The Photoionization of a Star-Forming Core in the Trifid Nebula

B. Lefloch[1], J. Cernicharo[2],

and

L. F. Rodríguez[3], M.A. Miville-Deschênes[4], D. Cesarsky[5], A. Heras.[6]

ABSTRACT

We have carried out a comprehensive multiwavelength study of Bright-Rimmed Globule TC2 in the Trifid Nebula, using the IRAM 30m 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 Ly-c flux of the exciting star of the nebula ($\sim 10^{10}\,\mathrm{cm^{-2}\,s^{-1}}$). The globule consists of a cold dense core of mass 27 $M_{\odot}$ surrounded by a lower density envelope of molecular gas. The impinging Ly-c photons induce the propagation of an ionization front into the globule. The evaporation of the ionized gas forms a thin layer of density $n_e = 1 - 2 \times 10^3\,\mathrm{cm^{-3}}$ around the globule, which could be mapped with the VLA. The globule is illuminated mainly on its rear side, by a FUV field of intensity $G_0 \simeq 1000$. 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) onboard the Infrared Space Observatory. The physical conditions derived from the analysis of the far-infrared lines [OI] 63μm, 145μm and [CII] 158μm, and the continuum emission are in good agreement with some

[1]Laboratoire d'Astrophysique, Observatoire de Grenoble, BP 53, F-38041, Grenoble Cedex 9, France
lefloch@obs.ujf-grenoble.fr

[2]Consejo Superior de Investigaciones Científicas, Instituto de Estructura de la Materia, Serrano 121, E-28006 Madrid

[3]Instituto de Astronomía, UNAM, Campus Morelia, A.P. 3-72, Morelia, Mich. 58089, México

[4]ENS, LRA, 24 rue Lhomond, Paris, France

[5]Max-Planck Institut für Extra-Terrestrische Physik, 85741 Garching, Germany

[6]ESTEC/SCI-SAF, P.O. Box 209, NL-2200 AG Noordwijk The Netherlands

recent PDR models. The emission of the PAHs band at 6.2, 7.7, 8.6 and 11.3μm 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 10^5 yr ago, in the large burst which 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 newly born object(s) reach smoothly the ultimate stages of protostellar evolution. The impact of photoionization on the star formation process appears limited.

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

1. Introduction

It is well established that the bright-rimmed globules found in HII 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 et al. (1991) confirmed that they are indeed active "stellar factories" which produce intermediate-mass (Herbig AeBe) stars. These condensations are local clumps which 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; Bertold & McKee, 1990; Lefloch & Lazareff, 1994) and and the numerous observational studies on bright-rimmed globules (see e.g. Cernicharo et al. 1992; Lefloch & Lazareff, 1995) have enabled to draw the following evolutionary picture, summarized in Fig. 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 HII region, inducing the formation of a photoionized envelope around the globule. It is the ionization front and the photoionized envelope which are detected in the optical as a bright rim (region II). The incident FUV field drives the formation of a Photon-Dominated Region (hereafter PDR, region III) while a shock front, driven by the surface overpressure, propagates towards the dense molecular core (region IV). Observational evidence of this mechanism, also called Radiatively-Driven Implosion (or 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 et al. 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 onto 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 HII 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 Radiatively-Driven Implosion and a spontaneously evolving globule which 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 HII region : the Trifid nebula. It appears as a small dusty nebula of $10'$ diameter at an heliocentric distance of 1.68 kpc (Lynds et al. 1985), with a dynamical age of $0.3 - 0.4$ Myr . The nebula is excited by the O star HD 164492A. In a preliminary work (Cernicharo et al. 1998, CL98), we reported on the mapping of the thermal dust emission of the nebula at millimeter wavelengths. This mapping revealed the presence of several protostellar cores (dubbed TC1 to TC4) in the shell of dense molecular gas surrounding the HII region. It was not clear however if the birth of the protostars was triggered or not. For this reason, we undertook a more detailed analysis of the protostellar cores. In a subsequent paper (Lefloch & Cernicharo, 2000), we reported on the continuum and molecular line emission around the two most massive protostellar cores : TC3-TC4. Their masses are high, between 60 and 90 $M_{\odot}$. They harbour 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 et al. (1994) allowed 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, though 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 TC3-4 : unlike TC3-4 which are still embedded cores, TC2 has already emerged from the diffuse molecular gas layers and it 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. CL98 reported the presence of the Herbig-Haro jet HH399 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 quantify the relation both phenomenons hold to each other, and better constrain the role that Radiatively-Driven Implosion could play in the star formation process. In 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 photon-dominated region, 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 HII region (Sect. 3); the bright rim and the photo-evaporated envelope (Sect. 4); the PDR (Sect. 5); the dust continuum emission (Sect. 6) and the molecular core (Sect. 7). We then discuss the observational evidences of Radiatively-Driven Implosion in TC2 and the implications on the past history of the globule (Sect. 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 photo-ionization both on the protostar and the evolution of the globule (Sect. 9). The conclusions are presented in Sect. 10.

