THE WARM INTERSTELLAR MEDIUM AROUND THE CYGNUS LOOP

Joaquín Bohigas,1 Jean Luc Sauvageot,2 and Anne Decourchelle3

Received 1998 March 31; accepted 1998 September 22

ABSTRACT

Observations of the oxygen lines [O II] 3729 Å and [O III] 5007 Å in the medium immediately beyond the Cygnus Loop supernova remnant were carried out with the scanning Fabry-Pérot spectrophotometer Experience Spectroscopique d’Observation des Plasmas (ESOP). Both lines were detected in three different directions (east, northeast, and southwest), and up to a distance of 15 pc from the shock front. The ionized medium is in the immediate vicinity of the remnant, as evinced by the smooth brightening of both lines as the adiabatic shock transition (defined by the X-ray perimeter) is crossed. These lines are usually brighter around the Cygnus Loop than in the general background in directions where the Galactic latitude is ≥ 5°. There is also marginal (but significant) evidence that the degree of ionization is somewhat larger around the Cygnus Loop. We conclude that the energy necessary to ionize this large bubble of gas could have been supplied by an O8 or O9 type progenitor, or by the particles heated by the expanding shock front. The second possibility, although highly attractive, would have to be assessed by extensive modeling.

Subject headings: ISM: individual (Cygnus Loop) — supernova remnants

1. INTRODUCTION

An understanding of the properties and physics of the medium in which supernova remnants (SNRs) expand is essential for developing consistent scenarios for their evolution and physical structure. In turn, the sequence of events leading to a supernova remnant and its demise define to a very large extent the structure, physical and chemical state, and evolution of the interstellar medium. The Cygnus Loop is particularly well suited to a study of these questions. Being in an advanced evolutionary stage, different regions of the remnant are found interacting with different components of the interstellar medium. The remnant is close enough to study these interactions in great detail. In some circumstances, the structure of the surrounding medium is deduced from observations of the SNR in different spectral domains (e.g., Graham et al. 1991; Hester, Raymond, & Blair 1994; Decourchelle et al. 1997). When dealing with atomic or molecular gas, this information has been gathered directly (e.g., DeNoyer 1975; Scoville et al. 1977). Direct observations of ionized gas in the surrounding medium are considerably more complicated, since the emission lines arising from these regions are bound to be faint and prone to background confusion. In this respect the Cygnus Loop offers a substantial advantage, since it is placed at a large Galactic latitude (b = −8.6°).

Observations of faint emission lines in diffuse media have been carried out with a scanning Fabry-Pérot spectrophotometer. This technique has been successfully applied in searching for emission from Fe+9 and Fe+13 in SNRs (Ballet et al. 1989; Sauvageot et al. 1990; Sauvageot & Decourchelle 1995), or exploring line emission in the warm component of the interstellar medium (e.g., Reynolds 1983, 1985). In this paper, we searched for line emission from warm ionized gas in the direction of the Cygnus Loop using such an instrument, ESOP (Dubreuil et al. 1995). In comparison with a grating instrument, ESOP can sample a large solid angle with a substantial luminosity advantage, at the cost of a reduced spectral range. It has no spatial resolution and is less efficient than direct imaging observations, but the line of interest can be isolated from other spectral features and the underlying continuum. This is a precious advantage when the line is faint.

A description of the instrumental setup and the process followed in data reduction is presented in § 2. Results are described in detail in § 3, and a discussion of the viability of several possible ionizing sources is given in § 4. Finally, conclusions and research prospective are summarized in § 5.

2. OBSERVATIONS AND DATA REDUCTION

ESOP was mounted on the 1.5 m telescope of the Observatorio Astronómico Nacional at San Pedro Martir, B.C., México. Data were gathered in four runs: 1994 July, 1994 October, 1995 July, and 1996 August. The observations reported in this paper are for the [O II] lines at 3726 and 3729 Å, [O III] at 5007 Å, and He I at 5876 Å. We used narrow-band (~15 Å FWHM) interference filters centered at these lines when T = 20.5°C. Each observation consists of 50–100 scans of 100 steps each. The integration time at each step is 170 ms. Thus, the typical total integration time for each data point is ~20 minutes. The free spectral range (FSR) was 11.3 Å during the first [O II] observations and 14.5 Å in the following ones, in both cases centered at 3727 Å (with the [O II] filter FWHM = 15 Å). The FSR was not completely scanned by the Fabry-Pérot in the first [O II] observations. All [O III] observations were carried out with a FSR of 10.8 Å centered at 5007 Å (with the [O III] filter’s FWHM = 15 Å). Because our filters are well centered on the oxygen lines and because the FSR is greater than half the filters’ bandwidth, these are not contaminated. Sky lines lying far from the center of the filter may contain a contribution from another order. Since temperature variations shift the filter’s transmission curve and humidity affects the air capacitance in the Fabry-Pérot gap, the instrument works in a dry nitrogen atmosphere and is under temperature control (at T ≈ 20.5°C, with δT ≈ 0.2°C). White
and comparison lamps were regularly measured in order to follow any bandpass drift in the filter or any variation in the Fabry-Pérot gap. All observations were carried out with a 150° circular diaphragm.

