ionization structure.

8. SUMMARY

We have obtained new RRL observations of CTB 102 that show that the filamentary structure surrounding the central region is physically associated with the central region. We provide the first ever distance estimate for this H\textsc{ii} region, 4.3 kpc. We argue that the best explanation for the size and appearance of the whole complex is that it is a large H\textsc{ii} region combined with a wind-blown interstellar bubble/chimney structure. MSX, H\textsc{i} and 1.42 GHz observational data are consistent with this view.

The authors thank Dana Balser of NRAO, Green Bank, for his help and problem solving skills during the GBT observations. We thank the referee for many helpful comments. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Dominion Radio Astrophysical Observatory is operated as a national facility by the National Research Council of Canada. The Canadian Galactic Plane Survey is a Canadian project with international partners, and is supported by a grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). This work made use of data products from the Midcourse Space Experiment.

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