2. The 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-IR and FIR with the Infrared Space Observatory (ISO; Kessler et al. 1996). The conditions in the molecular core were derived from the emission of the cold dust and of various molecular tracers at millimeter wavelengths with the IRAM 30m telescope. The physical conditions in the PDR were determined mainly from the observations of the FIR [OI] lines at 63μm and 145μm and the [CII] line at 158μm. The dust properties were derived from the observation of the continuum emission between 5 and 197μm with the instruments onboard ISO. In all maps presented here the coordinates of all the maps are given in arcsec offsets with respect to the position of HD 164492A : $\alpha(2000) = 18^{\rm h}02^{\rm m}23.55^{\rm s}$, $\delta(2000) = -23°01'51''$. The observational data set is summarized in Table 1; the data described below are shown in Figures 2 to 9 and 11 to 16.

2.2. The VLA data

The Very Large Array observations at 3.6 cm were made with the array in its highest angular resolution A configuration in 1998 March 13. We used 1328+307 as absolute amplitude calibrator and 1748-253 as the phase calibrator. A bootstrapped flux density of 0.271±0.001 Jy was obtained for 1748-253. The observations were made in both circular polarizations with an effective bandwidth of 100 MHz. The data were edited and calibrated following the standard VLA procedures and using the software package AIPS. The final map at 3.6cm was made with the AIPS task IMAGR, the ROBUST parameter set to 5, and a Gaussian taper of 100 kλ to the (u,v) data to lower the angular resolution. The field of view is approximately 5′; the synthesized beam has a size of $1''.7 \times 1''.4$ (HPFW) and makes a position angle (P.A.) of 17°.

2.3. The Millimeter Continuum Observations

Observations of the 1.25mm continuum emission in the Trifid were carried out in March 1996 and March 1997 at the IRAM 30m-telescope (Pico Veleta, Spain) using the MPIfR 19-channel bolometer array. The resolution of the telescope is 11″. The final map was obtained by combining 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″ per sec; subsequent scans are displaced by 4″. We used a chopping secondary at 2Hz with a throw of 30 to 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 $8\,\mathrm{mJy}/11''$ beam. Hence, it is sensitive enough to detect at the 3σ level protostellar condensations of $1\,M_\odot$ 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 $5\,\mathrm{mJy\,beam}^{-1}$. All the results quoted in this paper are based on the non-degraded map with 0.09 pc resolution.

2.4. The Molecular Line Observations

We observed in July 1996 and July 1997 the Trifid nebula in the millimeter lines of SiO, HCO^+, $H^{13}CO^+$ and CS, with the IRAM 30m-telescope. The lines were observed with a spatial sampling of $15''$: the data are almost Nyquist-sampled at 3mm. We used an autocorrelator as spectrometer, which provided a velocity resolution of $\approx 0.2\,\mathrm{km\,s}^{-1}$ in all three bands. The rejections of the receivers were always higher than 10dB, and checked against W51D (Mauersberger et al. 1989). The Trifid was mapped at full sampling in the CO $J = 2 \rightarrow 1$, $J = 1 \rightarrow 0$, ^{13}CO $J = 1 \rightarrow 0$ and $C^{18}O$ $J = 1 \rightarrow 0$ lines with the IRAM 30m telescope in July 1996. The autocorrelator provided a kinematic resolution of $0.2\,\mathrm{km\,s}^{-1}$ for all the transitions. Additionnal observations of the CO $J = 3 \rightarrow 2$ transition were carried out at the CSO during various observing runs between 1998 and 1999. The receiver was connected to an AOS which provided a kinematic resolution of $0.4\,\mathrm{km\,s}^{-1}$. All the observed lines, their frequency, the telescope beamwidth and the main-beam efficiencies are summarized in Table 2.

2.5. The Mid-Infrared Observations

We observed the Trifid nebula with ISOCAM (Cesarsky et al. 1996) onboard ISO. An image of the whole nebula was obtained using the broad band 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 mode (CVF) between 5 and $17\mu m$. The pixel size is $1.5'' \times 1.5''$ and the spectral resolution is 40. The 32×32 pixel detector covered a total field of view of $48'' \times 48''$ centered on the globule at $\alpha(2000) = 18^{\mathrm{h}}02^{\mathrm{m}}28.7^{\mathrm{s}}$, $\delta(2000) = -23°03'51''$. 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 45μm was observed with the SWS spectrometer onboard 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 towards the bright rim and the HII region and towards the main body of the globule respectively. The positions are marked in Fig. 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 consists of an "up" scan, towards decreasing wavelengths, and a "down" scan towards 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 2.5μm to 30% at 45μm (SWS ISO Handbook, 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 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, *but the [NeIII] line at* 15.55μm, 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 [NeIII] line.

