THE INTERSTELLAR ENVIRONMENT OF FILLED-CENTER SUPERNOVA REMNANTS.

III. THE CRAB NEBULA

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ABSTRACT

The H I environment of the Crab Nebula is investigated using 2.75 and 9′ resolution data from the Dominion Radio Astrophysical Observatory Synthesis and Effelsberg 100 m Radio Telescopes, respectively. No clear evidence for an interaction between the Crab and the surrounding H I is found; the Crab probably lies within the boundaries of a large-scale, low-density void in the H I distribution. The presence of a wind-blown H I bubble near the Crab is confirmed, and it is suggested that the unidentified star that powers this bubble is responsible for the stellar wind material detected along the line of sight toward the Crab.

Subject headings: ISM: bubbles — ISM: general — ISM: individual (Crab Nebula) — radio lines: ISM — supernova remnants

1. INTRODUCTION

The Crab Nebula is the prototype of a small subclass of supernova remnants (SNRs) known as either “Crab-like,” “filled-center,” (FC) or “plerionic” SNRs. SNRs that fall into this class have centrally brightened radio morphologies, flat radio-spectral indices, and high levels of linear polarization, and they lack associated limb-brightened shells.

It is not clear why FC SNRs do not have associated limb-brightened shells. The cause could be intrinsic, i.e., there is a fundamental physical difference between FC and other SNRs, or extrinsic, i.e., the lack of a shell is due to an environmental effect. The extrinsic explanation was put forward by Chevalier (1977), who hypothesized that the Crab Nebula (and, by extension, all other FC SNRs) lie in low-density regions of the interstellar medium (ISM). In Chevalier’s scenario the supernovae that produce FC SNRs are no different than other explosions that produce neutron stars. Such explosions cast off the outer envelope of the progenitor star at ~10⁴ km s⁻¹, and the interaction between the resulting blast wave and the ISM results in the typical SNR shell. Assuming that the strength of the emission from the shell is related to the density of the ISM, the interaction between the fast-moving ejecta and a sufficiently low-density ISM might result in emission well below present detection limits. FC SNRs would then be the result of SN explosions that occur in low-density environments.

This paper is the third in a series in which the ISM around FC SNRs is probed to test Chevalier’s hypothesis. The first two papers (Wallace et al. 1997a; Wallace, Landecker, & Taylor 1997b) have suggested that, contrary to expectations, at least two FC SNRs (G74.9+1.2 and G63.7+1.1) do not lie in low-density regions of the ISM. Instead, clear indication is seen for interaction between the SNRs and their surrounding ISM. These results stand in contrast to previous investigations of the ISM around the Crab Nebula itself (Romani et al. 1990; Wallace, Landecker, & Taylor 1994, henceforth WLT94), which suggest that the Crab does lie in a low-density region of the ISM. However, interactions such as those between G74.9+1.2 and G63.7+1.1 and their surroundings would have been missed at the low resolution used for the existing studies of the Crab (36′); higher resolution observations are thus required for definitive statements regarding the environment of the Crab Nebula.

In this paper we map the H I distribution around the Crab Nebula at the highest resolution yet attempted. In our earlier paper (WLT94) we suggest that the Crab Nebula lies within a low-density void, which we referred to as “bubble 2;” in this paper we use the Effelsberg 100 m radio telescope to image this feature at 9′ resolution. In addition, the Dominion Radio Astrophysical Observatory (DRAO) Synthesis Telescope is used to image the H I environment immediately around the Crab at 1′ × 3′ resolution. The primary purpose of these data is to determine whether the Crab Nebula lies in a low-density void in the ISM.

We also use these data to elaborate on the nature of the optical emission detected by Murdin (1994) and Fesen, Shull, & Hurford (1997). Murdin (1994) reports detecting faint Hβ emission, which he ascribes to the remnant stellar wind from the Crab’s progenitor. Fesen et al. (1997) show that this emission is more widely spread than Murdin reported, suggesting that the material is not associated with the Crab. We discuss here whether this material is associated with the wind from an O star lying in the direction of the Crab.

