THE PHOTOIONIZATION OF A STAR-FORMING CORE IN THE TRIFID NEBULA

B. Lefloch,1 J. Cernicharo,2 L. F. Rodríguez,3 M. A. Miville-Deschênes,4 D. Cesarsky,5 and A. Heras6

Received 2002 February 8; accepted 2002 August 6

ABSTRACT

We have carried out a comprehensive multiwavelength study of the bright-rimmed globule TC2 in the Trifid Nebula, using the IRAM 30 m telescope, the VLA centimeter array, and the Infrared Space Observatory (ISO). TC2 is one of the very few globules to exhibit signs of active ongoing star formation while being photoevaporated by the Lyman continuum flux of the exciting star of the nebula (~1010 cm−2 s−1). The globule consists of a cold dense core of mass 27 M⊙ surrounded by a lower density envelope of molecular gas. The impinging Lyman continuum photons induce the propagation of an ionization front into the globule. The evaporation of the ionized gas forms a thin layer of density ne ≈ (1–2) × 103 cm−3 around the globule, which could be mapped with the VLA. The globule is illuminated mainly on its rear side, by a far-ultraviolet field of intensity G0 ≈ 1000. It creates a photon-dominated region (PDR) below the surface, which was mapped and characterized with the ISOCAM circular variable filter and the Short Wavelength Spectrometer (SWS) on board ISO. The physical conditions derived from the analysis of the far-infrared lines [O i] 63, 145 μm and [C ii] 158 μm and the continuum emission are in good agreement with some recent PDR models. The emission of the polycyclic aromatic hydrocarbon band at 6.2, 7.7, 8.6, and 11.3 μm is detected over the whole globule. The relative intensity variations observed across the globule, in the PDR and the photoionized envelope, are consistent with the changes in the ionization fraction. In the head of TC2, we find a second kinematic component, which is the signature of the radiatively driven collapse undergone by the globule. This component indicates that the PDR propagates at low velocity inside the body of TC2. The molecular emission suggests that the star formation process was probably initiated a few times 105 years ago, in the large burst that led to the formation of the nebula. The globule has already evaporated half the mass of its envelope. However, the ionization timescale of the globule is long enough (~2 Myr) to let the protostellar objects reach smoothly the ultimate stages of protostellar evolution. The impact of photoionization on the star formation process appears limited.

Subject headings: dust, extinction — H ii regions — ISM: globules — ISM: individual (Trifid Nebula) — ISM: jets and outflows — stars: formation

1. INTRODUCTION

It is well established that the bright-rimmed globules found in H ii regions are often sites of star formation. Reipurth (1983) first showed that these objects do form stars, and subsequent work based on IRAS data by Sugitani, Fukui, & Ogura (1991) confirmed that they are indeed active “stellar factories” that produce intermediate-mass (Herbig AeBe) stars. These condensations are local clumps that emerge from the expanding nebula or form from the fragmentation of the dense molecular layer surrounding the ionized gas. The various theoretical works (Bertoldi 1989; Bertoldi & McKee 1990; Lefloch & Lazareff 1994, hereafter LL94) and the numerous observational studies on bright-rimmed globules (see, e.g., Cernicharo et al. 1992; Lefloch & Lazareff 1995) have enabled us to draw the following evolutionary picture, summarized in Figure 1.

As a globule of neutral gas is exposed to the ionizing field of the exciting star(s) of the nebula (region I in Fig. 1), an ionization front (IF) forms at the surface of the condensation. For standard ionization conditions, the pressure of the surface ionized gas is much higher than in the nebular gas and in the molecular globule. As a consequence, the photoionized gas expands into the H ii region, inducing the formation of a photoionized envelope around the globule. It is the ionization front and the photoionized envelope that are detected in the optical as a bright rim (region II). The incident far-ultraviolet (FUV) field drives the formation of a photon-dominated region (PDR; region III), while a shock front, driven by the surface overpressure, propagates toward the dense molecular core (region IV). Observational evidence of this mechanism, also called radiatively driven implosion (RDI), has been reported in a few objects by Cernicharo et al. (1992) and Lefloch & Lazareff (1995). Progressively, a dense core forms behind the surface, and the globule adjusts its internal structure to balance the pressure of the ionized gas, while the bulk of its mass is photoevaporated. Eventually, the globule reaches a quasi–steady state, the “cometary phase,” in which the shock front has disappeared. The globule now consists of a small dense “head” prolonged by a long tail of diffuse gas.
It has long been suggested that the shock front inside the globule could trigger the star formation inside the bright-rimmed globules (see, e.g., Reipurth 1983; Lefloch, Lazareff, & Castets 1997). These objects appear therefore as ideal laboratories to test the scenarios of star formation triggered by an external compression wave. Most of the studies led until now were focused on the molecular core of bright-rimmed globules (see, e.g., Lefloch et al. 1997). Therefore, the physical conditions reigning in the PDR and in the shocked molecular gas are not well characterized, and the impact of photoionization on the gravitational collapse is therefore difficult to evaluate. Moreover, all the bright-rimmed condensations studied until now are found in relatively old H II regions, with ages of a few Myr. Because the condensations are usually found at rather large distances from the ionizing stars, they experience a reduced UV field, and it is difficult to discriminate between a star formation induced by RDI and a spontaneously evolving globule that has already started to form stars by the time it is hit by the ionization front.

This is why we have started a systematic multiwavelength study of a young H II region: the Trifid Nebula. It appears as a small dusty nebula of 10' diameter at a heliocentric distance of 1.68 kpc (Lynds, Canzian, & O’Neil 1985), with a dynamical age of 0.3–0.4 Myr (see Fig. 2). The nebula is excited by the O star HD 164492A. In a preliminary work (Cernicharo et al. 1998, hereafter C98), we reported on the continuum and molecular line emission around the two most massive protostellar cores: TC3 and TC4. Their masses are high, between 60 and 90 $M_\odot$. They harbor a Class I source and one of the few high-mass Class 0 candidates known until now. Comparison of their properties with the models of Elmegreen & Lada (1977) and Whitworth, Bhattacharya, & Chapman (1994) allowed us to conclude that the formation of TC4 had probably been triggered in the fragmentation of the dense shell surrounding the ionized gas. The molecular properties of TC3 and TC4 are similar to those of the protostellar cores discovered in Orion, although at an earlier, “pre-Orion,” evolutionary stage.

We report here on the TC2 protostellar core, which is associated with a bright-rimmed globule on the southern border of the Trifid. TC2 appears to be in a more advanced stage of photoionization than TC3 or TC4: unlike TC3 and TC4, which are still embedded cores, TC2 has already emerged from the diffuse molecular gas layers and exhibits the optical bright rim and the cometary shape typical of photoionized globules. As discussed in this work, TC2 is exposed to a rather strong ionizing field, which drives a shock into the condensation, in agreement with the evolutionary scheme presented above. Like TC3 and TC4, TC2 displays signs of protostellar activity. C98 reported the presence of the Herbig-Haro jet HH 399 coming out of the head of the globule and propagating into the ionized nebula. It is the best example of globules undergoing at the same time strong photoevaporation and active star formation. It offers a good opportunity to study the relation both phenomenons hold to each other and to better constrain the role that RDI could play in the star formation process.

For this purpose, we have led a detailed study of the structure and the physical conditions of the globule (density, temperature, velocity). Because TC2 lies almost in the plane of the sky, it provides also a good opportunity to study the structure of a typical low-density PDR and to confront its properties against the existing models. This work provides the first comprehensive study of the whole gas structure of a bright-rimmed globule, from the ionized surface layers to the cold dense molecular core.

The paper is organized as follows. We first derive the structure of the globule: the H II region (§3), the bright rim and the photoevaporated envelope (§4), the PDR (§5), the dust continuum emission (§6), and the molecular core (§7). We then discuss the observational evidences of RDI in TC2 and the implications on the past history of the globule (§8). In the following section we first study the star-forming conditions in TC2 and attempt to characterize the protostellar source and the outflowing material, before studying the impact of photoionization on both the protostar and the evolution of the globule (§9). The conclusions are presented in §10.

2. OBSERVATIONS

2.1. Observational Approach

The determination of the physical conditions in the various regions in TC2 requires a compared study of the spectral line and continuum emission mapped at various wavelengths. The photoionized envelope at the surface of TC2 was characterized from observing the radio free-free
emission with the Very Large Array (VLA), following the same approach as LeFloch et al. (1997). Additional constraints on the envelope and the surrounding nebular gas in the Trifid were brought by the fine-structure atomic and ionic lines detected in the mid-infrared and far-infrared (FIR) with the Infrared Space Observatory (ISO; Kessler, Steinz, & Anderegg 1996). The conditions in the molecular core were derived from the emission of the cold dust and of several individual fields centered on the brightest condensations of the nebula. Each field was scanned in the horizontal direction by moving the telescope at a speed of 4″ s⁻¹; subsequent scans are displaced by 4″. We used a chopping secondary at 2 Hz with a throw of 30″–60″ depending on the structure of the region to be mapped. Calibration was checked against Mars. The weather conditions were good and rather stable during the two observing sessions. The opacity was monitored every hour on average, and we found typical zenith opacities between 0.1 and 0.35. Pointing was checked every hour as the source transits at low elevation at Pico Veleta, and corrections were always found to be lower than 3″. The final rms is 8 mJy/11″ beam. Hence, it is sensitive enough to detect at the 3 σ level protostellar condensations of 1 M⊙ at 20 K in one 11″ telescope beam (0.09 pc at the distance of the Trifid). In order to outline the weak extended dust components in the nebula, we degraded the angular resolution of our map down to 15″ (0.13 pc at the distance of the Trifid) by convolving the emission with a Gaussian of 11″ HPFW. The resulting rms in the map is 5 mJy beam⁻¹. All the results quoted in this paper are based on the nondegraded map with 0.09 pc resolution.

2.4. Molecular Line Observations

We observed in 1996 July and 1997 July the Trifid Nebula in the millimeter lines of SiO, HCO⁺, H13CO⁺, and CS, with the IRAM 30 m telescope. The lines were observed with a spatial sampling of 15″; the data are almost Nyquist sampled at 3 mm. We used an autocorrelator as the spectrometer, which provided a velocity resolution of ≈0.2 km s⁻¹ in all three bands. The rejections of the receivers were always higher than 10 dB and checked against W51D (Mauersberger et al. 1989). The Trifid was mapped at full sampling in the CO J = 2 → 1, J = 1 → 0, 13CO J = 1 → 0, and C18O J = 1 → 0 lines with the IRAM 30 m telescope in 1996 July. The autocorrelator provided a kinematic resolution of 0.2 km s⁻¹ for all the transitions. Additional observations of the CO J = 3 → 2 transition were carried out at the Caltech Submillimeter Observatory (CSO) during various observing runs between 1998 and 1999. The receiver was connected to an acousto-optical spectrometer (AOS) that provided a kinematic resolution of 0.4 km s⁻¹. All the observed lines, their frequency, the telescope beamwidth, and the main-beam efficiencies are summarized in Table 2.

### Table 1

| Zone | Instrument | Observations | Wavelength | Figures |
|------|------------|--------------|------------|---------|
| I (H II region) | VLA | Free-free radiation | 3.6 cm, 20 cm | 6a, 6b, 16 |
| II (bright rim) | NOT | Hα, [S II] | Optical | 2, 4 |
| | SWS, CVF, LWS | Atomic lines: [Ne II], [Ne III], [S III], [N II], [O II], [S II], [C II] | 2.5–197 μm | 5, 7 |
| | SWS | Continuum (dust) | 2.5–45 μm | 11 |
| III (PDR) | ISO/CAM | LW10 | 8–15 μm | 3 |
| | CVF | PAH bands | 5–17 μm | 7, 8 |
| | SWS, LWS | Continuum (dust) | 2.5–197 μm | 11, 12 |
| | SWS, LWS | Atomic lines: [O I], [C II], [S II] | 2.5–197 μm | 5, 7 |
| | IRAM 30 m | Continuum (dust) | 45–197 μm | 12 |
| | CO, 12CO, C18O, HCO⁺, SiO, CS | CO | 1–3 mm | 13, 14, 15 |
| | CSO | CO | 0.8 mm | 13 |
2.5. Mid-Infrared Observations

We observed the Trifid Nebula with ISOCAM (Cesarsky, Abergel, & Agnese 1996) on board ISO. An image of the whole nebula was obtained using the broadband LW10 filter ($\lambda = 11.5$ $\mu$m, $\Delta \lambda = 7$ $\mu$m) with a pixel size of 3". The mid-infrared emission around TC2 was observed in the circular variable filter (CVF) mode between 5 and 17 $\mu$m. The pixel size is 1.5" $\times$ 1.5", and the spectral resolution is 40. The 32 $\times$ 32 pixel detector covered a total field of view of 48" $\times$ 48" centered on the globule at $\alpha = 18^h02^m28.7^s$, $\delta = -23^\circ03'51''$ (J2000.0). The size of the point-spread function varies between $\approx 1.5$ at 5 $\mu$m and $\approx 6''$ at 17 $\mu$m. The data were reduced with the SLICE software and following the method of Miville-Deschenes et al. (2000).