The emission between 45 and 197μm was observed towards the globule with the LWS spectrometer onboard ISO (Clegg et al. 1996). The size of the LWS beam is known to vary between $66''$ and $86''$ 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 spectrometer (Gry et al., 2001). The large-scale emission of the nebula was estimated by observing a nearby reference position $90''$ away of TC2, at position $\alpha(2000) = 18^h02^m35.1^s$, $\delta(2000) = -23^\circ03'51.8''$ (see Fig. 2). The data was reduced using the Off The Line package (OLP) version 7 and with the ISAP package. The fluxes measured are given following the standard flux calibration, assuming a point-like 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 which 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) to the emission measured ON source.

3. The HII region : zone I

We proceed first with the analysis of the HII 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 HII region.

3.1. Emission from the nebular gas

We show in Fig. 6 the various atomic and fine-structure atomic lines detected with the LWS and SWS spectrometers. Many of the identified lines exhibit weak variations between the On and Off positions.

The best example is provided by [CII] at 158μm. On the other hand, the largest variations are observed for the [OI] lines at 63.3 and 145.5μm. In particular, almost no emission at all is detected in the 145μm line at the reference position

The [OIII] $52, 88 \mu m$ and [NIII] 57μm lines are useful tools to diagnose the electron density in the ionized gas. The ([OIII] 52/88) and ([OIII] 52/[NIII] 57) 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 HII 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 spectrometer, Gry et al. 2001). Since the emission at the reference position comes from the HII region and fills the whole LWS beam, the fluxes have been calibrated according to the ISO manual prescription. We then obtain ([OIII] 52/88) = 0.69. This corresponds to a mean density $n_e \simeq 50\,\mathrm{cm^{-3}}$, which is consistent with the previous determination from [SIII]. In this density range, the emissivity of the 52μm line is : $\epsilon_{52} = 8.0 \times 10^{-23}\,\mathrm{erg\,cm^3\,s^{-1}\,sr^{-1}}$ (Dinerstein et al., 1985). If we assume a standard abundance $[OIII]/[H^+] = 2 \times 10^{-4}$, we derive an estimate of the emissivity $\int n_e^2 dl = 2.6 \times 10^3 \mathrm{cm^{-6}}\,\mathrm{pc}$ and the size of the emitting region : $l \simeq 1\,\mathrm{pc}$.

In the density range measured in the HII region, the emissivity ratio ([NIII] 57/[OIII] 52) 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

1.88×10^3 cm^{-3} and 3.25×10^3 cm^{-3} respectively) this discrepancy mainly reflects the different relative elemental abundances. We obtain an elemental abundance ratio ([NIII]/[OIII]) $\simeq 0.5$. This ratio agrees with other determinations in a sample of HII regions by Lester et al. (1983) who obtained 0.25-0.43.

In the SWS spectra, the line [NeII] 12.7μm is detected at the three observed positions : towards 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 HII region, which fills the SWS beams, dominates the emission from the globule. The SWS fluxes of the [NeIII] $15.5\mu m$ line suffer large statistical errors which casts some doubt on the variations measured with the SWS : whereas the fluxes in the Northen and Central positions are similar (better than 30%), there seems to be hardly any emission detected in the Southern position.

Similarly to the [NeII] line, the [SIII] lines at 18.7 and $33.7\mu m$ exhibit only weak variations between the three positions observed with SWS. In order to determine the origin of the [SIII] emission, we first estimate the electron density from the [SIII] 18/33μm 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 the interstellar extinction should be rather low and we will neglect the latter in what follows. We estimate an emissivity ratio $\epsilon_{18.7}/\epsilon_{33.7} \simeq 0.7$ for the Northern spectrum. This ratio allows only to set an upper limit on the electron density (Rubin 1989) : $\mathrm{n_e} \leq 200\,\mathrm{cm}^{-3}$. If the contribution of the bright rim were dominant, one would obtain a much larger emissivity ratio, of ~ 2, as expected for the electron densities obtained with the VLA ($\sim 10^3\,\mathrm{cm}^{-3}$). This agrees with previous determinations of the *nebular* gas density by Lynds et al. (1985) and Rosado et al. (1999) from the optical [SII] 6717, 6731Å 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 [SIII] flux arises from the HII region.