We discuss these observations and present the data in § 2. In § 3 we interpret the data with respect to the Crab and a nearby O star, and we summarize the paper in § 4.

2. OBSERVATIONS AND RESULTS

Figure 1 reproduces images from WLT94, showing H I emission around the Crab Nebula with an angular resolution of 36′. In that paper, three approximately circular...
"bubbles" were identified in the H\textsc{i} distribution. The boundaries of these features are overlaid on the images in Figure 1: the larger bubble was denoted "bubble 1" and the middle one "bubble 2." WLT94 associated the smallest bubble, which we will refer to here as "bubble 3," with the O-star SAO 77293; this association is reassessed below. We have also indicated the positions of the Crab Nebula and SAO 77293 with asterisks in Figure 1 (the lower asterisk denotes the position of SAO 77293).

2.1. Effelsberg Observations

The Effelsberg data image a 4\textdegree 5 square region centered on bubble 2, indicated by the white box in Figure 1. Details of the observations can be found in Table 1. The data were taken during the winter of 1993–1994, during periods of weather too poor for observations at higher frequencies; the resulting data are thus a patchwork of several observations. Individual spectra were baseline corrected using a third-
order polynomial and were adjusted for stray radiation (Kalberla, Mebold, & Reif 1982) before conversion to channel maps. Baselines were determined using data between $-170$ and $-70$ km s$^{-1}$ and between $50$ and $130$ km s$^{-1}$.

Because of the strong absorption of the Crab Nebula, the baseline fitting algorithm failed for spectra in a $\sim 25'$ region on and immediately around the Crab Nebula, rendering the data in that area inadequate for addition to the DRAO data (see below). The data for this region were excised and replaced with values estimated from the surrounding emission. The estimated values were derived by fitting a "twisted-plane" (a plane that varies linearly in intensity along any cut in x or y) to the emission immediately around the excised region. The Effelsberg data are intended to image the large-scale structure around the Crab, and this process does not affect our interpretation of these structures.

The final channel maps include a small amount of striping, a result of calibration differences in data collected at different epochs. Some channels also have pixels with unusually high values compared with adjacent pixels; these defects pose no problems to the present work and have been left in the data. The rms noise in the maps is 0.25 K.

Plots of the Effelsberg data are presented in Figure 2. There is a significant gradient in the level of emission across the field of view, so a twisted-plane background has been fitted to edges of the field and removed from each channel for presentation purposes. The lack of velocity dispersion toward the Galactic anticenter implies that H I associated with the Crab Nebula may be found in almost any velocity channel, and we present a wide range of velocity channels for the sake of completeness. Nevertheless, we discuss only those features that we consider to be in the vicinity of the Crab Nebula and the O star that lies near it in the sky.

2.2. DRAO Synthesis Telescope Observations

Two overlapping fields were observed using the DRAO Synthesis telescope (Roger et al. 1973; Veidt et al. 1985). One field is centered on the position of the Crab, while the second is centered approximately $1^\circ$ to the southeast near the center of a H I bubble that overlaps the position of the Crab Nebula. The details of these observations are presented in Table 2.

The continuum contribution to the data was estimated by averaging data between 22.8 and 35.0 km s$^{-1}$ and between $-32.6$ and $-57.4$ km s$^{-1}$ to create two end-channel continuum maps. The strong emission from the Crab Nebula, coupled with nonlinearities in the observing system (which are not important when observing weaker sources), result in artifacts that vary with velocity from map to map. Individual continuum maps were created for each channel by linearly interpolating between the two extreme continuum maps in order to subtract the most reasonable estimate of the continuum emission (complete with artifacts) from each channel map. The interpolated channel maps were scaled by the Crab Nebula's integrated absorption in each channel before subtraction to avoid oversubtraction of artifacts related to the SNR in channels where the Crab Nebula is strongly absorbed.