The emission between 2 and 45 $\mu$m was observed with the Short Wavelength Spectrometer (SWS) on board ISO (de Graauw et al. 1996) in the SW01 mode (2.4–45 $\mu$m grating scan). The spectral resolution was 300. A spectrum was taken right on the head of TC2; two additional spectra were taken at a position shifted by +20$''$ and -20$''$ in declination, in order to measure the emission toward the bright rim and the H ii region and toward the main body of the globule, respectively. The positions are marked in Figure 4. We note that there is some overlap between the three beams. In particular, the beam centered 20$''$ north of the globule encompasses the northern part of the bright rim. The SWS data consist of an “up” scan, toward decreasing wavelengths, and a “down” scan, toward increasing wavelengths. The lines identified and their flux (obtained after averaging the “up” and “down” scans) are given in Table 3. The calibration accuracy varies from 5% at 2.5 $\mu$m to 30% at 45 $\mu$m (Leech et al. 2001). Because of the high noise, the statistical errors in the line fluxes are a priori not negligible in front of the systematic errors in the flux calibration. Therefore, we

| Table 2 | Millimeter Lines Observed toward TC2: Frequency, Telescope Beamwidth, and Efficiency |
|---------|-----------------------------------------------------------------------------------|
| Line    | Frequency (GHz) | Beamwidth (arcsec) | $B_{eff}$ |
| H$^{13}$CO$^+$ $J = 1 \rightarrow 0$... | 86.75429 | 28 | 0.77 |
| SiO $J = 2 \rightarrow 1$.............. | 86.84700 | 28 | 0.77 |
| HCO$^+$ $J = 1 \rightarrow 0$........... | 89.18852 | 27 | 0.75 |
| CS $J = 2 \rightarrow 1$.............. | 97.98097 | 24 | 0.71 |
| C$^{18}$O $J = 1 \rightarrow 0$........ | 109.78218 | 22 | 0.68 |
| $^{13}$CO $J = 1 \rightarrow 0$........ | 110.20135 | 22 | 0.68 |
| CO $J = 1 \rightarrow 0$.............. | 115.27120 | 21 | 0.67 |
| SiO $J = 3 \rightarrow 2$.............. | 130.26870 | 18 | 0.58 |
| CS $J = 3 \rightarrow 2$............... | 146.96905 | 16 | 0.53 |
| SiO $J = 5 \rightarrow 4$.............. | 217.10494 | 11 | 0.42 |
| CO $J = 2 \rightarrow 1$.............. | 230.53800 | 10 | 0.39 |
| CO $J = 3 \rightarrow 2$............... | 345.79599 | 22 | 0.75 |

Fig. 2.—[H$\alpha$] image of the Trifid Nebula observed with the Nordic Optical Telescope (NOT; C98). The location of bright-rimmed globule TC2 is marked by a white rectangle. The positions observed with ISO/LWS and the telescope beams are indicated by circles.
have compared the emission in the up and down scans in order to estimate the actual uncertainty in the line fluxes. For all the lines detected, except the [Ne\textsc{iii}] line at 15.55 $\mu$m, a very good agreement was found between both measurements. On the contrary, very large variations, up to a factor of 4, were observed in the flux of the [Ne\textsc{iii}] line.

The emission between 45 and 197 $\mu$m was observed toward the globule with the Long Wavelength Spectrometer (LWS) on board ISO (Clegg et al. 1996). The size of the LWS beam is known to vary between 66$^\prime\prime$00 and 86$^\prime\prime$00 HPFW depending on the detector’s band. This effect was taken into account to estimate the line fluxes: the detector beam sizes were taken from the ISO Handbook for the LWS (Gry et al. 2002). The large-scale emission of the nebula was estimated by observing a nearby reference position 90$^\prime\prime$00 away from TC2, at position $\alpha$ = 18$^h$02$^m$35$^s$1, $\delta$ = $-23^\circ$03$'$51$''$8 (J2000.0) (see Fig. 2). The data were reduced using the OLP package, Version 7, and the ISAP package. The fluxes measured are given following the standard flux calibration, assuming a pointlike source. The uncertainty in the absolute flux calibration quoted for LWS is 10%–15%. However, as discussed in the text, part of the emission in the LWS beams arises from the nebular gas, i.e., very extended emission that depending on the detector’s band. This effect was taken into account to estimate the line fluxes: the detector beam sizes were taken from the ISO Handbook for the LWS (Gry et al. 2002). The large-scale emission of the nebula was estimated by observing a nearby reference position 90$^\prime\prime$ away from TC2, at position $\alpha$ = 18$^h$02$^m$35$^s$1, $\delta$ = $-23^\circ$03$'$51$''$8 (J2000.0) (see Fig. 2). The data were reduced using the OLP package, Version 7, and the ISAP package. The fluxes measured are given following the standard flux calibration, assuming a pointlike source. The uncertainty in the absolute flux calibration quoted for LWS is 10%–15%. However, as discussed in the text, part of the emission in the LWS beams arises from the nebular gas, i.e., very extended emission that

### Table 3

| Line   | Band | $\lambda$ (\micro m) | Aperture (arcsec) | $F_0^{(0, +40)}$ (W cm$^{-2}$) | $F_0^{(0, +20)}$ (W cm$^{-2}$) | $F_0^{(0, -20)}$ (W cm$^{-2}$) |
|--------|------|----------------------|-------------------|-------------------------------|-------------------------------|-------------------------------|
| [Ne\textsc{ii}]| 3A   | 12.8                 | 14 $\times$ 27    | (7.5 ± 0.7)(−19)              | (9.0 ± 0.9)(−19)              | (8.4 ± 0.8)(−18)              |
| [Ne\textsc{ii}]$^a$ | 3A   | 15.5                 | 14 $\times$ 27    | (6.9 ± 0.7)(−19)              | (9.0 ± 0.9)(−19)              | (9.0 ± 0.9)(−19)              |
| [S\textsc{ii}]| 3C   | 18.7                 | 14 $\times$ 27    | (1.3 ± 0.1)(−18)              | (1.3 ± 0.1)(−18)              | (9.0 ± 0.9)(−19)              |
| [S\textsc{ii}]| 4    | 33.5                 | 20 $\times$ 33    | (4.2 ± 1.2)(−18)              | (3.9 ± 1.0)(−18)              | (3.6 ± 1.0)(−18)              |
| [Si\textsc{ii}] | 4    | 34.8                 | 20 $\times$ 33    | (9.6 ± 2.9)(−19)              | (9.6 ± 2.9)(−19)              | (8.3 ± 2.5)(−19)              |

\textbf{Note.}—The fluxes are uncorrected for the mid-IR extinction. Notation $a(b)$ indicates $a \times 10^b$.

$^a$ Unreliable as a result of large statistical errors.
fills the beam. Therefore, we adopt in this case a somewhat more conservative number of 20%. The identified lines and the fluxes are listed in Table 4. The spectrum of the globule was obtained after subtracting the emission of the reference position (Off source) from the emission measured On source.

3. H II REGION: ZONE I

We proceed first with the analysis of the H II region as TC2 is embedded in the ionized gas and an estimation of the physical conditions of the ionized bright rim (see next section) requires a knowledge of the contribution to the atomic fine-structure lines from the H II region.
3.1. Emission from the Nebular Gas

We show in Figure 5 the various atomic and fine-structure atomic lines detected with the LWS and SWS. Many of the identified lines exhibit weak variations between the On and Off positions.

The best example is provided by \([\text{C}\text{ ii}]\) at 158 \(\mu\)m. On the other hand, the largest variations are observed for the \([\text{O}\text{ i}]\) lines at 63.3 and 145.5 \(\mu\)m. In particular, almost no emission at all is detected in the 145 \(\mu\)m line at the reference position.

The \([\text{O}\text{ iii}]\) 52 and 88 \(\mu\)m and \([\text{N}\text{ iii}]\) 57 \(\mu\)m lines are useful tools to diagnose the electron density in the ionized gas. The \([\text{O}\text{ iii}]\) 52/88 \(\mu\)m and \([\text{O}\text{ iii}]\) 52 \(\mu\)m/\([\text{N}\text{ iii}]\) 57 \(\mu\)m ratios have the advantage of being rather insensitive to the temperature and mainly trace the electron density \(n_e\) in the ionized gas. Like for the SWS data, the situation is made complicated by the fact that the LWS beam encompasses regions with very different physical conditions. In order to gain more insight on the background emission from the \(\text{H}\text{ ii}\) region and the PDR associated with the parent molecular cloud, we first consider the reference position.

The LWS flux scale is based on a point-source calibration. In the case of extended source emission, some correcting factors have to be applied to derive the correct fluxes (see paragraph 4.9.3 in the ISO Handbook for the LWS; Gry et al. 2001). Since the emission at the reference position comes from the \(\text{H}\text{ ii}\) region and fills the whole LWS beam, the fluxes have been calibrated according to the ISO manual prescription. We then obtain \([\text{O}\text{ iii}]\) 52/88 \(\mu\)m) = 0.69. This corresponds to a mean density \(n_e \approx 50 \text{ cm}^{-3}\), which is consistent with the previous determination from \([\text{S}\text{ iii}]\). In this density range, the emissivity of the 52 \(\mu\)m line is \(\epsilon_{52} = 8.0 \times 10^{-23} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\) (Dinerstein, Lester, & Werner 1985). If we assume a standard abundance \([\text{O}\text{ iii}]\)/[H\(^+\)] = 2 \times 10^{-4}, we derive an estimate of the emissivity \(\int n_e^2 dl = 2.6 \times 10^3 \text{ cm}^{-6} \text{ pc}\) and the size of the emitting region \(l \approx 1 \text{ pc}\).

In the density range measured in the \(\text{H}\text{ ii}\) region, the emissivity ratio \([\text{N}\text{ iii}]\) 57 \(\mu\)m/\([\text{O}\text{ iii}]\) 52 \(\mu\)m) is predicted to be close to 1.6 (see, e.g., Lester et al. 1987), whereas the measured line ratio is only 0.88. Since both lines trace physically...
similar regions (their critical densities are $1.88 \times 10^3$ and $3.25 \times 10^3$ cm$^{-3}$, respectively) this discrepancy mainly reflects the different relative elemental abundances. We obtain an elemental abundance ratio ([N iii]/[O iii]) $\approx 0.5$. This ratio agrees with other determinations in a sample of H ii regions by Lester et al. (1983), who obtained 0.25–0.43.

In the SWS spectra, the line [Ne ii] 12.7 $\mu$m is detected at the three observed positions: toward the head, the bright rim, and the main body of the globule. The fluxes exhibit only weak variations between the three positions. This suggests that the contribution of the H ii region, which fills the SWS beams, dominates the emission from the globule. The SWS fluxes of the [Ne iii] 15.5 $\mu$m line suffer large statistical errors, which casts some doubt on the variations measured with the SWS: whereas the fluxes in the northern and central positions are similar (better than 30%), there seems to be hardly any emission detected in the southern position.