3.2. The 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 $\mathrm{T_{eff}}$ by comparison with models of HII 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 $< O^{2+}/O > / < S^{2+}/S >$ spans 3 orders of magnitude when the effective temperature of the exciting star ranges from 3 to 4×10^4 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 ionic ratio O^{2+}/S^{2+} from the [OIII] lines at 52 and 88μm and the [SIII] 19μm line. The emissivities for [OIII] and [SIII] are taken from Dinerstein et al. (1985) and Rubin et al. (1994) respectively. We adopted O/S = 47 as elemental abundance, which is the value found in the Orion nebula (Rubin et al. 1991). We obtain $< O^{2+}/O > / < S^{2+}/S > \simeq 0.04$ and 0.09 towards the Off and On position respectively. The variations of $< O^{2+}/O > / < S^{2+}/S >$ versus the effective stellar temperature T_{eff} for ionizing luminosities in the range $\log N_L = 49 - 50$, indicates $T_{eff} \simeq 35500$ (Fig. 8 in Simpson et al. 1995). An effective temperature of 38000 K, typical of an O7 V star, requires a ratio $< O^{2+}/O > / < S^{2+}/S >$ of a few, i.e. 10 to 20 times larger. There is a priori a restriction in directly applying the models of Rubin since the density of the Trifid ($100\,\mathrm{cm^{-3}}$) is somewhat less than the density considered in the calculations. However, in the range of temperatures and Ly-continuum luminosities considered, the ratio of the ionic lines is almost independent of the density in the range $100 - 1000\,\mathrm{cm^{-3}}$ (Rubin, 1994).

Therefore, the effective stellar temperature of the central star exciting the Trifid is $T_{eff} \simeq 35500\,\mathrm{K}$. Interestingly, this value is typical of an O7.5 III star, a spectral type proposed by Walborn (1973) for HD 164492A, and not an O7 V star (the classification proposed by Lynds et al. 1985). In both cases, the physical properties of the exciting star are very similar, and, in particular the number of Lyman-Continuum photons varies by $\approx 30\%$, reaching $9.6 \times 10^{48}\,\mathrm{s^{-1}}$ for an 07.5 III [7].

3.3. The FUV field Intensity

A simple estimate of the FUV field intensity can be obtained for spherical, ionization-bounded, HII regions excited by standard O stars and in pressure equilibrium with the parent cloud (Spitzer, 1978). The FUV field intensity G_0 is related to the hydrogen nuclei density n_H via $G_0 \simeq 3 \times 10^5 \left((n_H/10^4\,\mathrm{cm^{-3}})/C\right)^{1.33}$ (Spitzer, 1978). Here, $C = n_H/n_e \sim 100$ in an HII region in pressure equilibrium with the ambient cloud, $n_e = 100\,\mathrm{cm^{-3}}$ is the mean electron density in the HII region (Chaisson & Willson, 1975) and G_0 is measured in units of the

[7] There is an error in Table II of the article of Panagia (1973) : the correct number of Ly-c photons for an 07.5 III star is not 49.98, as mentionned, but 48.98, as can be checked from the excitation parameter U in the following column.

average interstellar field flux of $1.6 \times 10^{-3}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ (Habing, 1968). One derives a FUV field $G_0 \simeq 700 - 1700$ at the border of the HII region.

A more accurate value is obtained by considering the infrared dust continuum emission. If one makes the simple hypothesis that in the PDR the dust is heated only by the incident FUV field, then, at first order, the dust temperature is related to G_0 via $T_d = 12.2 G_0^{0.2}$ K (Hollenbach, Tielens & Takahashi, 1991). The temperature estimated for the warm dust layer in TC2 (≈ 46 K; see Sect. 6) yields a FUV field intensity $G_0 \simeq 800$. This value is in good agreement with the (crude) previous estimate. It is also consistent with the ([OI] 145/63μm) and ([OI] 63/[CII] 158μm) line ratios measured towards TC2, as we discuss in the following paragraphs. We will adopt $G_0 = 1000$ in the rest of the article.

4. The Bright Rim and the Photoionized Envelope : zone II

The Bright-Rimmed Globule TC2 is located on the Southern border of the HII region, at approximately 1 pc of the exciting star of the nebula : HD 164492A. An optical Hα image of the nebula (taken from CL98), is shown Fig. 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 : $R_g \simeq 4 \times 10^{17}$ cm.

Some weak extended [SII] 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 (Lefloch et al. 2002). Therefore TC2 is "bathing" in the nebular ionized gas.

The peak of brightness is found, as expected, in the direction of the ionizing star of the nebula HD 164492A. However, the major axis of the globule does not point towards the star but in the North direction. This difference in the orientations might reflect some inhomogeneties in the gas distribution or the influence of other stars which formed at the same time as HD 164492A : the energy released would have affected the expansion of the HII region. Indeed, Lefloch et al. (2001) have reported the presence of several young high-and intermediate-mass stars in the HII 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. 4-5b) is detected as a conspicuous bright filament which seems to penetrate the surface and makes a P.A. of $\sim 20\,$deg 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 Sect. 3.2) the Lyman-continuum (Ly-c) luminosity of the star lies in the range $7 - 10 \times 10^{48}\,\mathrm{s}^{-1}$. 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 non-negligible role. CL98 presented a map of the free-free emission at 20 cm, obtained with the VLA at $10''$ resolution. We show in Fig. 5a 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.