The resulting maps reveal a large amount of H I structure, but imaging artifacts remain. In particular, the field centered on the Crab Nebula has noticeable residual rings centered on the SNR. Greisen (1973) showed that H I absorption is not constant across the face of the Nebula and that the absorption varies with velocity. The continuum subtraction process works correctly only if the absorption across the face of the nebula is constant and, as a result, this process improperly subtracts the continuum component (and, more importantly, associated artifacts) from our data. An attempt was made to remove the effects of this nonuniform absorption by CLEANing both the original and continuum-subtracted maps, but there was only limited improvement over the unCLEANed maps, possibly because of nonlinearities in the receiver system. Nevertheless, the data used here for the field centered on the Crab have been CLEANed. No CLEANing was necessary for data from the southern field; the residual grating rings in this field are below the noise in the map, because primary beam attenuation of the Crab's emission has reduced the effects of the nonuniform absorption across the Crab.

The DRAO Synthesis Telescope is not sensitive to structures on size scales greater than $\sim 1^\circ$ at 21 cm. To portray the full range of H I structure, it is necessary to add single-antenna information, in this case the data from the Effelsberg radio telescope presented above, to the DRAO data. The short and long-spacing data sets were filtered in complementary fashion in the u-v plane and, after correction for the primary beams of the two instruments, added in the image plane. The results of this process are entirely trust-
The Effelsberg H\textsc{i} data for the region around the Crab Nebula are shown in gray scale with overlaid contours; the contours and gray-scale limits are different for each page and are given below. The position of the Crab Nebula (top) and SAO 77293 (bottom) are given by the small white circles in the channel maps. A twisted-plane background has been subtracted from each channel for presentation purposes. The gray scale runs from $-2.3$ K (white) to 9.3 K (black) in (a), $-14.8$ to 21.2 K in (b), $-23.0$ to 32.3 K in (c), $-28.2$ to 34.3 K in (d), $-13.4$ to 21.8 K in (e), $-4.5$ to 9.5 K in (f), $-1.8$ to 5.4 K in (g), and $-1.4$ to 2.2 K in (h). Contours appear approximately every 0.7 K in (a), 2.0 K in (b), 3.1 K in (c), 3.5 K in (d), 2.0 K in (e), 0.8 K in (f), 0.4 K in (g), and 0.2 K in (h).
Fig. 2g

Fig. 2h
Fig. 3—DRAO H I data for region around the Crab Nebula shown in gray scale. The limits of the gray scales are different for each page and are given below. The Crab Nebula is located in the center of the upper field at the center of the artifacts. The gray scales run from $-27.5$ (white) to $24.5$ K (black) in (a) and $-26.2$ to $25.6$ K in (b).
worthy for regions more than 25' from the Crab Nebula. For regions closer to the Crab, the absolute flux may be affected by the interpolation of the Effelsberg data in this region, discussed above, but the morphology of the small-scale emission is trustworthy. The DRAO data (without short-spacings added) were consulted when interpreting emission in the region immediately around the Crab Nebula.

After the short spacing data had been added to each of the DRAO fields, the data were reprojected to a common grid and mosaicked to form the final data cube. The noise level near the center of the southern field is 0.9 K. The residual rings seen in the northern field are up to 20 K in magnitude and decrease in strength with distance from the Crab.

The final DRAO image data are presented in Figure 3. A constant background, determined from the average level of emission near the center of the observed region, has been removed from each channel for presentation purposes.

3. DISCUSSION

In the following sections we discuss the relationships among the H I bubbles, the Crab Nebula, and SAO 77293. For reference we have listed the observed characteristics of these objects in Table 3.

### 3.1. Does the Crab Nebula Lie in a Void?

Based on their low-resolution H I maps, WLT94 conclude that the Crab Nebula lies in a low-density void: bubble 2. The higher resolution images presented here allow us to reexamine this conclusion and study in more detail the environment of the Crab Nebula.