Data reduction and analysis has been amply described in Ballet et al. (1989) and Sauvageot & Decourchelle (1995). This takes into account that the geocoronal contribution—lines and continuum—is unstable. No attempt is made to subtract a blank sky directly. Instead, the observation is modeled with a combination of sky and source lines and continuum. χ² tests are performed to estimate the statistical error of measurements.

The sky continuum and lines must be monitored carefully in this type of observations. Typical spectra for the medium contiguous to the Cygnus Loop and randomly selected positions are presented in Figures 1 and 2 (for [O II] and [O III], respectively). Although absolute wavelength calibrations are wrong, relative ones (i.e., dispersion) are correct. This is not of consequence, since this paper is only concerned with photometric results and there can hardly be any confusion regarding the identification of the line, given its relative prominence (for instance, the bright feature at 5010.94 Å in Figure 2b is obviously the [O III] 5007 line). For further clarity, arrows located on the upper part of Figures 1a, 1b, 2a, and 2b indicate which line is being studied. As can be seen from these figures, the O⁺ lines are easily recognized and discriminated. Regarding the [O III] filter, there can hardly be any confusion about the identification and measurement of [O III] 5007, since sky lines were found to be very weak in this spectral region. Since He I 5876 was not detected outside the bright optical filaments of the Cygnus Loop, a discussion of the sky lines admitted by this filter is not necessary. Our observations were flux calibrated by observing standard stars 29 Pisc and 58 Aql several times during the night. For the [O III] calibration, we had to take into account contamination from the other order to the standard star continuum. At its worst, we estimate that the absolute values for the specific intensity are accurate at the 25% level, comparable to our statistical error bars.

3. RESULTS

Regions within the Cygnus Loop and the medium surrounding it were observed in three directions (northeast, east, and southwest), along lines approximately perpendicular to the shock front. Our observational pointings are shown in Figure 3. The shock front is defined as the outer X-ray boundary of the supernova remnant (Ku et al. 1984; Ballet & Rothenflug 1989). Our results for the O⁺ and O⁺² lines are compiled in Tables 1, 2, and 3 (for the northeast, east, and southwest traces, respectively). These tables give the code name and coordinates for each position, the angular distance (θ, in arcseconds) between the observed position and the shock front (with negative values for regions inside the SNR), the angular distance from the center of the SNR in terms of its radius, 1 + δ/θ, where
\[ \theta = 5850^\circ \] is the angular radius of the Cygnus Loop (mean value of the semiaxes; Green 1988), the specific intensity of [O II] 3729 and [O III] 5007 in \(10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\), and the ratio of these lines (\(\lambda 3729/\lambda 5007\)). Except for pointings in the optical filaments of the Cygnus Loop (such as NE0, NE1, E0, E1, and SW0), the ratio [O II] \(\lambda 3727/\lambda 3729\) is always at the low-density limit (\(\approx 0.67, N_e \lesssim 50 \text{ cm}^{-3}\)), so there is no need to report the flux of the other [O II] line. Upper and lower bounds for the specific intensity are given for a 90\% confidence level in the fitting procedure. Uncer-