Similarly to the [Ne ii] line, the [S iii] lines at 18.7 and 33.7 $\mu$m exhibit only weak variations between the three positions observed with the SWS. In order to determine the origin of the [S iii] emission, we first estimate the electron density from the [S iii] 18/33 $\mu$m ratio. In the case of extended sources, a correcting factor has to be applied to the SWS flux obtained with the reduction pipeline in order to derive the correct source flux (Salama 2000). It is difficult to estimate the interstellar absorption on the line of sight. Since the emission arises from the region close to the optical bright rim, we believe that the interstellar extinction should be rather low, and we will neglect the latter in what follows. We estimate an emissivity ratio $\epsilon_{18.7}/\epsilon_{33.7} \approx 0.7$ for the northern spectrum. This ratio allows us only to set an upper limit on the electron density (Rubin 1989): $n_e \leq 200$ cm$^{-3}$. If the contribution of the bright rim were dominant, one would obtain a much larger emissivity ratio, of $\sim 2$, as expected for the electron densities obtained with the VLA ($\sim 10^3$ cm$^{-3}$). This agrees with previous determinations of the nebular gas density by Lynds et al. (1985) and Rosado et al. (1999) from the optical [S ii] $\lambda\lambda 6717, 6731$ lines and with our determination from the atomic fine-structure lines detected with the LWS (see above). We conclude that the main contribution to the [S iii] flux arises from the H ii region.

3.2. Effective Stellar Temperature of HD 164492A

Simpson et al. (1995) showed that it is possible to use the ionization fraction ratios of heavy elements such as S, O, or N in order to constrain the effective stellar temperature $T_{\text{eff}}$ by comparison with models of H ii regions. In particular, Rubin (1985) calculated the integrated fluxes of numerous ionic lines of such heavy elements for a wide range of conditions including the neutral gas density and the effective stellar temperature. These models predict that the ionization fraction ratio $\langle O^{+2}/O^{+}\rangle/\langle S^{+2}/S^{+}\rangle$ spans 3 orders of magnitude when the effective temperature of the exciting star is in the range (3–4) $\times 10^4$ K (see, e.g., Fig. 8 in Simpson et al. 1995).

The method to derive the ionization fraction ratio is fully discussed in Simpson et al. (1995). We first estimate the ion ratio $O^{+2}/S^{+2}$ from the [O iii] lines at 52 and 88 $\mu$m and the [S iii] 19 $\mu$m line. The emissivities for [O iii] and [S iii] are taken from Dinerstein et al. (1985) and Rubin et al. (1994), respectively. We adopted $O/S = 47$ as the elemental abundance, which is the value found in the Orion Nebula (Rubin et al. 1991). We obtain $\langle O^{+2}/O^{+}\rangle/\langle S^{+2}/S^{+}\rangle \approx 0.04$ and 0.09 toward the Off and On positions, respectively. The variations of $\langle O^{+2}/O^{+}\rangle/\langle S^{+2}/S^{+}\rangle$ versus the effective stellar temperature $T_{\text{eff}}$ for ionizing luminosities in the range log $L_v$ = 49–50 indicate $T_{\text{eff}} \approx 35,500$ K (Fig. 8 in Simpson et al. 1995). An effective temperature of 38,000 K, typical of an O7 V star, requires a ratio $\langle O^{+2}/O^{+}\rangle/\langle S^{+2}/S^{+}\rangle$ of a few, i.e., 10–20 times larger. There is a priori a restriction in directly applying the models of Rubin since the density of the Trifid (100 cm$^{-3}$) is somewhat less than the density considered in the calculations. However, in the range of temper-

![Fig. 9.—Comparison of the mid-infrared emission in the core of the globule (position F; bottom spectrum) with the emission in the PDR at position D without absorption (top spectrum) and with an absorption of 20 mag (dashed contour). The flux scale of the spectra in the core of TC2 and in the absorbed PDR has been divided by 2.0.](image-url)
The bright-rimmed globule TC2 is located on the southern border of the H II region, at approximately 1 pc of the exciting star of the nebula, HD 164492A. An optical Hα image of the nebula (taken from C98) is shown in Figure 2. The TC2 region is marked by a white rectangle. The globule exhibits the typical bright rim of that class of photoionized condensations (see also the magnified view in Fig. 4); it indicates that the condensation lies almost in the plane of the sky, coplanar with HD 164492A, on the southern border of the nebula. Hence, the projected distance must be close to the physical distance between both objects. We determined the mean radius $R_g$ of TC2, based on the optical image: $R_g \approx 4 \times 10^{17}$ cm.

Some weak extended [S II] emission is detected south of the bright rim (Fig. 2). The brightness is much higher at the surface of the globule than in the dust lanes of the nebula. This indicates the presence of ionized gas between the globule and the observer and gives direct evidence of the physical association between TC2 and the Trifid. The kinematical analysis of the molecular gas shows that the globule belongs to a large-scale feature connected to the dust lanes on the front side and does not lie on the back side of the nebula (B. Lefloch, J. R. Pardo, & J. Cernicharo 2002, in preparation). Therefore, TC2 is “bathing” in the nebular ionized gas.

The peak of brightness is found, as expected, in the direction of the exciting star of the nebula HD 164492A. However, the major axis of the globule does not point toward the star but in the north direction. This difference in the orientation might reflect some inhomogeneities in the gas distribution or the influence of other stars that formed at the same time as HD 164492A: the energy released would have affected the expansion of the H II region. Indeed, Lefloch et al. (2001) have reported the presence of several young high- and intermediate-mass stars in the H II region, some of which have been identified as strong X-ray emitters (Rho et al. 2001).

On the left side of the bright rim, close to the offset position (+75°, −95°), the HH 399 jet powered by TC2 (Figs. 4–6) is detected as a conspicuous bright filament that seems to penetrate the surface and makes a P.A. of ~20° with respect to north. At the basis of the jet, a “dark filament” is detected in absorption against the bright rim and emerges from the globule. This filament is probably related to some inhomogeneities or some instabilities at the surface of the globule.

Depending on the spectral type adopted (see § 3.2), the Lyman continuum luminosity of the star lies in the range (7–10) × 10^{48} s^{-1}. Moreover, a fraction of the ionizing photons is consumed in radiative recombinations within the ionized gas or absorbed by the dust between the exciting star and the globule. The dusty aspect of the nebula in the optical images suggests that the absorption of the ionizing radiation might play a nonnegligible role. C98 presented a map of the free-free emission at 20 cm, obtained with the VLA at 10° resolution. We show in Figure 6 (left) an excerpt of this map, centered on the globule. The map reveals mainly the large-scale emission from the nebula. The photoionized layer is also detected as a region of maximum flux on the western side of the globule. However, the angular resolution is not high enough to discriminate the emission of the ionization front and the ionized gas close to the surface from the nebular emission, associated with lower density gas.

In this section we first evaluate the electron density and the intensity of the ionizing field at the surface of the globule from the free-free emission observed at the VLA. We then use the various fine-structure ionic lines detected with ISO to determine the geometry of the illumination with respect to the globule.

4. Bright Rim

In order to characterize the ionizing conditions at the surface of TC2 (ionizing field intensity, electron density), we have studied the emission of the bright rim with the VLA at high angular resolution (~1°5). The map of the 3.6 cm continuum emission is shown in Figure 6 (right).

The bright rim is clearly detected; it is marginally resolved in its transverse direction with a thickness
shell of uniform density molecular material of the globule from the incoming ion- 
detected in the optical as the bright rim. The radiative photoionization of the surface 
layers induces the forma-

\[ \frac{S_v}{(1 \text{ mJy})} = 2.36 \times 10^{-5} \left( \frac{n_e}{1 \text{ cm}^{-3}} \right)^2 \left( \frac{n_{R_{\text{g}}}}{0.1 \text{ pc}} \right) \times \left( \frac{T_e}{10^5 \text{ K}} \right)^{-0.35} \left( \frac{\nu}{1 \text{ GHz}} \right)^{-0.1} \left( \frac{\theta_e}{10^{\circ}} \right)^2. \]

We assume in this formula that the size of the emitting region along the line of sight is of the same order as the thickness of the ionized shell; i.e., we neglect any inclination effect. We adopted the mean electron temperature in the nebula determined by Chaisson & Willson (1975) from centimeter continuum measurements at 4' resolution: \( T_e \approx 8150 \text{ K} \). We measure a total flux of 2.3 mJy in an area of 74 arcsec\(^2\), defined by the contour level at 20 \( \mu \text{Jy}^{-1} \), assuming that the bright rim radial size is similar to the thickness of the ionized shell, i.e., \( \eta = 0.08-0.11 \). We derive an average electron density \( n_e = (1.0-1.2) \times 10^3 \text{ cm}^{-3} \) over the bright rim. At the brightness peak, the 3.6 cm flux is 2.6 \( \times 10^{-4} \text{ Jy beam}^{-1} \); hence, the electron density reaches a local maximum of \( n_e = 1800 \text{ cm}^{-3} \) over the telescope beam.

The effective flux of Lyman continuum photons ionizing fresh material is \( n_c c_0 \approx 10^9 \text{ cm}^{-2} \text{ s}^{-1} \) (\( c_0 \approx 10 \text{ km s}^{-1} \) is the ionized gas sound speed). As expected, this is much less than the flux of photons consumed in the photoionized layer, which is equal to \( \alpha_B m_e^2 R_{\text{g}} = 1.4 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \) (\( \alpha_B = 2.7 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1} \) is the recombination coefficient on hydrogen densities \( n \geq 2 \)). Taking into account the attenuation of the radiation between the star and the globule by the ionized gas, this value is consistent with the (absorption-free) value derived from the Lyman continuum luminosity of the exciting star, \( 8 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \) at the projected distance of TC2.

4.2. Fine-Structure Atomic Line Emission

We detected with the SWS the following ionic and fine-

structure atomic lines: [Ne ii] 12.7 \( \mu \text{m} \), [Ne iii] 15.5 \( \mu \text{m} \), [S ii] 18.7 \( \mu \text{m} \), [S iii] 33.5 \( \mu \text{m} \), and [Si ii] 34.8 \( \mu \text{m} \). The spectra are displayed in Figure 6. The fluxes of the lines identified are given in Table 3. A priori, several regions with very different physical conditions contribute to the emission detected: the H ii region (see § 3), the bright rim, and the PDR (in the case of [Si ii]). Since the [Si ii] 34.8 \( \mu \text{m} \) is believed to arise from the PDR, it is discussed below in § 5.4. The other lines have been discussed in § 3, and we concluded that within the SWS beam and the observational uncertainties the emission is dominated by the H ii region.

In order to determine the spatial distribution of the [Ne ii] and [Ne iii] lines, we use the CVF data, obtained with a much higher angular resolution (4'-6'). Moreover, the CVF data benefit a better signal-to-noise ratio (S/N) because of the low spectral resolution (\( \approx 40 \)). In order to determine the emission from the globule itself, we have subtracted the contribution of the H ii region, estimated from a nearby reference position (position E; Fig. 7). The emission from the globule, once the contribution of the nebular gas was removed, is displayed in Figure 7. The [Ne ii] emission is mostly detected along the border of the globule, at the surface, slightly shifted outside with respect to the emission of the PDR. This spatial shift is shown in Figure 7 where the contours of the polycyclic aromatic hydrocarbon (PAH) 11.3 \( \mu \text{m} \) band are superposed on the [Ne ii] emission map. The emission delineates a thin layer of \( \approx 5 \alpha \). It can be seen that there is no [Ne ii] emission detected over the body of the globule. A spectrum at position F in the main body of TC2 (Fig. 8f) confirms the absence of emission longward of 8 \( \mu \text{m} \). Therefore, the front side of the globule is hardly illuminated by the Lyman continuum photons from the exciting star. In particular, the main body of the globule is not photoionized. Some weak [Ne ii] emission is detected all around the globule, especially in the northwestern direction, i.e., toward the ionizing stars. We suggest that it could trace the freely expanding layers of the photoionized envelope around TC2. This gas is expected to leave the surface of TC2 with a velocity close to the ionized gas sound speed, \( \approx 10 \text{ km s}^{-1} \) (LL94). The detection of high gas velocities, from spectroscopic measurements, and the study of their spatial distribution would allow us to confirm the association of this component with the photoevaporated envelope of the globule.

The distribution of the [Ne iii] 15.5 \( \mu \text{m} \) emission was obtained following the same procedure and is displayed in Figure 7. The [Ne iii] map looks much noisier than [Ne ii]. Again, there is no emission detected toward the body of the globule. The [Ne iii] emission is limited to the northwestern quadrant, between the globule and the ionizing stars. It overlaps with the outer part of the [Ne ii] flux distribution, at the surface of the globule, and in the extended component that possibly traces the photoevaporated envelope. This is consistent with the high ionization potential of the [Ne iii] line (41 eV) with respect to the [Ne ii] line (22 eV).