4.1. The 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 ($\sim 1.5''$). The map of the 3.6cm continuum emission is shown in Fig. 5b.

The bright rim is clearly detected; it is marginally resolved in its transverse direction with a thickness $\approx 1.5 - 2.0'' = (3.5 - 5) \times 10^{16}\,$cm. Integrating over the bright rim, we derive a total flux of $2.4 \pm 0.2\,$mJy. The photo-ionization of the surface layers induces the formation of a shell of ionized gas around the globule, which is detected in the optical as the bright rim. The radiative recombinations which take place in the shell shield the molecular material of the globule from the incoming ionizing flux. Previous theoretical work (Bertoldi, 1989; Lefloch & Lazareff 1994) showed that the ionized shell can be modeled as a shell of uniform density $\mathrm{n_e}$ and thickness $\eta\mathrm{R_g}$: $\mathrm{n_e}$ is the ionized gas density at the surface of the globule, $\mathrm{R_g}$ is the radius of the globule, essentially the radius of the cross-section to the ionizing field, and η is a geometrical factor of the order 0.1-0.2. For standard ionization conditions most of the impinging ionizing photons are consumed in the shell. The free-free radiation flux across the ionized shell detected in an area of size θ_s can be expressed as a function of the electronic density and temperature, and θ_s (Lefloch et al. 1997) :

$$\left(\frac{S_\nu}{1\,\mathrm{mJy}}\right) = 2.36\times10^{-5}\left(\frac{n_e}{1\,\mathrm{cm^{-3}}}\right)^2\left(\frac{\eta\mathrm{R_g}}{0.1\,\mathrm{pc}}\right) \times\left(\frac{T_e}{10^4\,\mathrm{K}}\right)^{-0.35}\left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-0.1}\left(\frac{\theta_s}{10''}\right)^2$$

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 : $\mathrm{T_e}\simeq 8150\,\mathrm{K}$. We measure a total flux of 2.3 mJy in an area of 74 $\mathrm{arcsec^2}$, defined by the contour level at 20 μJy $\mathrm{beam^{-1}}$. Assuming that the bright rim radial size is similiar to the thickness of the ionized shell, i.e., $\eta = 0.08 - 0.11$. We derive an average electron density $\mathrm{n_e} = (1.0 - 1.2)\times10^3\,\mathrm{cm^{-3}}$ over the bright rim. At the brightness peak, the 3.6 cm flux is 2.6×10^{-4} Jy $\mathrm{beam^{-1}}$, hence the electron density reaches a local maximum of $n_e = 1800\,\mathrm{cm^{-3}}$ over the telescope beam.

The effective flux of Ly-c photons ionizing fresh material is $n_e c_i \simeq 10^9\,\mathrm{cm^{-2}\,s^{-1}}$ ($c_i \simeq 10\,\mathrm{km\,s^{-1}}$ 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 $\alpha_B\eta n_e^2 R_g = 1.4\times10^{10}\,\mathrm{cm^{-2}\,s^{-1}}$ ($\alpha_B = 2.7\times10^{-13}\,\mathrm{cm^3\,s^{-1}}$ is the recombination coefficient on hydrogen levels $n\geq 2$). 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 Ly-c luminosity of the exciting star, $8\times10^{10}\,\mathrm{cm^{-2}\,s^{-1}}$ at the projected distance of TC2.

4.2. Fine-Structure Atomic Line Emission

We detected with the SWS spectrometer the following ionic and fine-structure atomic lines : [NeII] 12.7μm, [NeIII] 15.5μm, [SIII] 18.7μm, [SIII] 33.5μm and [SiII] 34.8μm. The spectra are displayed in Fig. 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 HII region (see Sect. 3), the bright rim and the PDR (in the case of [SiII]). Since the [SiII] 34.8μm is believed to arise from the PDR, it is discussed below in Sect. 5.4. The other lines have been discussed in Sect. 3 and we concluded that within the SWS beam and the observational uncertainties the emission is dominated by the HII region.