| Position | R.A. (1950) | Decl. (1950) | \(\delta\) (arcsec) | \(1 + \delta/\theta\) | \(I([\text{O II}]) 3729\) | \(I([\text{O III}]) 5007\) | \(\lambda 3729/\lambda 5007\) |
|----------|-------------|--------------|---------------------|-------------------|-------------------|-------------------|-------------------|
| NE0...... | 20 53 55.8 | +31 35 05    | \(-884\)             | 0.85              | \(\ldots\)         | 30.1\(+6.1\)      | \(\ldots\)         |
| NE1...... | 20 54 05.0 | +31 37 35    | \(-663\)             | 0.89              | \(79.0\(+0.0\)      | \(67.8\(+9.3\)     | \(1.17\(+0.14\)    |
| NE2...... | 20 54 20.0 | +31 39 20    | \(-390\)             | 0.93              | \(2.91\(+0.34\)    | 2.89\(+0.21\)     | 1.01\(+0.18\)     |
| NE3...... | 20 54 19.0 | +31 41 05    | \(-325\)             | 0.94              | \(1.71\(+0.19\)    | 1.82\(+0.36\)     | 0.93\(+0.26\)     |
| NE4...... | 20 54 26.0 | +31 42 50    | \(-162\)             | 0.97              | \(1.13\(+0.22\)    | 1.38\(+0.33\)     | 0.82\(+0.19\)     |
| NE5...... | 20 54 33.0 | +31 44 35    | \(0\)                | 1.02\(+0.18\)    | \(0.85\(+0.24\)    | 1.20\(+0.41\)     | \(\ldots\)        |
| NE6...... | 20 54 40.0 | +31 46 20    | \(162\)              | 1.03              | \(0.90\(+0.20\)    | 0.99\(+0.44\)     | 0.91\(+0.32\)     |
| NE7...... | 20 54 47.0 | +31 48 05    | \(325\)              | 1.06              | \(0.80\(+0.19\)    | 0.96\(+0.24\)     | 0.83\(+0.30\)     |
| NE8...... | 20 54 54.0 | +31 49 50    | \(487\)              | 1.08              | \(0.67\(+0.23\)    | 0.71\(+0.29\)     | 0.94\(+0.38\)     |
| NE9...... | 20 55 01.0 | +31 51 35    | \(650\)              | 1.11              | \(0.78\(+0.23\)    | 0.73\(+0.26\)     | 1.07\(+1.02\)     |
| NE12......| 20 55 22.0 | +31 54 50    | \(1137\)             | 1.19              | \(0.65\(+0.21\)    | \(\ldots\)        | \(\ldots\)        |
| NE14......| 20 55 31.0 | +32 00 00    | \(1485\)             | 1.25              | \(0.70\(+0.19\)    | \(\ldots\)        | \(\ldots\)        |
| NE15......| 20 55 43.0 | +32 02 05    | \(1702\)             | 1.29              | \(0.77\(+0.20\)    | \(0.65\(+0.19\)    | 1.18\(+0.34\)     |
| NE18......| 20 56 04.0 | +32 07 20    | \(2189\)             | 1.37              | \(0.83\(+0.13\)    | \(0.85\(+0.13\)    | 0.98\(+0.34\)     |
| NE22......| 20 56 23.0 | +32 17 02    | \(2754\)             | 1.47              | \(0.65\(+0.19\)    | \(0.97\(+0.24\)    | 0.69\(+0.35\)     |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Intensity in \(10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\).
Fig. 3.—Observational pointings. North is up, east is to the left
### Table 2
#### Eastern Trace

| Position | R.A. (1950) | Decl. (1950) | $\delta$ (arcsec) | $1 + \delta/\theta$ | $I([\text{O} \text{II}] 3729)$ | $I([\text{O} \text{III}] 5007)$ | $\lambda 3729/\lambda 5007$ |
|----------|-------------|--------------|-------------------|---------------------|-------------------|-------------------|-------------------|
| E0       | 20 55 13.8  | +30 54 30    | -705              | 0.88                | 45.20$^{+1.30}_{-1.70}$ | 198.0$^{+15.8}_{-15.0}$ | 0.23$^{+0.02}_{-0.01}$ |
| E1       | 20 55 24.0  | +30 54 30    | -531              | 0.91                | 18.20$^{+0.40}_{-1.10}$ | 111.3$^{+11.8}_{-11.0}$ | 0.16$^{+0.02}_{-0.01}$ |
| E2       | 20 55 34.0  | +30 54 30    | -354              | 0.94                | 2.98$^{+0.36}_{-0.27}$  | 4.86$^{+0.24}_{-0.25}$  | 0.62$^{+0.10}_{-0.09}$  |
| E3       | 20 55 44.0  | +30 54 30    | -177              | 0.97                | 1.45$^{+0.10}_{-0.10}$  | 2.04$^{+0.10}_{-0.10}$  | 1.30$^{+0.18}_{-0.18}$  |
| E4       | 20 55 54.0  | +30 54 30    | 0                 | 1.0                 | 1.54$^{+0.10}_{-0.10}$  | 1.43$^{+0.10}_{-0.10}$  | 1.08$^{+0.18}_{-0.18}$  |
| E5       | 20 56 04.0  | +30 54 30    | 177               | 1.03                | 1.50$^{+0.27}_{-0.10}$  | 1.61$^{+0.14}_{-0.10}$  | 0.96$^{+0.12}_{-0.06}$  |
| E6       | 20 56 14.0  | +30 54 30    | 354               | 1.06                | 1.15$^{+0.22}_{-0.22}$  | 2.14$^{+0.24}_{-0.24}$  | 0.54$^{+0.18}_{-0.18}$  |
| E8       | 20 56 34.0  | +30 54 30    | 708               | 1.12                | 0.91$^{+0.16}_{-0.19}$  | 1.09$^{+0.26}_{-0.33}$  | 0.84$^{+0.56}_{-0.50}$  |
| E10      | 20 56 54.0  | +30 54 30    | 1062              | 1.18                | 0.78$^{+0.13}_{-0.22}$  | 1.04$^{+0.18}_{-0.24}$  | 0.75$^{+0.68}_{-0.70}$  |
| E14      | 20 57 34.0  | +30 54 30    | 1770              | 1.30                | 0.72$^{+0.15}_{-0.10}$  | 0.93$^{+0.12}_{-0.10}$  | 0.83$^{+0.40}_{-0.29}$  |
| E18      | 20 58 14.0  | +30 54 30    | 2478              | 1.42                | 0.81$^{+0.10}_{-0.19}$  | 0.45$^{+0.18}_{-0.18}$  | 1.80$^{+1.37}_{-1.37}$  |
| E26      | 20 59 34.0  | +30 54 30    | 3894              | 1.67                | 0.61$^{+0.19}_{-0.08}$  | 0.46$^{+0.20}_{-0.13}$  | 1.31$^{+0.29}_{-0.29}$  |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Intensity in 10$^{-7}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