Additional lines were detected in the FIR with the LWS. The emission from TC2 was estimated by subtracting the emission of the reference position (see § 3) to the spectrum toward the globule. In this case, no correcting factor was applied to the fluxes since TC2 fills only half the LWS beam (Fig. 4). We observe a marked increase of the density around the globule. The ([O ii] 52/88 \( \mu \text{m} \) ratio yields \( n_e = 170 \text{ cm}^{-3} \). A more pronounced increase is observed using the ([N ii] 57 \( \mu \text{m} / [O iii] 52 \mu m \) ratio, \( n_e = 550 \text{ cm}^{-3} \), when adopting an abundance ratio of 0.5.

One cannot exclude that the contribution of the H ii region along the line of sight of TC2 is somewhat underestimated by the procedure described in § 3. On the other hand, an additional factor can account for the observed increase in density: the photoionized envelope of the globule. As discussed in § 4.1, the latter can be modeled as a layer of effective thickness \( 5 \times 10^{10} \text{ cm} \) and density \( n_e = (1-2) \times 10^3 \text{ cm}^{-3} \), which expands almost freely around the globule. The
emission of this layer could account for the observed increase in density toward TC2 and for the discrepancy between the density estimates from the \([\text{O} \, \text{iii}]\) 52/88 \(\mu\)m and \([\text{N} \, \text{iii}]\) 57 \(\mu\)m/\([\text{O} \, \text{iii}]\) 52 \(\mu\)m ratios. This is because the \([\text{O} \, \text{iii}]\) 52 \(\mu\)m and \([\text{N} \, \text{iii}]\) 57 \(\mu\)m lines are more sensitive to dense material than the \([\text{O} \, \text{iii}]\) 88 \(\mu\)m line (their critical densities are similar to the ionization front density, whereas it is only \(\sim 460\, \text{cm}^{-3}\) for \([\text{O} \, \text{iii}]\) 88 \(\mu\)m). Indeed, a simple modeling with two layers of density 200 and 2000 \(\text{cm}^{-3}\) and thickness 1.3 \(\times\) \(10^{18}\) and 5 \(\times\) \(10^{16}\) \(\text{cm}\), respectively, can account for the emission observed. The contribution of the dense layer is almost unnoticed at 88 \(\mu\)m, whereas it constitutes 20\%–30\% of the observed flux for the 57 and 52 \(\mu\)m lines, respectively.

4.3. Summary of the SWS and LWS Observations

The analysis of the various fine-structure atomic lines detected with the SWS and LWS confirms that the bright-rimmed globule is bathing in the nebular gas of density \(n_e = 50\ling 100\, \text{cm}^{-3}\). For most of the fine-structure atomic lines, the nebular gas dominates the contribution of the photoionized layer surrounding the globule. The photoionized gas envelope is detected at the VLA; it is indirectly detected in the \([\text{N} \, \text{iii}]\) 57 \(\mu\)m and \([\text{O} \, \text{iii}]\) 52 \(\mu\)m lines. The surface density is \(\sim 1000\, \text{cm}^{-3}\) and rises up to 2000 \(\text{cm}^{-3}\). The photoionized envelope of TC2 is also detected in the \([\text{Ne} \, \text{ii}]\) and \([\text{Ne} \, \text{iii}]\) lines. The mapping of these lines shows that the globule is illuminated on the rear side.

5. PHOTON-DOMINATED REGION: ZONE III

In this section we characterize the properties of the PDR: geometry, hydrogen density, and gas column density. We first study the geometry of the PDR from the emission of the unidentified infrared bands (UIBs) at 6.2, 7.7, 8.6, and 11.3 \(\mu\)m as observed with ISOCAM. The UIBs are a good tracer of the strong UV field region associated with a PDR. Although the exact chemical composition of these bands is still not known, the best candidates appear to be the PAHs (Puget & Léger 1989). We will use indistinctly the former or the latter denomination in what follows. The physical conditions in the PDR are quantified from the emission of dust and of the mid-infrared lines detected with LWS and SWS: \([\text{Si} \, \text{ii}]\) 34.8 \(\mu\)m, \([\text{O} \, \text{ii}]\) 63 \(\mu\)m, \([\text{O} \, \text{i}]\) 145 \(\mu\)m, and \([\text{C} \, \text{ii}]\) 158 \(\mu\)m. The \([\text{O} \, \text{i}]\) and \([\text{C} \, \text{ii}]\) lines are especially interesting tools in the study of PDRs since they can be used to probe the excitation conditions in the gas. The line fluxes are compared with the recent models of Kaufman et al. (1999, hereafter K99) and Wolfire, Tielens, & Hollenbach (1990). These models extend the work by Tielens & Hollenbach (1985) and Hollenbach et al. (1991). The main difference is that the model of K99 uses very recent grain photoelectric heating rates, which include treatments of small grains and large molecules (PAHs). We estimated that such a contribution might be important in the case of TC2 since our CVF data show that the infrared emission shortward of 15 \(\mu\)m is dominated by the PAH emission bands.

5.1. Emission of the UIBs

As can be seen in Figure 8, the UIBs (or PAH bands) at 6.2, 7.7, 8.6, and 11.3 \(\mu\)m dominate the spectral emission in the mid-infrared range 5–17 \(\mu\)m, as observed with the CVF. One notes also in the spectra a strong 12.7 \(\mu\)m line that is a combination of the \([\text{Ne} \, \text{ii}]\) line and a PAH band, the presence of a continuum emission at wavelength greater than 13 \(\mu\)m, also well detected in the SWS spectra (see § 6.2), and the presence of the \([\text{Ne} \, \text{ii}]\) 15.5 \(\mu\)m line. To study the spatial distribution of the various features in the CVF spectra, we have made a spectral decomposition using a Gaussian function for the \([\text{Ne} \, \text{ii}]\) line, Lorentzian lines for the PAH bands (Boulanger et al. 1998), and a graybody for the continuum emission. The resulting maps are shown in Figure 7.

All the UIBs are unambiguously detected and have the same spatial distribution, following closely the border of the globule. We note that there is no spatial segregation between the PAH bands as a consequence of the remote distance to the Trifid Nebula. The emission is shifted by \(\sim 2''\) toward the interior of the globule with respect to the photoionized region, as traced by the \([\text{Ne} \, \text{ii}]\) line (Fig. 7).

The emission shows a local minimum in the center of the globule. The flux distribution is the brightest in the PDR and reaches its maximum close to the offset position (+65'' , −125''). The PAH emitting region in the PDR is mostly unresolved at all wavelengths; this prevents any detailed physical analysis of the latter. The dark filament absorbs a fraction of the infrared radiation coming from the PDR, causing the presence of a local minimum in the brightness distribution. Because of the weakness of the radiation field, almost no emission at all is detected over the body of the globule. Only a weak feature is detected around 7.7 \(\mu\m\) (Fig. 8). Some weak emission is also detected outside the globule, behind the ionization front (Fig. 7).

We now compare the relative variations of the PAH bands measured at a few positions over the globule and the \([\text{H} \, \text{ii}]\) region. In order to increase the S/N, the emission has been averaged over 4 pixels at each position. The resulting spectra are displayed in Figure 8. The contribution of the nebula, as estimated from the reference position (Fig. 8e), has been subtracted from the spectra in order to outline the emission of the globule. The almost flat spectrum obtained in the core TC2, especially the absence of ionic lines in either absorption or emission, shows that the nebular gas emission was removed properly. It is also consistent with TC2 being heated on the rear side.

We concentrate on the 7.7 and 11.3 \(\mu\m\) as they have the highest S/N. The bands have a ratio 7.7/11.3=0.9 in the PDR. This ratio is \(\sim 1.2\) at the reference position (Fig. 8e) in the \([\text{H} \, \text{ii}]\) region and reaches \(\sim 2\) in the direction of the ionizing star. Part of this variation of the 7.7/11.3 ratio is probably related to variations in the charge of the PAHs. The current models and laboratory experiments on the PAH emission show that the relative intensity of the various bands is strongly sensitive to the ionization state. In particular, the intensities of the C—C stretching modes (6.2 and 7.7 \(\mu\m\)) and the C—H in-plane bending mode (8.6 \(\mu\m\)) are generally stronger in PAH cations than in PAH neutrals by a factor of 10 (see, e.g., Joblin et al. 1996), whereas the intensity of the C—H out-of-plane bending mode (11.3 \(\mu\m\)) seems to decrease with the ionization.

In the PDR of the globule, the models of Bakes & Tielens (1998) and Dartois & d’Hendecourt (1997) predict a very small fraction of PAH cations (0.01 or less). In the photoionized gas around TC2, on the contrary, the spectra look very similar to those of a mix of PAH cations superposed to a weak continuum (see Fig. 3d in Allamandola, Hudgins, & Sandford 1999). Therefore, the decrease of the 11.3 \(\mu\m\) band can be understood as the dehydrogenation and
photoionization of the smallest PAHs exposed to the strong UV field of the H\ II region. A similar effect has been reported in the H\ II region M17 by Verstraete et al. (1996) and Crete et al. (1999) and in NGC 1333 by Joblin et al. (1996).

However, we observe a marked increase of the 7.7/11.3 ratio, above 2, inside the globule. This value is comparable to that observed in the ionized gas, whereas the ionizing field at the surface of the globule, as traced by the [Ne\ II] and [Ne\ III] lines, is much lower. Hence, the relative variation of the 7.7/11.3 ratio cannot be directly accounted for by standard models of PAH excitation. As we discuss below, the PAH emission observed toward the main body of the globule actually comes from the PDR located on the rear side and has suffered strong absorption from the globule material (the millimeter dust map indicates an average $A_v \approx 20$ over the body of the globule). The absorption by the silicates is so large that hardly any radiation escapes from the globule longward of 8 $\mu$m. This effect is illustrated by the CVF spectrum taken at position F, in the main body of TC2. Almost no emission at all is detected in the spectral window, apart from a weak feature coinciding with the PAH band at 7.7 $\mu$m.

It is interesting to compare the emission maps of the globule at 7.7 $\mu$m and in the [Ne\ II] line at 12.7 $\mu$m. In both maps, there is no emission in the northeastern region. This is the region where the reference spectrum was taken (position E; Fig. 7). The border of the globule looks very bright at both wavelengths. Whereas the main body of TC2 appears void of [Ne\ II] emission, as mentioned before, it is still radiating some flux at 7.7 $\mu$m (see Fig. 7). Cernicharo et al. (2000) showed that at 5.3, 6.6, and 7.5 $\mu$m there is a narrow window in which the absorption by the ices and the silicates is low enough to let the radiation escape even from the deeply embedded cores of Class 0 protostars.

In order to test our hypothesis, we have calculated the spectrum of the radiation emerging at the front side of the globule, assuming the emitting region (the PDR) to be located at the rear surface of the globule. The extinction through the globule was computed from an empirical absorption profile constructed by Cernicharo et al. (2000) and scaled with the visual extinction inside TC2. This empirical profile is based on the CVF spectrum of the Class I protostar VLA 4 in the L1641 molecular cloud in Orion. It takes into account the contribution of silicates, the ices of methanol CH$_3$OH, water H$_2$O, and carbon dioxide CO$_2$. As noted by Cernicharo et al. (2000), the spectrum of VLA 4 is very similar to the spectra observed toward deeply embedded objects in massive star-forming regions. We also note that VLA 4 and TC2 are in a similar evolutionary stage. Hence, we believe that despite some possible abundance variations between both protostellar cores, the VLA 4 absorption profile should represent a good approximation to the absorption profile in TC2.

We have applied this absorption profile to the spectrum of the bright PDR (position D) for a visual extinction $A_v = 20$, a value derived from the 1.3 mm continuum map, and similar to the average extinction over the globule. We show the calculated spectrum in Figure 9. The 7.7 $\mu$m band intensity is $\sim 70$ MJy sr$^{-1}$, whereas the intensity of the 11.3 $\mu$m band and the [Ne\ II] line is now only $\sim 40$ MJy sr$^{-1}$. The synthetic spectrum of the PDR appears very similar to the spectrum in the body of the globule at position F. The apparent strong enhancement of the 7.7 $\mu$m band with respect to the 11.3 $\mu$m band is mainly a selective absorption effect of material located on the rear side of the globule.