The lack of velocity dispersion in the Galactic anticenter direction makes assigning a systemic velocity to the Crab Nebula a difficult task. The velocity crowding has the effect that even small noncircular motions in the gas in front of the Crab could give rise to absorption at velocities unrelated to the SNRs kinematic distance.

In Figure 4 we present an absorption spectrum for the Crab Nebula derived from the DRAO field centered on the Crab. For comparison we include an emission spectrum obtained from the combined Effelsberg and DRAO data for this same field. The emission spectrum was derived for an elliptical annulus around the Crab, the inner edge having major and minor axes of 32' and 16', respectively, and the outer edge having major and minor axes of 42' and 26'; the major axis of the ellipse is oriented along the declination axis. The inner edge of the ellipse was chosen to avoid contamination from the Crab Nebula and artifacts associated with it, while the choice of outer edge was arbitrary.

The large size of the annulus will undoubtedly allow contamination of the emission spectrum from gas some distance away from the Crab and will thus potentially overestimate the emission at the position of the Crab itself.

The emission spectrum shows a number of features. There are two strong emission peaks centered near 4 and \(-11\) km s\(^{-1}\), a weak plateau near \(-22\) km s\(^{-1}\), and a faint tail, which reaches zero near \(-52\) km s\(^{-1}\) (the velocity at which the emission reaches zero may be affected by our choice of channels used to create the end-channel continuum map at the negative end of the spectrum). The absorption spectrum reveals two major features, one centered near 11 km s\(^{-1}\) and one centered near 3 km s\(^{-1}\). Both absorption features lie within the velocity range covered by emission associated with the feature at 4 km s\(^{-1}\). There is no strong absorption associated with the emission feature centered near \(-11\) km s\(^{-1}\). There is some indication of a slight slope to the baseline of our absorption spectrum, and we are unable to comment on the weak absorption measured by Hughes, Thompson, & Colvin (1971).

Both Greisen (1973) and Radhakrishnan et al. (1972) fitted the absorption to the Crab with multiple Gaussian components, but neither study attempted to fit the weakest

### TABLE 3

**Observed Characteristics of Features and Objects**

| Name         | Center R.A. (J2000) | Center Decl. (J2000) | Maximum Size | Velocity Range (km s\(^{-1}\)) | Distance (kpc) |
|--------------|---------------------|----------------------|--------------|---------------------------------|----------------|
| Bubble 1     | 5 36                | 20 53                | 6'4          | (9.2, -16)                      | ...            |
| Bubble 2     | 5 37 36             | 21 47 44             | 3'8          | (5.8, -17.2)                    | ...            |
| Bubble 3     | 5 35 48             | 21 52 50             | 50'–75'      | (-6, -25)                       | ...            |
| Crab Nebula  | 5 34 29.8           | 22 1                 | 7' × 5'      | (1, -7)                         | 1.5–2.3        |
| SAO 77293    | 5 35 39.8           | 21 23 58.0           | ...          | <-11 ± 3                        | ~1.8           |

*Note:* Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
absorption. Radhakrishnan et al. (1972) fitted the last component at $-1.5 \text{ km s}^{-1}$, while Greisen fits one at $\sim -8 \text{ km s}^{-1}$, but weak H I absorption of the Crab's continuum emission persists to very high negative velocities (e.g., Hughes et al. 1971). The component at $-8 \text{ km s}^{-1}$ fitted by Greisen appears to be an attempt to account for this weak absorption and for the non-Gaussian shape of the deep absorption feature centered at $\sim 3 \text{ km s}^{-1}$. An absorption spectrum derived from our DRAO data shows that, at $-8 \text{ km s}^{-1}$, the absorption has declined smoothly to less than 1% of the continuum level; we do not feel that this absorption is significant.