In order to precise the spatial distribution of the [NeII] and [NeIII] lines, we use the CVF data, obtained with a much higher angular resolution ($4'' - 6''$). Moreover, the CVF data benefits a better SNR 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 HII 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 Fig. 7. The [NeII] 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 Fig. 7 where the contours of the PAH 11.3μm band are superposed on the [NeII] emission map. The emission delineates a thin layer of $\simeq 5''$. It can be seen that *there is no [NeII] emission detected over the body of the globule*. A spectrum at position F in the main body of TC2 (Fig. 8f) and confirms the absence of emission longwards of 8 μm. Therefore, *the front side of the globule is hardly illuminated by the Ly-c photons from the exciting star. In particular, the main body of the globule is not photoionized*. Some weak [NeII] emission is detected all around the globule, especially in the Northerwestern direction, i.e. towards 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, $\sim 10\,\mathrm{km\,s^{-1}}$ (LL94). The detection of high gas velocities, from spectroscopic measurements, and the study of their spatial distribution would allow to confirm the association of this component with the photoevaporated envelope of the globule.

The distribution of the [NeIII] 15.5μm emission was obtained following the same procedure, and is displayed in Fig. 7. The [NeIII] map looks much noisier than [NeII]. Again, there is no emission detected towards the body of the globule. The [NeIII] emission is limited to the Northwestern quadrant, between the globule and the ionizing stars. It overlaps with the outer part of the [NeII] flux distribution, at the surface of the globule, and in the extended component which possibly traces the photoevaporated envelope. This is consistent with the high ionization potential of the [NeIII] line (41 eV) with respect to to the [NeII] line (22 eV).

Additional lines were detected in the far-infrared with the LWS. The emission from TC2 was estimated by subtracting the emission of the reference position (see Sect. 3) to the spectrum towards 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 ratio ([OIII] 52/88) ratio yields $n_e = 170\,cm^{-3}$. A more pronounced increase is observed using the ([NIII] 57/[OIII] 52) ratio : $n_e = 550\,cm^{-3}$, when adopting an abundance ratio of 0.5.

One cannot exclude that the contribution of the HII region along the line of sight of TC2 is somewhat underestimated by the procedure descrived in Sect. 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 Sect. 4.1, the latter can be modeled as a layer of effective thickness 5×10^{16} cm and density $n_e = (1 - 2) \times 10^3\,cm^{-3}$, which expands almost freely around the globule. The emission of this layer could account for the observed increase in density towards TC2 and for the discrepancy between the density estimates from the ([OIII] 52/88) and ([NIII] 57/[OIII] 52) ratios. This is because the [OIII] 52μm and [NIII] 57μm lines are more sensitive to dense material than the [OIII] 88μm line (their critical densities are similar to the ionization front density whereas it is only $\sim 460\,cm^{-3}$ for [OIII] 88μm). Indeed, a simple modelling with two layers of density $200\,cm^{-3}$ and $2000\,cm^{-3}$, thickness $\ell = 1.3 \times 10^{18}$ cm and $5 \times 10^{16}\,cm^{-3}$ respectively can account for the emission observed. The contribution of the dense layer is almost unnoticed at 88μm whereas it constitutes $20 - 30\%$ of the observed flux for the 57μm and 52μm 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 the LWS spectrometers confirms that the bright-rimmed globule is bathing in the nebular gas of density $n_e = 50 - 100\,cm^{-3}$. 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 [NIII] 57μm and [OIII] 52μm lines. The surface density is $\simeq 1000\,cm^{-3}$ and rises up to $2000\,cm^{-3}$. The photoionized envelope of TC2 is also detected in the [NeIII] and [NeII] lines. The mapping of these lines shows that the globule is illuminated on the rear side.

5. The 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 11.3μm 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 Polycyclic Aromatic Hydrocarbons, or 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 : [SiII] 34.8μm, [OI] 63μm, [OI] 145μm and [CII] 158μm. The [OI] and [CII] 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), Hollenbach, Takahashi & Tielens (1991) The main difference is that the model of K99 use very recent grain photoelectric heating rates, which include treaments 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 shortwards of 15μm is dominated by the PAHs emission bands.