To summarize, the PAH bands at 6.2, 7.7, 8.6, and 11.3 $\mu$m are unambiguously detected in TC2. The variations of their relative intensities are in agreement with the models of PAH excitation. They show evidence for the main body of TC2 being illuminated on the rear side and not on the front side. This is in agreement with the analysis of the [Ne\ II] and [Ne\ III] lines. As a consequence, the line intensities can be obtained, at first order, from the integrated fluxes by dividing by the area of the globule encompassed by the telescope beam.

5.2. [C\ II] Line Emission in the Globule

The LWS spectra of the [C\ II] and [O\ I] lines are shown in Figure 6. The emission from the globule was obtained by subtracting a reference position to the spectra taken toward TC2 (see § 2.5). The uncertainties in the flux of the [O\ I] lines are rather weak since the emission at the reference position appears much weaker than toward the globule. On the contrary, the variations of the [C\ II] line are much weaker, and the contribution of TC2 amounts to $\approx 25\%$ of the total flux (see Table 4). The procedure applied to estimate the emission from the globule ignores a possible contribution of the photoionized envelope surrounding TC2 to the observed flux. Indeed, the analysis of the FIR [S\ II] and [O\ I] lines carried out in § 3.1 suggested that this region was contributing to the flux detected. The [C\ II] line is one of the main tools used to probe the physical conditions in PDRs as it provides a direct estimate of the mass and column density of PDR gas. It is therefore important to estimate as accurately as possible the [C\ II] flux coming from the PDR itself and leave aside any other contribution to the flux measured.

We consider the 20 cm free-free emission map of the Trifid presented in C98 (Fig. 5a). These data were obtained at a resolution of 10$''$. This allows us to trace the extended emission from the main body of the globule, unlike the high angular resolution observations presented in § 3.1. We apply the method described by Heiles (1994), who showed that intensity $I_C$ of the [C\ II] line scales with the brightness temperature of the free-free emission in the low-density region, and we derive the relation

$$\frac{I_C}{T_{B,20cm}} = 0.8\delta_C \ K^{-1},$$

where $I_C$ is expressed in units of ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and $\delta_C$ is the ionic abundance C$^+$/H$^+$ in units of $3 \times 10^{-4}$. The exact ionic abundance of C$^+$ depends on various factors, such as density and effective stellar temperature. Based on the models of Rubin (1985), we estimate $\delta_C$ to range between 0.5 and 0.8.

The free-free emission map shows some extended emission in addition to the bright rim. The emission peaks at 33 mJy beam$^{-1}$ in the bright rim. From the distribution of the contour levels around the globule, we find that the average intensity in the surrounding nebular gas is 20 mJy beam$^{-1}$. This implies a peak flux of 13 mJy beam$^{-1}$ in the bright rim. Following the same method as in § 3.1, we infer a local density $n_e = 1900$ cm$^{-3}$, in good agreement with our measurement at higher angular resolution. After subtracting the contribution of the nebular gas and integrating the emission over the globule, we obtain a mean brightness temperature $T_{B,20cm} = 4$ K for the residual emission. Since the contribution of the nebular gas was removed, this residual is the emission of the photoionized envelope and the ionization...
front, i.e., the bright rim. Hence, the intensity of the [C ii] line \( I_\text{C} \approx 1.5 \times 10^{-4} \text{ ergs cm}^{-2} \text{s}^{-1} \text sr^{-1} \). This value represents approximately 30\% of the flux detected with the LWS toward the globule. After correcting for the contribution of the surface ionized layers, we obtain that the flux of the [C ii] line in the PDR gas is \( \approx 1.8 \times 10^{-11} \text{ ergs cm}^{-2} \text{s}^{-1} \).

In the optically thin limit, the mass of atomic gas can be easily obtained from the observed [C ii] line flux, using the analytic formula derived by Wolfire et al. (1990):

\[
M_a = 5.8 \left( \frac{d}{1 \text{ kpc}} \right)^2 \left[ \frac{1.4 \times 10^{-4}}{x(\text{C ii})} \right] \left( \frac{F_{\text{C ii}}}{10^{-17} \text{ W cm}^{-2}} \right) \times \left( \frac{10^{-21} \text{ ergs cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{atom}^{-1}}{\Lambda(\text{C ii})} \right)M_\odot,
\]

where \( \Lambda(\text{C ii}) \) is the cooling rate in the [C ii] 158 \( \mu \text{m} \) line per carbon atom and per steradian and \( x(\text{C ii}) \) is the abundance of ionized carbon per hydrogen atom. Here we adopt a carbon abundance \( x(\text{C ii}) = 1.4 \times 10^{-4} \) (see K99). The atomic gas temperature in the PDR of TC2 is close to 300 K (see next section). For hydrogen densities of \( 10^4 \text{ cm}^{-3} \), comparable to that in the PDR gas, the cooling rate \( \Lambda(\text{C ii}) \) is then \( (0.8-1.0) \times 10^{-21} \text{ ergs cm}^{-2} \text{sr}^{-1} \text{atom}^{-1} \). The mass of atomic gas in the PDR is therefore \( M_a = 2.9-3.7 \, M_\odot \). From the fraction of the globule’s area that fills the LWS beam, we derive the average hydrogen column density of PDR gas:

\[
N(\text{H}) = (1.5-1.9) \times 10^{21} \text{ cm}^{-2}.
\]

5.3. Physical Conditions in the PDR from the [O i] and [C i] Lines

We present below the physical conditions derived from the analysis of the FIR lines and based on the model of K99. We find a good agreement between this model and the observational data. The physical parameters of the globule are summarized in Table 5.

Based on the FUV field intensity \( G_0 \approx 1000 \) and using the model of K99, we find that the gas is heated by photoelectrons to a temperature of \( \geq 300 \) K at the surface of the PDR, a value that actually depends rather little on the actual density in the PDR (see their Fig. 2). This value is also a good estimate of the actual temperature in the PDR.

The hydrogen density in the PDR was estimated from a large velocity gradient (LVG) analysis of the [O i] lines. This approach offers the advantage of being independent of the oxygen elemental abundance. The size of the emitting region in the LWS beam is taken to be 45°. We took 1.3 km s\(^{-1}\) as the line width, based on the observations of the millimeter lines of HCO\(^+\) and CS in the head of the globule (§ 7.2). The core density derived from the millimeter dust thermal emission provides an upper limit to the density in the PDR:

\[
n(\text{H}_2) = 3 \times 10^{15} \text{ cm}^{-3}.
\]

Hence, in order to account for the observed [O i] fluxes at 63 and 145 \( \mu \text{m} \), the gas temperature has to be larger than 200 K. The best match is obtained for a column density \( N(\text{O}) = 7 \times 10^{17} \text{ cm}^{-2} \) (Fig. 10). At a temperature of 300 K, as derived above for the PDR, the molecular hydrogen density is \( n(\text{H}_2) = 6 \times 10^{14} \text{ cm}^{-3} \). Adopting an oxygen elemental abundance \( [\text{O}]/[\text{H}] = 3.0 \times 10^{-4} \), the corresponding gas column density in the PDR is \( \approx 2 \times 10^{21} \text{ cm}^{-2} \).

There is a possible bias in this analysis as the globule is illuminated under some inclination angle while it is viewed face-on by us. This anisotropy in the illumination drives heterogeneous conditions across the globule (i.e., in the plane of the sky). As a consequence, the filling factor of the [O i] 63 \( \mu \text{m} \) line, more easily excited, is likely to be larger than that of the 145 \( \mu \text{m} \) line. This effect was not taken into account in the present calculation and results in an underestimate of the [O i] column density, whereas the hydrogen density is overestimated.

The \([\text{O i}] 63 \mu\text{m}/[\text{C i}] 158 \mu\text{m} \) and \([\text{O i}] 145/63 \mu\text{m} \) line ratios provide another method to derive the parameters of the PDR. These ratios are 0.066 and 4.2, respectively; using Figures 4 and 5 in K99, we obtain direct estimates of the FUV field intensity \( G_0 = 1000 \) and of the hydrogen nuclei density \( n(\text{H}) = 2 \times 10^{14} \text{ cm}^{-3} \). This estimate of \( G_0 \) is in good agreement with the previous, independent, determination, based on the FIR dust continuum. In the range of values taken by the \([\text{O i}] 63 \mu\text{m}/[\text{C i}] 158 \mu\text{m} \) ratio, the ratio is not very sensitive to the FUV field intensity \( G_0 \). Hence, an overestimate of the [C i] line flux would imply that the actual PDR density is somewhat larger. An upper limit of 10 on this ratio yields a hydrogen nuclei density of \( \approx 3 \times 10^{14} \text{ cm}^{-3} \). We determine the electron density in the PDR from the photoelectric heating efficiency \( \varepsilon \) which is governed by the factor \( G_0 T_\text{FUV}^{1/2}n_e^{-1} \) (see, e.g., Bakes & Tielens 1994). The integrated intensity of all the FIR lines is well approximated by the sum of the [O i] 63 \( \mu\text{m} \) and [C i] 158 \( \mu\text{m} \) intensities, which amounts to \( 2.6 \times 10^{-3} \text{ ergs cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \). We note that since the cooling of the PDR gas is dominated by the [O i] 63 \( \mu\text{m} \) line, the uncertainties in the [C i] line flux do not affect significantly the total cooling or the conditions of

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**TABLE 5**

| Parameter | Value |
|-----------|-------|
| FUV radiation field \( (G_0) \) | 1000 |
| Infrared luminosity \( (L_\text{IR}) \) | 1200 |
| Total mass \( (M_\odot) \) | 63 |
| Mean radius \( R_\odot \) | \( 4 \times 10^7 \) |
| Mean \( H_2 \) column density \( (\text{cm}^{-2}) \) | \( 2.3 \times 10^{22} \) |
| Core: | | |
| Dimensions \( (10^{17} \text{ cm}) \) | 3 \times 8 |
| Dust temperature \( (K) \) | 22 |
| Maximum \( H_2 \) column density \( (\text{cm}^{-2}) \) | \( 8.0 \times 10^{22} \) |
| Mean \( H_2 \) column density \( (\text{cm}^{-2}) \) | \( 5.1 \times 10^{22} \) |
| Mass \( (M_\odot) \) | 27 |
| \( H_2 \) density \( (\text{cm}^{-3}) \) | \( 3 \times 10^{5} \) |
| Central source luminosity \( (L_\odot) \) | \( \leq 500 \) |
| Molecular envelope: | | |
| \( H_2 \) density \( (^{13}\text{CO}) \) \( (\text{cm}^{-3}) \) | \( 3.0 \times 10^4 \) |
| Gas temperature \( (K) \) | 30 |
| Photon-dominated region: | | |
| Thickness \( (\text{cm}) \) | 1 \times 10^{17} |
| Dust temperature \( (K) \) | 46 |
| Atomic gas temperature \( (\text{O} = 2) \) \( (K) \) | 300 |
| Gas column density \( (\text{cm}^{-2}) \) | 2.0 \times 10^{21} |
| Oxygen column density \( (\text{cm}^{-2}) \) | 7 \times 10^{17} |
| Oxygen abundance | \( 3 \times 10^{-4} \) |
| Carbon column density \( (\text{cm}^{-2}) \) | \( 3 \times 10^{17} \) |
| Carbon abundance | \( 1.4 \times 10^{4} \) |
| Density \( (\text{H}_2) \) \( (\text{cm}^{-3}) \) | \( 1.0-6.0 \times 10^4 \) |
| Atomic gas mass \( (\text{C} \odot) \) \( (M_\odot) \) | 3-4 |
| Velocity field | RDI |
| Photoionized envelope (bright rim): | | |
| Thickness \( (\text{cm}) \) | \( \approx 5 \times 10^{16} \) |
| Electron density \( (\text{cm}^{-3}) \) | \( 1.0-2.0 \times 10^3 \) |

\( ^a \) From dust observations.
Adopting a carbon abundance of $1.4 \times 10^{-4}$, we obtain an estimate of the hydrogen density $n(H_2) = 1.3 \times 10^4$ cm$^{-3}$.