### Table 3
#### Southwestern Trace

| Position | R.A. (1950) | Decl. (1950) | $\delta$ (arcsec) | $1 + \delta/\theta$ | $I([\text{O} \text{II}] 3729)$ | $I([\text{O} \text{III}] 5007)$ | $\lambda 3729/\lambda 5007$ |
|----------|-------------|--------------|-------------------|---------------------|-------------------|-------------------|-------------------|
| SW0      | 20 44 55.3  | +30 00 36    | -631              | 0.89                | 7.02$^{+0.48}_{-0.32}$  | 15.1$^{+0.25}_{-0.18}$  | 0.46$^{+0.06}_{-0.04}$  |
| SW1      | 20 44 35.3  | +29 57 36    | -314              | 0.95                | ...                | 48.5              | ...            |
| SW1.5    | 20 44 25.3  | +29 56 08    | -158              | 0.97                | 1.71$^{+0.16}_{-0.20}$  | 1.66$^{+0.35}_{-0.44}$  | 1.03$^{+0.79}_{-0.70}$  |
| SW2      | 20 44 15.3  | +29 54 36    | 0                 | 1.0                 | 1.14$^{+0.17}_{-0.21}$  | 0.78$^{+0.18}_{-0.21}$  | 1.47$^{+1.34}_{-1.34}$  |
| SW4      | 20 43 35.3  | +29 48 36    | 633               | 1.11                | 0.85$^{+0.18}_{-0.18}$  | 0.89$^{+0.18}_{-0.18}$  | 0.96$^{+0.40}_{-0.34}$  |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Intensity in 10$^{-7}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$.
tainties on the $\lambda3729/\lambda5007$ line ratio were determined from these bounds. Both lines were detected at every position, some of them very far from the shock front; for instance, region E26 is 3894′ distant from it, $\simeq 15$ pc at the distance of the Cygnus Loop (770 pc). Except for the remnant’s optical filaments, the He i line was not detected.

The northeast and east traces of [O II] 3729 and [O III] 5007 as a function of $1 + \delta/\theta$ are plotted in Figure 4. As can be seen, both traces are nearly identical, and the specific intensities well away from the shock front are roughly constant (particularly [O II] 3729). Note that the adiabatic shock transition is revealed as [O II] 3729 and [O III] 5007 brighten up smoothly as the X-ray perimeter of the SNR is crossed (at $1 + \delta/\theta = 1$). This brightening is caused by adiabatic compression of the plasma and enhanced line emissivities, which overcompensate for the decreasing concentration of both ions, since these are now immersed in a higher temperature medium. The southwestern trace is not plotted, but our measurements (see Table 4) also reveal the shock transition. The adiabatic transition is apparently complete at $1 + \delta/\theta \approx 0.95$ or $\approx 1$ pc inside the shock front. This is the most compelling evidence that this medium is not a projected H II region or a parcel from the general background, but is in the immediate vicinity of the Cygnus Loop. Our most distant pointing (region E26) is $\approx 36$ pc away from the remnant’s center, which implies that the surrounding medium is ionized up to a distance of at least $\approx 50$ pc. An additional and less conspicuous feature is that the specific intensity of both lines seems to increase slightly even before the shock front is crossed (from $1 + \delta/\theta \approx 1.1$, or $\approx 2$ pc away from the shock). This seems to indicate that the plasma immediately beyond the edge of the Cygnus Loop is being affected by the SNR before it encounters the blast wave, although this turn-up may also be due to irregularities in the boundary of the remnant.