5.1. The Emission of the UIBs

As can be seen in Fig. 8, the UIBs (or PAHs) bands at 6.2, 7.7, 8.6 and 11.3μm dominates the 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 12.7μm line that is a combination of the [NeII] line and of a PAH band, and the presence of a continuum emission at wavelength greater than 13μm, also well detected in the SWS spectra (see Sect. 6.2), and the presence of the [NeIII] 15.5 μm 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 [NeII] line, Lorentzian lines for the PAHs bands (Boulanger et al. 1998) and a grey body for the continuum emission. The resulting maps are shown in Fig. 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 PAHs bands probably as a consequence of the remote distance to the Trifid nebula. The emission is shifted by $\approx 2''$ towards the interior of the globule with respect to the photoionized region, as traced by the [NeII] 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 7.7μm (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 HII region. In order to increase the SNR, the emission has been averaged over four pixels at each position. The resulting spectra are displayed in Fig. 8. The contribution of the nebula, as estimated from the reference position (Fig. 8e) has been subtracted to 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 either in absorption or in 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 11.3μm as they have the highest SNR. The bands have a ratio 7.7/11.3$\simeq$ 0.9 in the PDR. This ratio is $\sim$1.2 at the reference position (panel e) in the HII region and it reaches ≈ 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 PAHs emission show that the relative intensity of the various bands are strongly sensitive to the ionization state. In particular the intensities of the C-C stretching modes (6.2 and 7.7μm) and the C-H in-plane bending mode (8.6μm) 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 (11.3μm) 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 11.3μm band can be understood as the dehydrogenation and photoionization of the smallest PAHs exposed to the strong UV field of the HII region. A similar effect has been reported in the HII 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 [NeII] and the [NeIII] 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 towards 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 $A_v = 20$ over the body of the globule). The absorption by the silicates is so large that hardly any radiation escapes from the globule longwards 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 [NeII] 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 [NeII] emission, as mentionned 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 VLA4 in the L1641 molecular cloud in Orion. It takes into account the contribution of silicates, the ices of methanol CH_3OH, water H_2O and carbon dioxide CO_2. As noted by Cernicharo et al. (2000), the spectrum of VLA4 is very similar to the spectra observed towards deeply embedded objects in massive star-forming regions. We also note that VLA4 and TC2 are in a similar evolutionary stage. Hence, we believe that despite some possible abundance variations between both protostellar cores, the VLA4 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 1.3mm continuum map, and similar to the average extinction over the globule. We show the calculated spectrum in Fig. 9. The $7.7\mu m$ band intensity is ~ 70 MJy/sr whereas the intensity of the 11.3μm band and the [NeII] line is now only ~ 40 MJy/sr. 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 7.7μm band with respect to the 11.3μm 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 11.3μm are unambigusouly 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 [NeII] and [NeIII] 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. [CII] line emission in the globule

The LWS spectra of the [CII] and [OI] lines are shown in Fig. 6. The emission from the globule was obtained by subtracting a reference position to the spectra taken towards TC2 (see Sect. 2.5). The uncertainties in the flux of the [OI] lines are rather weak since the emission at the reference position appears much weaker than towards the globule. On the contrary, the variations of the [CII] 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 far-infrared [SIII] and [OIII] lines carried out in Sect. 3.1 suggested that this region was contributing to the flux detected. The [CII] 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 [CII] 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 CL98 (Fig. 5a). These data were obtained at a resolution of 10$''$. This allows to trace the extended emission from the main body of the globule, unlike the high-angular observations presented in Sect. 3.1. We apply the method described by Heiles (1994), who showed that intensity I_C of the [CII] line scales with the brightness temperature of the free-free emission in low-density region and we derive the relation :

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

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

The free-fre emission map shows some extended emission in addition to the bright rim. The emission peaks at 33 mJy/beam 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. This implies a peak flux of 13 mJy/beam in the bright rim. Following the same method as in Sect. 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 [CII] line $I_C \simeq 1.5 \times 10^{-4}\,erg\,cm^{-2}\,s^{-1}\,sr^{-1}$. This value represents approximately 30% of the flux detected with the LWS towards the globule. After correcting for the contribution of the surface ionized layers, we obtain that the flux of the [CII] line in the PDR gas is $\simeq 1.8 \times 10^{-11}\,erg\,cm^{-2}\,s^{-1}$.

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

$$M_a = 5.8 \left(\frac{d}{1\,\mathrm{kpc}}\right)^2 \left[\frac{1.4\times10^{-4}}{x(\mathrm{CII})}\right] \left(\frac{F_{\mathrm{CII}}}{10^{-17} W\,\mathrm{cm}^{-2}}\right) \times \left(\frac{10^{-21}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}atom^{-1}}}{\Lambda(\mathrm{CII})}\right) M_\odot$$

where Λ(CII) is the cooling rate in the [CII] 158μm line per carbon atom and per steradian, x(CII) is the abundance of ionized carbon per hydrogen atom. Here, we adopt a carbon abundance $x(\mathrm{CII}) = 1.4 \times 10^{-4}$ (see K99). The atomic gas temperature in the PDR of TC2 is close to 300 K (see next section). For hydrogen densities of $10^4\,cm^{-3}$, comparable to that in the PDR gas, the cooling rate Λ(CII) is then $0.8 - 1.0 \times 10^{-21}\,erg\,cm^{-2}\,sr^{-1}atom^{-1}$. 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 : $N(H) = (1.5 - 1.9) \times 10^{21}\,cm^{-2}$.