### 5.4. Emission of the [Si ii] 34.8 μm Line

The emission of the [Si ii] 34.8 μm line can be produced in the PDR of molecular clouds that are illuminated by strong FUV fields (Tielens & Hollenbach 1985) and also in H$^\text{ii}$ regions (Rubin 1985). In the case of Orion, a prototype massive star-forming region, Walmsley, Pineau des Forêts, & Flower (1999) showed that the [Si ii] emission comes mainly from the PDR and not from the H$^\text{ii}$ region or the ionization front region.

We try to determine the origin of the emission observed toward the globule. It is difficult to draw any definite conclusion because of the lack of angular resolution and hence of information about the spatial distribution of the emission. In addition, the noise in this band of the SWS is known to be high, so that the actual variations between the three positions might be somewhat more pronounced. An important constraint comes from the measurements of the thermal dust emission at 1.3 mm; they indicate an average visual extinction $A_v = 20$ across the globule (see § 6). The values of the interstellar extinction tabulated by Mathis (1990) allow us to estimate the opacity of the globule at 35 μm: $\tau_{35} \approx 0.08$. Therefore, the globule is mainly transparent at this wavelength.

For the physical conditions encountered in the PDR of TC2, the model of Wolfire et al. (1990) predicts a typical value of 0.015 for the ([Si ii] 34.8 μm/[O i] 63 μm) ratio, whereas the observed ratio is 0.5. Assuming that all the emission arises from the PDR, this implies a silicon gas-phase abundance about 30 times higher than that assumed in their computation, corresponding to [Si]/[H] $\approx 2.5 \times 10^{-5}$, i.e., 0.6 times the solar elemental silicon abundance ($\approx 3.6 \times 10^{-5}$). This is unrealistically high as observations in other H$^\text{ii}$ regions like Orion indicate that about 90% of silicon is tied up in dust grains (Walmsley et al. 1999), a value also similar to that found in diffuse interstellar clouds. Therefore, the PDR of TC2 alone cannot account for the measured [Si ii] flux.

Indeed, the SWS spectra show that the [Si ii] flux at the northern position is only $\sim 15\%$ less than at the southern and central positions, whereas the globule fills only one-third of the SWS beam. Since the globule is transparent to the [Si ii] radiation and is illuminated mostly on its rear side, one would rather expect a flux approximately one-third of that detected in the central beam, i.e., $\sim 3 \times 10^{-19}$ W cm$^{-2}$. This is much less than the flux detected and reinforces our previous conclusion about the origin of the [Si ii] line.

Assuming that the flux variation between the central and northern positions is due to the variation of the PDR filling factor in the SWS beam, one can derive an estimate of the relative contribution of the PDR and the H$^\text{ii}$ region. The emitted flux is then $2.2 \times 10^{-19}$ and $7.4 \times 10^{-19}$ W cm$^{-2}$ for the PDR and the H$^\text{ii}$ region, respectively; the emission of the PDR is somewhat dominated by the contribution of the H$^\text{ii}$ in the SWS beam. The model of Wolfire et al. (1990) is then consistent with a gas-phase abundance of $6 \times 10^{-6}$, i.e., 17% of the solar abundance. This value is much more compatible with the determination obtained in other H$^\text{ii}$ regions. Nevertheless, we stress again that new observations with a better S/N are required to determine more precisely the silicon abundance in the PDR and the H$^\text{ii}$ region.
6. DUST CONTINUUM EMISSION

6.1. Warm Dust in the PDR: Zone III

Here we analyze the continuum emission detected with the SWS in the range 2–45 μm. The full spectra obtained at the three positions are shown in Figure 11. The continuum emission becomes significant longward of 30 μm in all the positions. We have fitted the continuum using a blackbody modified by a power law \( \tau_v \propto \nu^\beta \). A satisfactory fit was obtained for a dust temperature of 46 K and a dust spectral index \( \beta = 1.3 \), typical of the values observed in the mid-infrared (Hildebrand 1983). Here we assume that the mid-IR flux originates from the PDR and fills the SWS beam. Following the reddening law determined by Lynds et al. (1985) for the Trifid, we estimate a hydrogen column density \( N(H) = 1.7 \times 10^{21} \text{ cm}^{-2} \). Adopting the standard reddening law yields \( N(H) = 2.9 \times 10^{21} \text{ cm}^{-2} \). These values are only indicative since they rely on the geometry assumed for the emitting region. Reasonable fits can be obtained with the temperature in the range 43–48 K and hydrogen column densities of \( (1-4) \times 10^{21} \text{ cm}^{-2} \).

The same procedure has been applied to the other positions observed with the SWS. At the northern position, the PDR of the globule fills only partially the SWS beam. We have estimated a size of \( \approx 15'' \) for the region encompassed by the beam. The other parameters for the warm layers were left identical otherwise. At the southern position, the continuum emission could be fitted with similar parameters and assuming a smaller column density of warm dust \( [N(H) \approx 0.9 \times 10^{21} \text{ cm}^{-2}] \) at about the same temperature. The fits are shown superposed on the spectra in Figure 11. They succeed rather well in reproducing the continuum flux longward of 30 μm.

It is therefore possible to explain the observed continuum emission by a warm dust layer at about 46 K and a column density \( \approx (2-3) \times 10^{21} \text{ cm}^{-2} \). As we show below, such parameters also allow us to account for the continuum emission detected at longer wavelengths.

6.2. Hot Dust around TC2: Zones II and III

Comparison between the fit of the warm dust component and the SWS data shows actually the presence of a residual flux as a flat continuum between 10 and 30 μm. The continuum emission shortward of 30 μm is almost identical at the northern and central positions. It is somewhat weaker in the south.

The continuum emission is maximum between 15 and 30 μm. Our CVF map of the continuum emission in the range 13–15 μm brings some more information on the distribution and the nature of this hot dust component. The continuum emission at 15 μm revealed from our spectral decomposition is shown in Figure 7. The map shows a good spatial correlation with the 7.7 μm band and the photoionized envelope. The continuum is brightest in the PDR. It is shifted outward by \( \approx 1''-2'' \) and gets stronger as one moves outside of the globule, in the photoevaporated gas. There is almost no emission from the body of the globule. We detect a higher continuum level in the western side of the globule with respect to the northern one. This difference might result from a higher heating efficiency on the western side because the UV photons arrive almost normal to the surface. The rise of the continuum could also be related to an increase of the gas density similar to what was observed in other PDRs (Abergel et al. 2002) and in cirrus clouds (Miville-Dechênes et al. 2002). Within the present understanding of the nature of the mid-infrared emitters, it is impossible to determine the origin of the increase of the continuum emission in denser regions, but one plausible explanation could be related to a change of the dust size distribution. There is also a rather good spatial correlation between the 15 μm continuum and the distribution of the ionizing gas, as traced by the [Ne III] line. The correlation of this emission with the photoionized envelope suggests that the emission detected probably comes from very small grains heated by the strong UV field.

6.3. Cold Dust in TC2: Zone IV

The thermal emission of the cold dust was observed with the MPIfR 19 channel bolometer array at the IRAM 30 m telescope (Fig. 3). We detected some weak emission, at typical fluxes of 5–15 mJy/15'' beam, which spatially coincides with the region of high obscuration in the optical image.
south of the ionization front. The millimeter continuum emission is sharply limited by the ionization front, and the brightness contours are closely spaced between the bright rim and the emission peak. The globule peaks at 160 mJy/11″ beam at the offset position (70°, −124°), only 15″ behind the ionization front. From the contour at half-power, we estimate a size (beam deconvolved) of ≈12″ × 32″ (3.0 × 10^{17} cm by 8.0 × 10^{17} cm) for the core. Assuming an average dust temperature \( T_d = 20 \) K, a spectral index \( \beta = 2 \), and an absorption coefficient \( k_{250} = 0.1 \) cm² g⁻¹, we derive a hydrogen column density \( N(H) = 1.6 \times 10^{23} \) cm⁻² at the flux peak. Integrating over the contour at 80 mJy/11″ beam (HPFW), we find a total flux of 0.29 Jy and estimate a core mass \( M = 27 \, M_\odot \). This implies a typical density \( n(H_2) = 3 \times 10^6 \) cm⁻³ for the core.

6.4. Spectral Energy Distribution

The spectral energy distribution of the globule between 45 and 197 \( \mu \)m was obtained by subtracting the emission of the reference position from the LWS spectrum taken toward TC2. The size of the emitting region encompassed by the LWS beam is ≈45″, based on the ISOCAM 12 \( \mu \)m image and the cold dust millimeter emission (Fig. 3). We measured the 1.3 mm continuum filling the LWS beam solid angle in order to constrain the fit to the cold dust component. It was found to be ≈0.83 Jy. The spectral energy distribution is shown in Figure 12. The emission could be satisfactorily fitted by a two-component model: a cold core of column density \( N(H) = 4.6 \times 10^{22} \) cm⁻² at a temperature \( T_d = 22 \) K, with a dust spectral index \( \beta = 2.0 \), surrounded by a warm layer at a temperature \( T_d = 46 \) K, with a hydrogen column density \( N(H) = 1.9 \times 10^{21} \) cm⁻² and a dust spectral index \( \beta = 1.3 \).

The gas column density of the warm layer is not very high as it corresponds to \( A_v = 1-2 \). We note that it is very similar to the column density of the PDR gas traced by the [C ii] 158 \( \mu \)m and the [O i] lines. The warm layer detected with the LWS also accounts for the mid-infrared continuum emission detected with the SWS longward of 30 \( \mu \)m. Integrating under the fit of the warm dust component and correcting for dilution in the LWS beam, we obtain the infrared intensity radiated by the warm layer: \( I_{IR} = 0.21 \) ergs s⁻¹ cm⁻² sr⁻¹. The temperature and the infrared luminosity of the warm layer are those expected for a PDR exposed to an FUV field \( G_0 = 1000 \). This is consistent with the intensity of the FIR [O i] and [C ii] lines as observed with LWS (see § 5.3). The whole set of observational data leads us to the conclusion that the warm dust component detected with the LWS is actually tracing the PDR of the globule. The average hydrogen column density is \( N(H) = 2.0 \times 10^{21} \) cm⁻². With a typical hydrogen nuclei density \( n(H) = 2 \times 10^4 \) cm⁻³, as estimated from the FIR line ratios (§ 5.3), we estimate the thickness of the PDR to be \( \approx 1.0 \times 10^{17} \) cm.

The cold dust component revealed in the spectral energy distribution is therefore tracing the innermost part of the globule (the core), which is protected from the external U V radiation field. Hence, it seems a good reasonable approximation to adopt 22 K as the temperature of the dust core traced by the 1.3 mm continuum emission in order to estimate the mass of the core. This temperature is similar to those observed in the molecular cloud surrounding the nebula (Lefloch & Cernicharo 2000). A more accurate determination of the mass and column density of the core and the globule would require a better knowledge of the temperature profile. This is not allowed by the low angular resolution of the LWS observations, which averages the emission over a much too large region (~80′). We define the total mass \( M_t \) of the dust condensation by integrating over the flux contour at 30 mJy/11″ beam; this area of mean size 40″ contains a total flux of 0.68 Jy. Adopting a uniform dust temperature \( T_d = 22 \) K, we obtain the average gas column density over the globule 2.3 × 10^{22} cm⁻², the total mass of the globule \( M_t = 63 \, M_\odot \), and the average density in the globule \( n(H_2) = 4 \times 10^4 \) cm⁻³.

Hence, we find that it is only a small mass fraction of the whole globule (~5%) that lies in the atomic surface layers, exposed to the strong FUV field of the stars exciting the Trifid. The ratio of the atomic to molecular gas masses is much lower in TC2 than in the OMC-1 in Orion and in the Galactic center, where it is about 16%. On the contrary, the ratio takes a very similar value to that in the young massive star-forming region W49N. This region is one of the youngest massive star-forming places in the galaxy, where several recently born O stars have just started to excavate the parent cloud (Vastel et al. 2001). The low atomic to molecular gas ratio measured in TC2 is therefore consistent with a very early evolutionary age for the globule. This point is more thoroughly addressed in § 8.2.