As mentioned above, [O II] 3729 maintains an approximately constant level beyond $\simeq 0.1$–0.2 times the radius of the SNR. This level is nearly identical in the northeast and east directions (for which we have sufficient data points). It is worth noting that [O II] 3729 is practically the same in regions separated by as much as $\approx 5800$′ (NE22 and E26), some 22 pc at the distance to the Cygnus Loop. Thus, the [O II] 3729 data indicate that the medium beyond the shock front of the Cygnus Loop is very extended, and quite possibly surrounds the eastern face of the remnant. Furthermore, the data for the southwest trace, albeit limited,
suggest that this medium exists all around the Cygnus Loop. \([\text{O} \text{~iii} ]\) 5007 does not display such a regular behavior. Along the northeast trace, it dims slightly at positions NE8, NE9, and NE15, but brightens up again farther away (positions NE18 and NE22). Along the eastern trace, \([\text{O} \text{~iii} ]\) 5007 behaves more regularly, weakening very noticeably in the two most distant pointings (E18 and E26). Thus, the \([\text{O} \text{~iii} ]\) 5007 observations imply that physical conditions in the surrounding medium are not homogeneous. If the temperature is uniform, there are variations in the oxygen degree of ionization: in the low-density limit, \(N(\text{O}^+)/N(\text{O}^{++}) \approx 2.7, 1.8, \) or 1.5 in most positions, and up to 4.8, 3.3, or 2.9 at E18 and E26 (for \(T_c = 6000, 8000, \) and 10,000 K, respectively). Alternatively, if the degree of ionization is constant, the temperature would have to be twice as large where \([\text{O} \text{~iii} ]\) 5007 is faintest. It seems difficult to maintain such high temperatures.

In order to assess whether there is a difference between the medium surrounding the Cygnus Loop and the general background, observations were carried out on randomly selected directions located at \(|b| \geq 5^\circ\), as the Cygnus Loop is. Specific intensities as low as \(\approx 0.07 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\) were measured, which gives an idea of the instrumental sensitivity. As expected, line brightness is not uniform in the Galactic background. \([\text{O} \text{~ii} ]\) 3729 was observed and detected 13 times over the four observing runs. Specific intensities comparable to some of those observed in regions contiguous to the Cygnus Loop (0.89 and \(0.64 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\)) were found in only two directions. Elsewhere they were markedly smaller, and in the mean, \([\text{O} \text{~ii} ]\) 3729 \(= 0.47 \pm 0.17 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\). Out of nine measurements, \([\text{O} \text{~iii} ]\) was detected in seven positions. \([\text{O} \text{~iii} ]\) 5007 \(= 0.68 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\) in the brightest sky background region, similar to what we found in some regions around the SNR, but in all other directions the line was much fainter. In the mean, \([\text{O} \text{~iii} ]\) 5007 \(= 0.25 \pm 0.24 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\). In most sites, we measured either one or the other line because of the complications involved in changing the instrumental setup. Both lines were measured in only two directions, where we found \(I(3729)/I(5007) = 3.13 \pm 1.8\). This implies that \(N(\text{O}^+)/N(\text{O}^{++}) \approx 6.4 \) and 16.8 (for \(T_c = 8000 \) K), a rather low level of ionization. \([\text{He} \text{~i} ]\) 5876 was not detected, confirming the faintness of this line in the general background (Reynolds & Tufte 1995).

As far as we know, this is the first time that \(\text{O}^+\) emission from the diffuse interstellar medium has been reported. Reynolds (1985) observed \([\text{O} \text{~iii} ]\) 5007 in three directions; the specific intensity was less than \(0.5 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\) in one direction, and 2 and \(1.8 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\), respectively, in the other two. In these last two directions, which are amongst the brightest sky background regions as defined by the Hz intensity (Reynolds 1983), \([\text{O} \text{~iii} ]\) 5007 is substantially brighter than anything we find beyond the Cygnus Loop. We measured \([\text{O} \text{~iii} ]\) 5007 at the second-brightest region \((l = 96^\circ, b = 0^\circ)\) and obtained \(0.68 \pm 0.12 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\), 2.6 times less than Reynolds (1985). The discrepancy is probably related to the vast difference in aperture sizes (49\arcsec \ versus 2.5\arcsec), which meant that a region with particularly intense emission was included in Reynolds’ diaphragm but not in ours.

Thus, there is a measurable background contribution to the intensity of the oxygen lines, but as can be seen from Tables 1–3, emission is generally larger in the medium surrounding the Cygnus Loop; \([\text{O} \text{~ii} ]\) 3729 is at least 1.5 times brighter around the Cygnus Loop than in the general background, whereas \([\text{O} \text{~iii} ]\) 5007 is between 2 and 5 times more intense. Thus, the data support the conclusion that \([\text{O} \text{~ii} ]\) 3729 and \([\text{O} \text{~iii} ]\) 5007 in the medium just beyond the Cygnus Loop are usually brighter than in the general Galactic background at least up to a distance of \(\approx 15 \text{ pc}\) from the shock front (about 0.6 times the radius of the remnant). There is also marginal but significant evidence indicating that the degree of ionization is higher in the medium around the Cygnus Loop.