Inspection of Figure 3 reveals that the gas giving rise to the absorption peak centered at $\sim 3 \text{ km s}^{-1}$ is part of the bright western rim of bubble 2, which extends in velocity to $\sim 1 \text{ km s}^{-1}$. The Crab Nebula must lie behind this gas. At $-7 \text{ km s}^{-1}$, a bar of emission crosses the position of the Crab; there is no indication of absorption of the Crab's emission at this velocity, and this gas must lie behind the Crab. These arguments allow us to place the Crab between these two features in velocity, and the systemic velocity of the Crab must therefore lie in the range from 1 to $-7 \text{ km s}^{-1}$.

In the following discussion, velocities quoted for various features are those derived from the data at full resolution. Figures 2 and 3 present images at a velocity separation of 2 km s$^{-1}$, and maps at the exact velocities quoted in the text may not appear. All features can, however, be seen in the data presented.

In Figure 1, bubble 2 is seen from $v_{\text{LSR}} = 5.8 \text{ km s}^{-1}$ to $v_{\text{LSR}} = -17.2 \text{ km s}^{-1}$, is roughly 3.8' in diameter, and is centered at $\alpha = 5^h 37^m 36^s$, $\delta = 21^\circ 47' 44''$. In the Effelsberg data, bubble 2 is seen very clearly at $-3.3$ and $-4.6 \text{ km s}^{-1}$, centered near $\alpha = 5^h 38^m 20^s$, $\delta = 21^\circ 50'$, and it has a diameter of $\sim 3'$. Although the structure is somewhat obscured by confusion, the diameter clearly decreases toward more positive velocities. It is first seen as a very faint shell at $7.8 \text{ km s}^{-1}$ and grows in prominence as velocity decreases. At $5.3 \text{ km s}^{-1}$ a prominent arc of emission defines the western edge of the bubble and at $1.2 \text{ km s}^{-1}$ there is a prominent arc to the east. The western arc disappears by $-0.5 \text{ km s}^{-1}$, at which point the bubble is defined largely by the semicircular bay to the west. The eastern edge merges with the bright emission to the northeast at $-2.1 \text{ km s}^{-1}$, and a faint arc to the south of the field bounds the structure in that direction. At $-3.8 \text{ km s}^{-1}$ the void is at its maximum size, and by $-6.2 \text{ km s}^{-1}$ it is no longer recognizable in the Effelsberg data. At more negative velocities, the H I peak located near the geometrical centre of bubble 2 at $-6.2 \text{ km s}^{-1}$ eventually grows into a ridge that defines one edge of the H I bubble centered at $v_{\text{LSR}} = -12 \text{ km s}^{-1}$.

Note that the uneven H I shell that bounds bubble 2 at $-7.3 \text{ km s}^{-1}$ in WLT94 is not seen in the Effelsberg data. If the shell exists at and beyond this velocity, it lies just at the edge of the field of view. For the purposes of this paper we use the velocity width derived from the Effelsberg data, from 7.0 to $-6.0 \text{ km s}^{-1}$.

We can identify bubble 2 over a velocity range of 13 km s$^{-1}$, roughly twice the width of the average ISM feature. Furthermore, bubble 2 changes its diameter systematically with velocity. We conclude that the bubble is expanding (or contracting) and that its width in velocity is not simply a product of turbulent motion. We take the expansion velocity to be $\sim 6.5 \text{ km s}^{-1}$. The average brightness temperature of the shell (above the background) is $3.8 \pm 0.6 \text{ K}$, and the mass of the shell is $4 \times 10^4 M_\odot$ (assuming helium is 1/10 as abundant as hydrogen by number and that the H I shell is at the same distance as the Crab Nebula [2 kpc]). The energy in the shell is $\sim 2 \times 10^{49} \text{ ergs}$, and the kinetic age is $8 \times 10^6 \text{ yr}$.