7. Molecular Condensation: Zone IV

7.1. Surface Layers

The molecular content of the bright-rimmed globule was first observed in the CO lines. The line profiles are complex and exhibit several components between −50 and 50 km s⁻¹ that correspond to various physical regions in the molecular cloud containing the H ii region (B. Lefloch et al. 2002, in preparation). Because of the large extent of the CO emission in the nebula, antenna temperatures are a better approximation than main-beam brightness temperatures to the brightness of the CO lines. We adopted the same approximation for the \(^{13}\)CO \( J = 1 \rightarrow 0 \) transition. On the contrary, we assumed main-beam brightness temperatures for \(^{12}\)CO. The spatial distribution of the kinetic components shows that
the emission of TC2 peaks at $v_{\text{LSR}} = 7.7$ km s$^{-1}$ (Fig. 13). The distribution of the emission follows closely the bright rim and drops abruptly beyond the ionization front. The antenna temperatures of the CO transitions are rather uniform over the globule, with values of $\lesssim 30$ K for the $J = 2 \rightarrow 1$ and $J = 1 \rightarrow 0$ transitions and 15 K for the $J = 3 \rightarrow 2$ one.

We have tried to constrain the temperature and density distribution in the globule by modeling with a radiative transfer code the excitation of the CO lines. A priori two zones are contributing to the emission: the molecular core and the PDR. The large ratio between the $J = 3 \rightarrow 2$ and the $J = 1 \rightarrow 0$ lines is very difficult to explain. Observations of the high-density gas show that the velocity shift between the quiescent core and the surface layers, which are accelerated by RDI, is small, of the order of 1 km s$^{-1}$ (see § 8.1). This is consistent with the symmetric profiles observed for all the molecular transitions (Fig. 13). This velocity shift is small enough that the PDR and the dense core are still radiatively well coupled. Therefore, most of the radiation coming from the PDR on the rear side of the globule is absorbed by the dense core. As a consequence, its contribution to the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ lines is almost negligible, and we detect mainly the emission of the cold core and the front-side layers. We infer a kinetic temperature of about 30–35 K for the gas, somewhat higher than the dust temperature. The discrepancy could be due to the heating of the front side by optical photons, since the globule is immersed in ionized gas.

The $^{13}$CO data show widespread emission over the entire globule, with typical brightness (antenna) temperatures of 13 and 12.5 K for the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions, respectively (Fig. 13). The $^{13}$CO $J = 1 \rightarrow 0$ has a main-beam brightness temperature of 2.3 K. From the ratio of the $^{13}$CO/$^{12}$CO $J = 1 \rightarrow 0$ brightness temperatures (=5.7) and assuming a standard relative abundance of 8, we derive the $^{13}$CO line opacity $\tau_{^{13}CO}$ $\approx 0.7$. We note that the opacity derived is fully consistent with the value of the ratio $^{12}$CO/$^{13}$CO $J = 1 \rightarrow 0$ brightness temperatures. An opacity $\tau_{^{12}CO} = 0.7$ implies a ratio of 2, whereas the actual value is 2.3. The mean H$_2$ density in the globule is high enough that the $J = 1 \rightarrow 0$ line of CO and its isotopes are thermalized. We have used the opacity and the brightness of the $^{13}$CO $J = 1 \rightarrow 0$ line to constrain the kinetic temperature and the gas column density. The best match is obtained for a gas temperature $T_k$ = 30 K and a column density $N(^{13}$CO) $\approx 4 \times 10^{16}$ cm$^{-2}$. Adopting a standard abundance $^{13}$CO/H$_2$ = 1.6 $\times$ 10$^{-6}$, we infer the total gas column density $N$(H$_2$) = 2.5 $\times$ 10$^{22}$ cm$^{-2}$, in good agreement with the value obtained from the dust measurements, and the average gas density $n$(H$_2$) = 3.0 $\times$ 10$^4$ cm$^{-3}$, after dividing the gas column density by the mean globule radius.

7.2. Dense Core

All the molecular lines observed toward the center of the globule peak at $v_{\text{LSR}} = 7.7$ km s$^{-1}$ without any significant variation between the tracers (Fig. 13). The optically thick HCO$^+$ $J = 1 \rightarrow 0$ line has a distribution similar to that of CO (Fig. 14). It was detected all over the globule, with typical main-beam brightness temperatures of 2–4 K. We also observed the isotopic H$^{13}$CO$^+$ $J = 1 \rightarrow 0$ line but failed to detect it.

The distribution of the dense gas was mapped in the CS $J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ lines. The CS emission is less extended than HCO$^+$, as it appears to trace the region associated with the cold dust core (Fig. 14). The CS lines are bright with main-beam temperatures of the order of 2 K, up to $\approx 4$ K (4.3 and 4.0 K for the $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ lines, respectively) at the position (72°, $-135^\circ$). The CS $J = 2 \rightarrow 1$ transition traces a region approximately circular with a typical size of 5 $\times$ 10$^{17}$ cm (HPFW), marginally resolved by the telescope beam. The higher angular resolution of CS $J = 3 \rightarrow 2$ data reveals two gas components: a weak, extended, component that overlaps very well with the globule, as traced in $^{12}$CO and the millimeter continuum, and a strongly peaked condensation in the center of the globule.
In order to determine the physical conditions in the dense core, we carried out an LVG analysis on the $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ lines assuming a gas kinetic temperature of 20 K, suggested by the millimeter continuum observations. Three positions were studied: the center of the core and two other positions offset by $15''$. The velocity width was estimated from a Gaussian fit to the line profiles: $\Delta v = 1.3$ km s$^{-1}$. In the central position we find a density $n(H_2) = 2.0 \times 10^5$ cm$^{-3}$ and a column density $N(CS) = 1.8 \times 10^{13}$ cm$^{-2}$. The line opacities are relatively low, with $\tau_{21} = 0.42$ and $\tau_{22} = 0.70$. Similar densities are obtained around the center ($\sim 2 \times 10^5$ cm$^{-3}$) and at the brightness peak, $15''$ south of the center. At this position, we find $N(CS) = 3.0 \times 10^{13}$ cm$^{-2}$. Hence, from the $H_2$ core density and the beam size, we find a core mass of $\sim 28 M_\odot$, in good agreement with the dust estimate. Adopting a typical abundance $[CS]/[H_2] = 5 \times 10^{-10}$, we estimate the size of the CS-emitting region to be $l = 3.0 \times 10^{17}$ cm. This value is consistent with the size HPFW derived from the maps of velocity-integrated emission at 3 and 2 mm.

The picture coming out of the molecular line and thermal dust continuum analysis is that the globule consists of a cold central core of density $n(H_2) = (2-3) \times 10^5$ cm$^{-3}$ surrounded by an envelope slightly warmer in the outer layers, at a temperature $T \sim 30$ K and a density of about $3 \times 10^4$ cm$^{-3}$.

8. RADIATIVELY DRIVEN IMPLOSION OF TC2

We recalled briefly in § 1 the overall evolution of a photoionized globule. The time evolution of a photoionized globule, the density, and the velocity fields were studied numerically and presented in LL94 (see in particular their Fig. 4) under a wide range of ionization conditions, including those typical of bright-rimmed globules. The evolution of the photoionized globule is determined by the two following parameters:

1. $\gamma = \eta \sigma n_e R_g / c_s$, the ratio of the impinging photons consumed to balance recombinations to those used to ionize neutral material. For TC2, we obtain $\gamma = 15$. Hence, most of the Lyman continuum photons are consumed in the ionized gas layer surrounding the neutral condensation (see also § 4.1).

2. $\delta = n_i / n(H)$, the ratio of the ionized gas density with respect to the neutral gas density. This factor is directly related to the overpressure exerted by the ionized gas and the intensity of the shock driven in the condensation.

The mean globule density, ahead of the PDR, is the most difficult term to estimate. It is probably a good approximation to assume a density comprised between the PDR density $[n(H_2) = 10^4$ cm$^{-3}$] and the molecular gas traced by $^{13}$CO [n(H$_2$) = $3 \times 10^4$ cm$^{-3}$]. Hence, we estimate that $\delta$ lies in the range 0.03-0.09. The values of $\delta$ and $\gamma$ found for TC2 are typical of a bright-rimmed globule. Following the convention defined by LL94, this corresponds to region IV in the ($\delta, \gamma$)-plane (see their Fig. 3). In this case, the whole evolution is governed by the propagation of a D-critical ionization front preceded by a shock front. In their study, LL94 showed that the morphology, density, and velocity structure of a photoionized globule mainly depend on the duration of the ionization, i.e., the time elapsed since the illumination began. It does not depend critically on the “real” values of $\delta$ and $\gamma$.

A direct estimate of the total (ram plus thermal) external pressure at the surface of the cloud yields $P_e / k_B = 2.11 \times 2 n_e T_e = 4.2 \times 10^9$ K cm$^{-3}$. We can estimate the inner pressure from the kinematic motions as measured by the line width of the $^{13}$CO and CS transitions: $\Delta v = 1.4$ km s$^{-1}$. We find a kinetic pressure $P_k / k_B = 2.3 \times 10^6$ K cm$^{-3}$. This is 20 times weaker than the outer pressure. Therefore, the inner pressure cannot sustain the globule against the overpressure of the ionized material. LL94
showed that in the course of its evolution, the pressure of the ionized gas increases as the radius of the globule decreases (§ 5.1 in LL94). In other words, the overpressure at the surface of the globule was less in the past.

8.1. Observational Evidence

Figure 15 shows the emission of the dense molecular gas in the HCO$^+$ $J = 1 \rightarrow 0$ and CS $J = 2 \rightarrow 1$ lines along a cut in declination across the border of the globule. The HCO$^+$ $J = 1 \rightarrow 0$ line is optically thick and is therefore well suited to trace the motions in the surface layers of the globule. Next to the HCO$^+$ emission main peak at 7.7 km s$^{-1}$, we detect a second component at “blue” velocities shifted by 0.7 km s$^{-1}$.

This feature appears as bright as the main-body gas emission. It is unambiguously detected in the CS $J = 2 \rightarrow 1$ line. It is detected only along the border of the globule, 15° north with respect to the center, and not inside the main body. It disappears again 30° north of the center, at the tip of the globule. The weakness of the line at these declinations is due to the small beam filling factor as the major fraction of the beam solid angle points toward the ionized gas in the H II region. The low S/N of the spectrum prevents us from leading any quantitative analysis.

This component is not related to protostellar activity. First, the blueshifted component is detected only at the border of the globule. There is no evidence of a blueshifted component toward the dust emission peak 15° south (more than $2 \times 10^4$ AU away from the border of the globule) where the protostar is expected to be found (see § 8.2). Second, the blueshifted component is kinematically separated from the main-body gas emission and does not exhibit the typical “wing” profile of molecular outflows. Third, there is no evidence for an additional, redshifted component that would trace the other wing of the molecular outflow.

On the contrary, the profile of this secondary kinematic component is much more suggestive of a shock propagating into the globule from the rear side. The detection of this secondary kinematic component at the border of the globule, well separated from the main-body gas emission, is typical of a globule in the early collapse phase and testifies that a shock is propagating into the globule from the surface. This is in agreement with the mid-IR analysis, which showed that the globule is photoionized on the rear side. This secondary molecular component is the kinematic signature of the PDR. It is completely unresolved by the 30 m telescope. However, since the FIR observations indicate a typical size of $10^{17}$ cm for the PDR ($\sim 4''$ at the distance of the Trifid), it could be resolved out by millimeter interferometers.

8.2. Comparison with Models

We compare the physical properties of TC2 with the numerical modeling of a photoionized globule presented in LL94. The simulation was done for ionization parameters similar to TC2: $\Lambda = 0.1$ and $\Gamma = 10$ ($\Delta$ and $\Gamma$ are the initial values of the parameters $b$ and $\gamma$). It is therefore possible to relate the properties of the observed globule to the simulated cloud via the simple scaling (LL94): $r \rightarrow kr$, $t \rightarrow kt$, $\rho \rightarrow k^{-1}\rho$.

As mentioned above, TC2 is undergoing the collapse phase, when a shock front propagates into the neutral gas. Based on a morphological comparison with the simulated globule (Fig. 4 in LL94), we find the best match for an age comprised between 0.13 and 0.18 Myr in the computation. At $t = 0.13$ Myr (Fig. 4b), a dense core has formed below the surface of the globule, which still exhibits a “barnacle”
shape. Later on, at 0.18 Myr (Fig. 4c), the bulk of the material has collapsed onto the main axis. The globule has now adopted an elongated shape. The best morphological match is obtained for an intermediate time $\tau \approx 0.15$ Myr. The numerical modeling indicates that the amplitude of the secondary kinematic component at such early photoionization stages is typically 1–2 km s$^{-1}$ (see their Fig. 14a). This velocity shift could be smaller depending on the inclination angle of the globule surface with respect to the line of sight. The 0.7 km s$^{-1}$ difference observed in TC2 between both kinematic components is therefore fully compatible with the numerical results.