The absence of \([\text{He} \text{~i} ]\) 5876 emission merits a discussion, given the detection of \([\text{O} \text{~iii} ]\) 5007, which requires more energetic photons for this ion to exist (35.1 versus 24.6 eV). We note that there is an antecedent: Reynolds (1985) found intense \([\text{O} \text{~iii} ]\) 5007 emission at \(l = 194^\circ, b = 0^\circ\), but Reynolds & Tufte (1995) searched for \([\text{He} \text{~i} ]\) 5876 at this location with negative results, implying that \(\text{He}^{++}/\text{He} \leq 0.3\). In general, \(I(5876)/I(5007) = (0.08, 0.02, 0.008) (\text{He}^{++}/\text{He}) (O^{++}/O)^2\) for \(T_c = 6000, 8000, \) and 10,000 K, respectively. The fraction of doubly ionized oxygen is determined from the previously calculated \(O^{++}/O^+\) ratio, assuming that there are no higher ionization stages and that \(O^+/(O^{++}) = 2\). Since \(I(5007) \approx 0.9 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\) in the medium surrounding the Cygnus Loop, it follows that \(I(5876) \approx (0.42, 0.09, 0.03) (\text{He}^{++}/\text{He}) \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\). Finally, the nondetection of \([\text{He} \text{~i} ]\) 5876 implies that \(I(5876) \leq 0.05 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\) (our detection limit). Consequently, \([\text{He} \text{~i} ]\) 5876 emission will be under our detection threshold if \((\text{He}^{++}/\text{He}) \leq (0.17, 0.78, \) or 1) for the aforementioned temperatures. In addition, since \(\text{He}^{++}/\text{He} \geq 0.20\), \(O^+/(O^{++})\), we conclude that the ambient temperature is larger than \(\approx 6000 \text{ K}\).

4. DISCUSSION

The medium revealed by our observations has the general properties of the partially ionized warm component of the interstellar medium, which is favorable for the observation of supernova remnants (Kafatos et al. 1980). But it is different insofar as it is generally brighter, and a couple of observations on sky background regions also suggest that the degree of ionization, given by \((N(O)/N(O^+))/N(O^{++})\), is larger around the Cygnus Loop. On the other hand, we did not detect \([\text{He} \text{~i} ]\) 5876 emission, and in this respect there is no difference between the medium just beyond the Cygnus Loop and the general Galactic background (Reynolds & Tufte 1995). However, there are several reasons to expect somewhat different properties in the medium surrounding the Cygnus Loop: the remnant has been included in the so-called Cygnus superbubble, along with several OB associations; the SN progenitor might have been a source of ionizing energy; the SN itself produced a large quantity of UV photons; and, finally, ionizing radiation is also generated by the expanding shock wave. We discuss these possible sources below.

The Cygnus Loop is at the southern edge of the extremely rich and complex region known as the Cygnus superbubble, which has been extensively described and analyzed by Bochkarev & Sitnik (1985). The superbubble has seven OB associations, containing 48 O-type stars and nearly 70 B-type stars. With the exception of Cyg OB4 and Cyg OB7,
all of these are at a distance of 1.2 kpc or more. Cyg OB7 is at approximately the same distance as the Cygnus Loop, but is located some 20° away from it (about 280 pc). Cyg OB4 is also relatively near, but although it has been classified as an OB association, it does not contain any O or B star. Thus, it is doubtful that these OB associations can account for the ionization of the medium surrounding the Cygnus Loop. We also contemplated the possibility that this medium is an extended low surface brightness H II region produced by an early-type star in the vicinity of the SNR. A visual inspection of POSS plates and a thorough search of O and B stars catalogs (Cruz-Gonzalez et al. 1974; Garmany, Conti, & Chiosi 1982) renders no support for this possibility. The SAO catalog was also explored with negative results.

The ionized medium around the Cygnus Loop may also be the relic H II region of the progenitor star. The progenitor should have produced $P_{UV} \sim 5 \times 10^{48} N_0^2$ UV photons s$^{-1}$ to create a 50 pc Strömgren sphere if the medium is fully ionized, as the presence of O$^+$ seems to imply (but note that Graham et al. 1991 found shocked H$_2$ in the Cygnus Loop). The mean particle density in the medium where the remnant evolved at least until recently is $0.1-0.2$ cm$^{-3}$ (Ku et al. 1984; Levenson et al. 1997), which signifies that the required spectral type of the progenitor star must have been earlier than or equal to B0. Furthermore, the $\lambda 3729/\lambda 5007$ ratio ($\approx 1$ with no reddening correction, about 1.5 for a 1 mag visual extinction), implies that the effective temperature of the ionizing star is close to $35,000$ K (Stasinska 1978), corresponding to a spectral type slightly later than O8. Under this hypothesis, the mass of the progenitor would have been between 20 and 25 M$_\odot$. Such a star would spend most of its lifetime as a blue giant and only $\approx 1\%$ of its existence ($\sim 10^5$ yr) as a red supergiant (Brunish & Truran 1982). This is substantially less than the recombination time ($\sim 10^5/N_H$ yr). Thus, an O8 or O9 progenitor surrounded by a pervasive low-density medium can account for our observations.