The Effelsberg data show that there is H I structure projected inside bubble 2 in the range of systemic velocities for the Crab. The resolution of the Effelsberg data is insufficient to investigate the immediate surroundings of the Crab, however. For this reason the DRAO H I data in this velocity range were examined for evidence of either a void or an interaction; these data are discussed below.

At $v = 3.7 \text{ km s}^{-1}$ in Figure 3 the Crab Nebula is seen near the inner edge of the bright western rim of bubble 2. As velocity decreases, the rim becomes less prominent, but H I emission still remains around the position of the Crab. From $v \sim 3 \text{ km s}^{-1}$ to $v \sim -5.5 \text{ km s}^{-1}$ there appears to be very little H I immediately around the position of the Crab, but by $v = -7.0 \text{ km s}^{-1}$ the emission that defines the southwest edge of the bubble centered at $v_{\text{LSR}} = -12 \text{ km s}^{-1}$ has crossed the position of the Crab.

The absorption in this range is quite weak, so it is difficult to decide whether the emitting material from $v \sim -3$ to $v \sim -5.5 \text{ km s}^{-1}$ is in front of, behind, or surrounding the Crab Nebula. If this (or other) material were actually surrounding the Crab, one might expect to see evidence of an interaction (e.g., a swept-up shell). The next question is whether there is any evidence of an interaction between the Crab and the H I. There are in fact two possibilities, based largely upon positional coincidences between the H I structures and the Crab.

The first appears at $v = -7.0 \text{ km s}^{-1}$. At this velocity there is some H I emission, in a rough semicircular arc, to the northwest of the SNR. By $v = -9.5 \text{ km s}^{-1}$ this arc has encircled the entire top of the SNR, with a small intensity depression just above the position of the Crab mirroring an intensity peak just below the Crab. Errors in the phase calibration of radio interferometer data often take the form of asymmetric artifacts in the resulting images, and the peak and depression are, in our opinion, residual mapping and calibration artifacts. The emission to the northwest is the brightest, and by $v = -12.0 \text{ km s}^{-1}$ the emission to the northeast has disappeared. The emission immediately around the Crab has disappeared totally by $v = -16.1 \text{ km s}^{-1}$.

The other indication of a possible interaction is first seen immediately to the east of the Crab at $v = -10.4 \text{ km s}^{-1}$. It is manifested as a thin arc of emission that appears to encompass the entire eastern edge of the SNR out to $v = -15.3 \text{ km s}^{-1}$. The structure lies within and along the contours of the Crab Nebula and may be an artifact caused by imperfect removal of the Crab's continuum emission, possibly due to the changing absorption across the face of the Crab.

We conclude that there is no strong evidence of an interaction between the Crab Nebula and any H I in its vicinity, and we confirm the conclusions of WLT94: that the Crab Nebula lies in the low-density region identified as bubble 2. The features that may be taken as evidence for an interaction between the Crab Nebula and its surroundings are explained as simple map artifacts resulting from the extreme brightness of the Crab Nebula. This does not mean that there is no interaction, only that the effects of any such
interaction are below the level of the artifacts in the present
data. Further observations, capable of a dynamic range
greater than the 400:1 that we have achieved, are required
to settle this question.

3.2. A Remnant Stellar Wind?

Murdin (1994) reports Hβ and optical continuum observa-
tions, which he interprets as revealing an extended halo of
stellar wind material around the Crab Nebula. He attributes
this wind material to the Crab Nebula’s progenitor. Fe-
sen et al. (1997) show that the Hβ-emitting material is
more widely distributed than Murdin (1994) reports, sug-
gestings that this material is unrelated to the Crab. In this
section we show that a stellar wind bubble exists along the
line of sight toward the Crab, and we hypothesize that the
emitting material found by Murdin (1994) and Feisen et al.
(1997) is associated with this bubble and not the Crab
Nebula.