At that stage, the simulated globule has lost about 25% of its initial mass (see Fig. 8 in LL94). Applying this result to TC2, it means that the initial mass of the globule was $\approx 80 M_\odot$. Since the initial mass of the simulated globule is 20 $M_\odot$, we can derive the scaling factor relating the properties of the observed globule to the model: $k \approx 2$. The radius of the scaled (simulated) globule is then $\approx 6 \times 10^{17}$ cm, whereas we measured 4.0 $\times 10^{17}$ cm. We note, however, that the density is assumed to be uniform in the simulated globule, whereas a core-envelope density structure, as in TC2, would lead to a smaller radius for the same ionization conditions. The duration of the photoionization, scaled from the simulations, is 0.3 Myr. This compares very well with the kinematical age of the Trifid, as measured from the luminosity of the exciting star and the expansion of the nebula (LeFloch & Cernicharo 2000). It is therefore very likely that the globule was very early exposed to the ionizing radiation, as soon as the O star turned on.

9. STAR FORMATION

9.1. HH 399 Jet

The first evidences of ongoing star formation in TC2 were presented by C98, based on an [S ii] image of the HH 399 jet running out of the bright rim of TC2. The jet has been studied in the optical by Rosado et al. (1999) and C98. These observations revealed the fragmented structure of the jet and could identify several “knots” from the head to the base of the jet, A–G, A being the most remote knot (see Fig. 5b).

Our VLA observations detect only the external part of the HH 399 jet. We could detect three “clumps,” which coincide with the knots dubbed A, C, and D by Rosado et al. (1999). The clumps are unresolved in the transverse direction by our observations. The flux peaks are rather similar (between 70 and 90 $\mu$Jy beam$^{-1}$). We take $0^\prime'.85$ ($\approx 2 \times 10^{16}$ cm) as an upper limit to the diameter of the jet, and adopting a temperature between 5000 and 10$^4$ K, we derive average electronic densities of $1.0-1.5 \times 10^5$ cm$^{-3}$ in the clumps. Our estimate is in agreement with Rosado et al. (1999) for knot A. There are larger discrepancies for knots C and D, which the authors estimate to have densities of $3 \times 10^3$ and $8 \times 10^3$ cm$^{-3}$, respectively. This could be due to clumpiness in the jet structure. This can also be explained by our assumption on the geometry of the jet, apart from the uncertainties in the 3.6 cm flux (the noise is $\approx 15-20$ $\mu$Jy beam$^{-1}$). For instance, assuming a jet diameter 10 times less would yield an electron density of $3 \times 10^3$ cm$^{-3}$, closer to the estimates derived at optical wavelengths.

As soon as the jet runs out of the PDR, it is exposed to the ionizing radiation of the exciting star. Integrating over the contour at 20 $\mu$Jy beam$^{-1}$, we obtain a total flux $S_\nu = 0.36$ mJy for the jet and an average emissivity $E_M = 8.8 \times 10^3$ pc cm$^{-6}$. The recombination rate per surface unit of the jet is $7.3 \times 10^9$ cm$^{-2}$ s$^{-1}$. This is only half the ionizing flux impinging on the globule, as estimated in § 3.1. Hence, there are enough Lyman continuum photons to maintain the jet fully ionized once it propagates out of the globule. HH 399 is one of the finest examples of photoionized jets reported so far (see also Reipurth et al. 1998).

We searched for some molecular outflow emission that would be the counterpart to the optical jet but did not find any evidence of such a phenomenon. This is probably because of the unfavorable orientation of the jet, very close to the plane of the sky (Rosado et al. 1999 estimate an inclination lower than 4°). We also searched for SiO emission as it is a tracer of young protostellar outflows, associated with Class 0 and/or massive sources (Bachiller 1996; LeFloch et al. 1998). Again, this search yielded only negative results. This suggests that the powering source has probably reached the Class I stage, characterized by a less active accretion phase than the Class 0, and has a typical evolutionary age of a few times $10^7$ yr. If this age is correct, it means that star formation began approximately at the time when the ionizing star HD 164492A turned on and ignited the nebula.

9.2. Protostellar Source

The observation of the molecular outflow emission and the overlap between the wings usually provides a good determination of the position of the driving source. Since this method cannot be applied here, in the absence of molecular outflow, the only indications on the source location are provided by the VLA observations. We have detected two small components inside the molecular core of TC2 (Fig. 16). Remarkably, they are both aligned with the jet.
propagation axis. Both components are unresolved and are only marginally detected with fluxes of 50 and 70 μJy beam\(^{-1}\), at a level of 3 and 4.5 σ, respectively. It is not clear whether these components trace some material associated with the counterjet or some material in the protostellar environment of the driving source itself. However, since they are located close to the millimeter dust emission peak, we favor the latter hypothesis. In the mid-infrared, as observed with ISOCAM in the broadband filters, there is no evidence of point-source emission in the globule. This indicates that the powering source of HH 399 is a much less luminous and massive object than the protostar detected in the southwestern molecular cloud (Lefloch & Cernicharo 2000). A close inspection of the continuum emission between 13 and 15 μm in the globule, however, reveals a local maximum of compact, unresolved emission at Δα = 70″, Δδ = -124″. This source is spatially separated from the PDR although close to it (≈7″). It coincides with the VLA sources to better than 2″, actually falling between them. Altogether, these observations give strong support for a physical association between the VLA component(s) and the driving source of the HH 399 jet.

The bolometric luminosity of the protostellar source is difficult to estimate since the PDR contributes to the luminosity of the globule too. We estimate the protostellar luminosity by taking into account only the cold dust component estimated from the fit of the SED: \(L \sim 520 L_\odot\). An upper limit is obtained by integrating under the spectral energy distribution: \(L_{\text{max}} = 1200 L_\odot\). This value is typical of intermediate-mass protostars, but we stress again that the actual luminosity could be lower.

9.3. Ultimate Fate

The radiation field has a deep impact on the Herbig-Haro jet as soon as it escapes the globule. However, it is less clear how much the star-forming process itself is perturbed. In the present stage, the size of the PDR represents approximately one-third of the globule’s radius. It is the low-density envelope, i.e., the mass reservoir, that is affected by the FUV field, and not the dense core where the mass is being accreted. An important parameter in the evolution of the globule is its mass-loss rate, which is determined by the ionizing flux and the radius of the globule (see LL94):

\[
\dot{M} = 14 \left( \frac{\Phi_1}{10^3 \text{ cm}^{-2} \text{ s}^{-1}} \right)^{1/2} \left( \frac{R_1}{1 \text{ pc}} \right)^{3/2} M_\odot \text{ Myr}^{-1}.
\]

For TC2, we estimate a present mass-loss rate of 34 \(M_\odot\) Myr\(^{-1}\). From comparison with numerical simulations, we found that the globule lost about 20 \(M_\odot\) since the ionization began. The globule has evaporated half the mass of its envelope until now, and its expected lifetime is therefore \(\tau_\odot = M_\odot / \dot{M} \sim 1.9\) Myr. This is a lower estimate as the mass-loss rate increases with radius. On the other hand, the active accretion phase is known to last a few times \(10^3\) yr (André, Ward-Thompson, & Barsony 2000). Therefore, the life expectancy of the globule is long enough to allow the protostellar objects to complete smoothly the accretion phase and turn into stars before the globule wholly evaporates. TC2 is going to develop progressively a low-density tail, turning into a so-called cometary globule. We speculate that within a few times \(10^3\) yr the situation should be very similar to the gas fingers observed in the Eagle Nebula (White et al. 1999), where the strong UV field is evaporating the ultimate dust and gas layers of the stellar nests, unveiling the star(s) formed in the early stages of the nebula.

10. Conclusions

We have carried out a multiwavelength study of bright-rimmed globule TC2 in the Trifid Nebula. The globule lies almost in the plane of the sky, immersed in the low-density gas of the H ii region (\(n_H \sim 50–100\) cm\(^{-3}\)). It is illuminated by the O star HD 164492A, mainly on the rear side. The globule consists of a very dense core of cold gas and dust [\(T = 22\) K, \(n(H_2) = 3 \times 10^5\) cm\(^{-3}\)] of small dimensions surrounded by a lower density envelope [\(n(H_2) = 3 \times 10^4\) cm\(^{-3}\)]. Its mass (\(\sim 63 M_\odot\)) is typical of bright-rimmed globules, equally distributed between the core and the envelope (27 and 36 \(M_\odot\), respectively). The ionization conditions at the surface of the globule were determined from VLA and ISO (LWS and SWS) observations. The impinging ionizing flux is \(1.4 \times 10^{20}\) cm\(^{-2}\) s\(^{-1}\); it creates an ionization front and a photoevaporated envelope of density (1–2) \(\times 10^3\) cm\(^{-3}\) at the surface of the globule.

The PDR is traced by the emission of the PAH bands at 6.2, 7.7, 8.6, and 11.3 μm. The observed variations of the relative intensities can be accounted for by the change in the excitation conditions. We find that the intensity of the 11.3 μm band drops outside of the PDR in the photoionized layers, as a consequence of the ionization of the PAHs. The 7.7 μm band is still detected in the photoionized envelope of the globule, although at a weaker level. Despite the high visual extinction of the globule, the 7.7 μm PAH band, excited in the PDR on the rear side, is detected in the body of the globule thanks to a minimum in the absorption of the ices and the dust in this wavelength range.

Millimeter line observations reveal the kinematical signature of the PDR that precedes the ionization front as a shock moving into the globule. The relative projected velocity is weak, \(\sim 0.7\) km s\(^{-1}\). Comparison with models of photo-ionized globules (LL94) indicates that TC2 has been exposed to the ionizing radiation for \(3 \times 10^5\) yr, almost as soon as the exciting star of the nebula turned on. The structure of the photon-dominated layer has been derived from the ISO FIR line and continuum observations. The agreement between all the data and the model of K99 is good. The intensity of the radiation field at the surface is \(G_0 \sim 1000\). The PDR has a typical column density of \(2 \times 10^{21}\) cm\(^{-2}\) and a molecular hydrogen density \(\sim 10^4\) cm\(^{-3}\). The FUV field heats the dust to a temperature \(\sim 46\) K, whereas the average gas temperature is found close to 300 K. The emission of the [Si ii] \(3.48\) μm line in the PDR can be accounted for by assuming a silicon gas-phase abundance of \(6 \times 10^{-6}\), i.e., \(\sim 17\)% of the solar value.

The globule is currently undergoing star formation. Our observations show that the globule is forming a low- or intermediate-mass star of luminosity \(\lesssim 500 L_\odot\). The protostar powers a Herbig-Haro jet, which appears fully ionized outside of the globule. No molecular counterpart (outflow) to the optical jet has been found. In particular, no SiO emission was found. This implies that the source is already in an intermediate stage between Class 0 and Class I, or even a full Class I member. The evolutionary age of the source is therefore typically a few times \(10^4\) yr, which suggests that star formation in TC2 probably started in the
large burst that accompanied the birth of HD 164492A. As a result of the photoevaporation of the surface layers, the globule has evacuated about half the mass in its envelope until now, but we have not found any evidence that the birth process itself has been perturbed. On the contrary, the photoevaporation rate is low enough to leave ample time for protostars to reach safely the ultimate stages of star formation.

We acknowledge Spanish DGES for this supporting research under grants PB96-0883 and ESP98-1351E. We thank J. R. Pardo for help with the observations at the CSO. L. F. R. is grateful to CONACyT, Mexico, for its support. This research made use of SIMBAD. The remarks of an anonymous referee helped a lot to improve the manuscript. It is a pleasure to thank C. Ceccarelli for many discussions and comments on this work.

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We acknowledge Spanish DGES for this supporting research under grants PB96-0883 and ESP98-1351E. We thank J. R. Pardo for help with the observations at the CSO. L. F. R. is grateful to CONACyT, Mexico, for its support. This research made use of SIMBAD. The remarks of an anonymous referee helped a lot to improve the manuscript. It is a pleasure to thank C. Ceccarelli for many discussions and comments on this work.

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