On the other hand, based on the X-ray morphology of the SNR, Levenson et al. (1997) favor a scenario with a progenitor of spectral type later than B0. According to them, the Cygnus Loop evolved within the $\sim 20$ pc homogeneous low-density H II region created by this progenitor, and is now bursting into the relatively dense and inhomogeneous medium surrounding it, in the manner described by McKee, Van Buren, & Lazareff (1984). This would explain the existence of abundant local inhomogeneities on the external surface of a nearly circular remnant. Note that an earlier type progenitor would create a larger homogeneous cavity.

The UV radiation produced by the SN explosion can also be an important ionizing source, as was palpably revealed when narrow emission lines appeared in the UV spectra of SN 1987A $\sim 70$ days after the event (Fransson et al. 1989). At least $\sim 10^{44}$ ergs of ionizing energy was required to produce these lines (Fransson et al. 1989), substantially less than the $10^{46}-10^{47}$ ergs that hydrodynamical models had predicted for the ionizing burst of SN 1987A (Shigeyama, Nomoto, & Hashimoto 1988; Woosley 1988). However, values as large as $10^{48}-10^{49}$ ergs in ionizing energy have been mentioned in the literature (Chevalier 1977; Chevalier 1990). If the mean photon energy is 20 eV, the largest radiation “pulse” ionizes the surrounding medium up to a distance of $14 N_H^{-1/3}$ pc at the most, where $N_H$ is the mean hydrogen density. The density would have to be smaller than 0.02 cm$^{-3}$ in order to produce a 50 pc bubble of ionized gas. Observations and models for the evolution of the Cygnus Loop lead to substantially larger mean densities in the surrounding medium (e.g., Ku et al. 1984).

Ultraviolet photons are constantly being supplied by the expansion of the SNR as the shock-heated particles produce ionizing radiation as they move downstream. This has been discussed in the numerous radiative shock wave models developed over the last 25 yr (e.g., Cox 1972; Dopita 1977; Raymond 1979; Cox & Raymond 1985; Shull & McKee 1979; Binette, Dopita, & Tuohy 1985; Sutherland, Bicknell, & Dopita 1993). The effect of this ionizing radiation on the upstream gas has been considered in the context of active galactic nuclei (AGNs) (Daltabuit & Cox 1972) or, more recently, the emission-line filaments in Centaurus A (Sutherland et al. 1993). A review of the many topics opened up by this question can be found in Dopita (1995). To the best of our knowledge, however, little attention has been directed to the effect of the photoionizing flux of SNRs on the Galactic interstellar medium. At this point, we are specifically interested in determining the size of the bubble of ionized gas that can result from the UV flux produced by the shock-heated particles, in order to establish whether the energy source is sufficient to create the large sphere of ionized gas that is implied by our observations. An estimate of this quantity can be determined by following a very simple line of arguments. The number of upstream-moving photons produced each second by a SNR expanding into a medium with density $N_0$ is given by

$$P_{UV} = 4\pi R_0^2 N_0 V_0 \phi_{UV},$$

where $\phi_{UV}$ is the number of upstream-moving UV photons produced per shocked particle, and $R_0$ and $V_0$ are the remnant’s radius and velocity. If this quantity is equal to the number of recombinations, then

$$R_i/R_0)^3 = 74.8 V_7 \phi_{UV}/(N_0 R_{pc}) + 1,$$

where $R_i$ is the radius of the ionized volume measured from the remnant’s center, $V_7$ is the shock velocity in $100$ km s$^{-1}$, and $R_{pc}$ is the radius of the SNR in parsecs. The latter can be determined by assuming that the evolution of the Cygnus Loop is described by Sedov’s solution (Sedov 1959). In the case of the Cygnus Loop, this assumption may be objectionable, but is probably adequate given the scope of this discussion. In this case,

$$R_{pc} = 19.4 (E_{50}/N_0)^{1/3} V_7^{-2/3},$$

where $E_{50}$ is the kinetic energy deposited in the SNR in $10^{50}$ ergs. Equations (2) and (3) lead to

$$(R_i/R_0)^3 = 3.86 V_7^{2/3} \phi_{UV}/(E_{50} N_0^{2/3}) + 1.$$
The size of the region that can be ionized by photons produced by the shock-heated particles, $R_n$, can now be determined from equations (3), (4), and (5). Results as a function of shock velocity are presented in Table 4 for three combinations of $(E_{50}, N_o)$: $(1, 1), (3, 0.2)$, and $(1, 0.2)$. The second set of parameters is representative of the Cygnus Loop (Ku et al. 1984). As can be seen, a 50 pc ionized bubble can be produced even in the most conservative case. The size of the region of ionized gas is surprisingly large when the standard parameters for the Cygnus Loop are considered. Furthermore, since the evolutionary timescale of a SNR is much shorter than the recombination time, it follows that the ionizing radiation supplied by the remnant as it continues evolving would further increase the size of the ionized region. Consequently, it appears that, at least from the point of view of the energy budget, radiative shock waves can produce a very extended environment of ionized matter around them. A stricter analysis is no doubt necessary, but it seems improbable that this will lead to a qualitatively different conclusion about the number of ionizing photons produced by the expanding SNR, and consequently the size of the region that will be influenced by them. But if there seems to be little doubt that SNRs can ionize large regions of the interstellar medium, it remains to be shown that these objects can do so in the course of their evolution. This is an essential point in relation to this work.