The new observations confirm the interpretation of
WLT94 that there is an expanding H I shell, which bounds
the feature we will call bubble 3, centered to the south of
the Crab Nebula, but they show that this bubble is not powered
by the O7.5 star SAO 77293 as suggested in that paper. The
feature that we interpret as this shell is clearly seen in both
the Effelsberg and DRAO H I data (Figs. 2 and 3). There are
two parts to the shell. From −6 to −12 km s−1 the appar-
ent radius increases from almost zero to 50′. Between −12
and −14 km s−1 the radius suddenly increases to 60′ and
continues to increase to a velocity of −25 km s−1, where
the shell fades from view having a radius of 75′. This sug-
ests an expanding shell in two parts with a systemic ve-
nocity near −12 km s−1, with the redshifted part expanding
into a more dense medium, while the blueshifted part
expands into a less dense region.

The brightest portion of the H I shell is its northwest
sector, where it joins a complex of bright emission running to
the northwest between −15 and −25 km s−1 (it should be
noted that this area includes the position of the Crab
Nebula and is the area where the Effelsberg data were
interpolated). It is unclear whether the northern bright
emission is physically associated with the shell or whether it
is an unrelated result of velocity crowding. We therefore
make two calculations of the H I mass, one including the
bright emission and one avoiding it. The calculations are
made by integrating the flux within a polygon around the
shell and subtracting a baseline determined by fitting a
 twisted plane to the vertices of the polygon. Errors are esti-
 mated by making several measurements using different
polygons and taking the standard deviation of the resulting
values. Including the bright emission to the north, the
average brightness temperature over the velocity range
from −6 to −26 km s−1 is $T_B = 4.9 \pm 0.4$ K; excluding it
yields $T_B = 3.5 \pm 0.4$ K. Using these estimates, the mass of
the H I shell is $(8.7 \pm 0.6) \times 10^3$ and $(4.1 \pm 0.6) \times 10^3 \, M_\odot$,
respectively.

A stellar wind bubble in a homogeneous medium with
number density $n_0$ (Weaver et al. 1977) expands in such a
way that its radius, $r_b$, at a given time is

$$r_b = 0.763 \left( \frac{E}{1.4 m_H n_0} \right)^{1/5} t^{4/5},$$

where $E$ is the mechanical luminosity of the wind
($= 1/2 M v^2$), $m_H$ is the mass of a hydrogen atom, and $t$ is the
age of the bubble. The bubble expansion velocity, $v_b$, is
found by taking the time derivative of its radius, giving

$$v_b = 0.6 r_b / t.$$

We can estimate the mechanical luminosity of the stellar
wind by first estimating the size, age, and preswpt density
of the bubble. As noted earlier, bubble 3 has two distinct
size scales; we attribute this to a “blow-out” of the bubble
into a lower density region. Using the size scale of the
smaller region (50′ = 29 pc at 2 kpc) and taking the expan-
sion velocity of the bubble to be 11 km s$^{-1}$ (half of its
velocity width), we use equation (2) to estimate the age of
the bubble as $1.5 \times 10^6$ yr. Finally, if we assume that the
entire mass of H I was evenly distributed in a volume corre-
sponding to the volume of the smaller shell, the undisturbed
ISM density was between ~1.6 and 3.5 cm$^{-3}$ for the lower
and higher mass, respectively. Substituting these values into
equation (1), we estimate the mechanical luminosity of the
powering wind to be $\sim 10^{36}$ erg s$^{-1}$, suggesting that an O6
($L_w \sim 1.8 \times 10^{36}$ erg s$^{-1}$) or O7 ($L_w \sim 6.8 \times 10^{35}$ ergs s$^{-1}$)
type star is at the heart of the bubble (assuming the empiri-
cal relationships for mass-loss rate and terminal velocity
derived by Howarth & Pinjka 1989).