It is worth pointing out that in comparison to other ionizing sources, the ionizing energy produced by SNRs can be of considerable importance. Integrating equation (I) with the aforementioned hypotheses, it is easy to see that a SNR will produce $1.2 \times 10^{50} E_{50}$ UV photons as it slows down from 250 to 80 km s$^{-1}$, $\sim 30\%$ of its initial kinetic energy if the mean photon energy is 15 eV. On the other hand, any main-sequence B0 or O-type star will produce $\sim 10^{43}$ UV photons during its lifetime. Considering that SNe are $\sim 20$ times more abundant than O-type stars, this implies that during their radiative phase, SNRs will generate about 1/10 of the UV flux produced by all B0 and O-type stars. This is not a small number. Furthermore, SNRs will be a major source of UV radiation in stellar systems lacking massive stars.

5. CONCLUSIONS

Evidence has been presented for the existence of an extended ionized medium surrounding the eastern face of the Cygnus Loop, and quite possibly the entire remnant. The shock transition is revealed by the slow rise in the specific intensity of [O II] $3729$ and [O III] $5007$ as the X-ray perimeter of the SNR is crossed. This is indisputable proof that this medium is in the immediate vicinity of the Cygnus Loop. Our most distant pointing (region E26) is $\sim 36$ pc away from the remnant’s center, which implies that there is ionized gas at least up to a distance of $\sim 50$ pc. It would be interesting to observe more distant regions, preferably in the O$^+2$ line, in order to see whether there is an outer boundary or if the medium merges smoothly with the general background. The medium around the Cygnus Loop is somewhat different from the general Galactic background: [O II] $3729$ and [O III] $5007$ are usually brighter, and there are indications that the degree of ionization, given by $N(0^+)/N(O^+)$, is also larger around the SNR. On the other hand, it is similar insofar as He I $5876$ emission is also conspicuously absent.

We explored several possible sources that may produce the ionizing energy required to account for the existence of this medium. Viable external sources, such as an isolated early-type star or an OB association, could not be found. We also concluded that the ionizing radiation produced by the SN explosion was probably insufficient. An early-type (between O8 and O9, but closer to the former) progenitor embedded in a low-density medium could account for the required energy budget, but a later type progenitor has been suggested by Levenson et al. (1997). Finally, we showed that the UV radiation produced by the shock-heated particles can generate a large bubble of ionized gas, but detailed modeling is required in order to see if it will do so during the SNR’s lifetime.

From the observational point of view, it is advisable to inspect other emission lines in order to explore the spectral properties of the medium surrounding the Cygnus Loop, and to decide if it is indeed distinct from the warm component of the interstellar medium. Unfortunately, our instrumental resolution is insufficient to discriminate between coronal and Galactic Hα emission, the key line in Reynolds’ research on the properties of this component of the medium. But other spectral lines, such as [N II] $6584$ Å and [S II] $6717, 6731$ Å, are open to inspection, since they are less affected by geocoronal emission. Needless to say, similar observations of the medium surrounding other SNRs should furnish valuable information. Targets located away from the Galactic plane are preferable, since background confusion is avoided. Further research along these lines may be helpful regarding the still open question of the origin of the warm partially ionized component of the interstellar medium, given the relatively large flux of UV photons produced by radiative shock waves. As we pointed out, the photoionizing flux produced by SNRs will be particularly important in systems lacking massive stars.

The excellent support received from C. Blondel, P. Mulet, and the technical staff at San Pedro Mártir observatory is gratefully acknowledged. We thank the anonymous referee for comments and suggestions that lead to great improvements of this paper, and in particular for pointing out the effect of contamination from the other order on the standard star continuum.

REFERENCES

Ballet, J., Caplan, J., Rothenflug, R., Dubreuil, D., & Soutoul, A. 1989, A&A, 211 217
Ballet, J., & Rothenflug, R. 1989, A&A, 218, 277
Binette, L., Dopita, M. A., & Tuohy, I. R. 1985, ApJ, 297, 476
Bochkarev, N. G., & Sitnik, T. G. 1985, Ap&SS, 108, 237
Brunish, W. M., & Truran, J. W. 1982, ApJS, 49, 447
Chevalier, R. A. 1977, ARA&A, 15, 175
—. 1990, in Supernovae, ed. A. G. Petschek (New York: Springer), 91
Cox, D. P. 1972, ApJ, 178, 143
Cox, D. P., & Raymond, J. C. 1985, ApJ, 298, 651
Cruz-González, C., Recillas-Cruz, E., Costero, R., Peimbert, M., & Torres-Peimbert, S. 1974, Rev. Mexicana Astron. Astrofís., 1, 211