The kinetic energy of the H I shell is $(4.5-7.8) \times 10^{48}$ ergs,
much less than $\sim 1.4 \times 10^{50}$ ergs that an O6 star would
inject into the ISM over its main-sequence lifetime of
$\sim 4.2 \times 10^6$ yr. The amount of energy lost through recom-
bination of the material in the swept-up shell can be esti-
mated as the number of hydrogen atoms in the shell times
the ionization potential; this comes to $\sim 10^{50}$ ergs given the
mass estimates above. For the parameters derived or
estimated here, we find that the ionization front associated
with an O6 or O7 star would become trapped after
$\sim (2-4) \times 10^6$ yr, depending on the preswpt density of
the ISM; this is consistent with the estimated age of the H I
bubble. These results indicate that the H I shell is due to a
trapped ionization front associated with the stellar wind
bubble.

The only known O-star along the line of sight to the H I
bubble is SAO 77293, which WLT94 associate with the H I
bubble. This star, at an estimated distance of 1.8 kpc, is of
type O7.5III. Despite the rough agreement in stellar type
with our estimates above and distance to the bubble, we
suggest that SAO 77293 is not associated with bubble 3.
Christy (1977) measured an absorption feature due to the
interstellar Ca II K line in the spectrum of SAO 77293 at a
velocity of $-11 \pm 3$ km s$^{-1}$, placing the star behind the gas
at this velocity. Our H I maps show a region of bright
emission, at the position of SAO 77293, from 1 to $-13$
 km s$^{-1}$; we associate the gas giving rise to the Ca II K-line
absorption with this complex of H I. The emission at these
velocities is part of the redshifted portion of the H I shell, and,
if the H I shell is expanding and not contracting, SAO
77293 must be located on the far-side of the H I bubble in
order for the Ca II K line absorption to exist. If SAO 77293
were to lie within the gas producing the Ca II K line
absorption, the radiation from the star would ionize the sur-
rounding gas; since we see no evidence for a hole in the H I
distribution at these velocities we rule out this possibility.
Finally, if the star were to lie at a systemic velocity at $-14$
 km s$^{-1}$ or beyond, it would clearly lie within the confines of
the blueshifted blow-out region of bubble 3, and it would be
in front of the gas giving rise to the Ca II K line absorption.
This means that SAO 77293 must be behind the H I bubble
and cannot be powering it, and we conclude that the star that powers the H\textsc{i} bubble has yet to be identified. We are then left with the unanswered question: why has that star not been detected?

The Crab lies projected on the edge of the H\textsc{i} shell defining the redshifted portion of bubble 3 and within the projected confines of the blueshifted portion. The stellar wind material within the H\textsc{i} shell is likely ionized and can give rise to H\textbeta emission. In addition, if the gas in the H\textsc{i} shell is not fully recombined, we can expect some additional H\textbeta emission from the shell itself. We thus suggest that the H\textbeta emission detected by Murdin (1994) and Fesen et al. (1997) is unrelated to the Crab Nebula and is, instead, due to material associated with the (as yet unidentified) star that is powering bubble 3.

4. SUMMARY

In this paper we have presented maps of the H\textsc{i} environment of the Crab Nebula obtained using the DRAO ST and the Effelsberg 100 m Radio Telescopes. The Crab Nebula lies within the physical confines of the H\textsc{i} structure that we call bubble 2. This association is based upon the observation that the central velocity of the H\textsc{i} bubble lies within the range of possible systemic velocities of the Crab Nebula. A few maps appear to show interaction, but these features are interpreted as artifacts resulting from the extreme brightness of the Crab Nebula.

We also confirm the presence of an expanding H\textsc{i} bubble (labeled bubble 3) along the line of sight to the Crab Nebula. The emission from the Crab is not absorbed by the H\textsc{i} shell associated with the bubble; bubble 3 must therefore lie behind the Crab. We conclude that an association between bubble 3 and the nearby O-star SAO 77293 is unlikely and that bubble 3 lies in front of this star. It is suggested that emission from material associated with bubble 3 has been detected by Murdin (1994) and Fesen et al. (1997).

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