5.3. Physical Conditions in the PDR from the [OI] and [CII] lines

We present below the physical conditions derived from the analysis of the far-infrared 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 $G_0 \simeq 1000$ and using the model of K99, we find that the gas is heated by photo-electrons to a temperature of $\simeq 300\ K$ at the surface of the PDR, a value which 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 analysis of the [OI] 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 $1.3\,\mathrm{km\,s^{-1}}$ as linewidth, based on the observations of the millimeter lines of HCO^+ and CS in the head of the globule (Sect. 7.2). The core density derived from the millimeter dust thermal emission provides an upper limit to the density in the PDR : $n(\mathrm{H_2}) = 3\times10^5\,\mathrm{cm^{-3}}$. Hence, in order to account for the observed [OI] fluxes at 63μm and 145μm, the gas temperature has to be larger than 200 K. The best match is obtained for a column density $\mathrm{N(O)} = 7\times10^{17}\,\mathrm{cm^{-2}}$ (Fig. 10). At a temperature of 300 K, as derived above for the PDR, the molecular hydrogen density is $\mathrm{n(H_2)} = 6\times10^4\,\mathrm{cm^{-3}}$. Adopting an oxygen elemental abundance $[\mathrm{O}]/[\mathrm{H}] = 3.0\times10^{-4}$, the corresponding gas column density in the PDR is $\approx 2\times10^{21}\,\mathrm{cm^{-2}}$.

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 [OI] 63μm line, more easily excited, is likely to be larger than that of the 145μm line. This effect was not taken into account in the present calculation and results in an underestimate of the [OI] column density whereas the hydrogen density is overestimated.

The ([OI] 63/[CII] 158) and ([OI]145/63) line ratios provide another method to derive the parameters of the PDR. These ratios are 0.066 and 4.2 respectively; using Figs. 4-5 in K99, we obtain direct estimates of the FUV field intensity $\mathrm{G_0} = 1000$ and of the hydrogen nuclei density $n(H) = 2\times10^4\,\mathrm{cm^{-3}}$. This estimate of $\mathrm{G_0}$ is in good agreement with the previous, independent, determination, based on the far-infrared dust continuum. In the range of values taken by the ([OI] 63/[CII] 158) ratio, the ratio is not very sensitive to the FUV field intensity $\mathrm{G_0}$. Hence, an overestimate of the [CII] 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 $\sim 3\times10^4\,\mathrm{cm^{-3}}$. We determine the electron density in the PDR from the photoelectric heating efficiency ϵ, which is governed by the factor $\mathrm{G_0 T^{1/2} n_e^{-1}}$ (see e.g. Bakes & Tielens 1994). The integrated intensity of all the FIR lines is well approximated by the sum of the [OI] 63μm and [CII] 158μm intensities, which amounts to $2.6\times10^{-3}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,sr^{-1}}$. We note that since the cooling of the PDR gas is dominated by the [OI] 63μm line, the uncertainties in the [CII] line flux do not affect significantly the total cooling nor the conditions of thermal balance. We estimate the integrated FIR continuum intensity radiated by the PDR from the warm component determined in the spectral energy distribution : $0.21\,\mathrm{erg\,s^{-1}\,cm^{-2}\,sr^{-1}}$. On the other hand, the FUV photon heating amounts to $\approx 1.6 \times 10^{-3} G_0/(4\pi) = 0.102\,\mathrm{erg\,s^{-1}\,cm^{-2}\,sr^{-1}}$. This value represents a lower limit to the total heating since the contribution of the photons outside the FUV band has been neglected here and could represent a substantial fraction (up to 1) of the FUV heating (Tielens and Hollenbach, 1985; Wolfire et al. 1989). The agreement between the FIR continuum radiation and the UV photon heating is therefore satisfactory and supports our view that the warm dust layer detected with ISO/LWS and SWS (see Sect. 6) is indeed tracing the PDR at the surface of the globule. This yields a photoelectric efficiency $\epsilon = 0.013$. From the variations of ϵ with the factor $\mathrm{G_0 T^{1/2} n_e^{-1}}$ (see Fig. 21 of Bakes & Tielens 1994), we estimate $\mathrm{G_0 T^{1/2} n_e^{-1}} \simeq 5 \times 10^3 \mathrm{K^{1/2}\,cm^{-3}}$, hence the electron density in the PDR : $\mathrm{n_e} = 3.5\,\mathrm{cm^{-3}}$. In the PDR, the ionization fraction is determined by the photoionization of carbon. Adopting a carbon abundance of 1.4×10^{-4}, we obtain an estimate of the hydrogen density $\mathrm{n(H_2)} = 1.3 \times 10^4\,\mathrm{cm^{-3}}$.

5.4. The Emission of the [SiII] 34.8μm line

The emission of the [SiII] 34.8μm line can be produced in the PDR of molecular clouds which are illuminated by strong FUV fields (Tielens & Hollenbach 1985) and also in HII regions (Rubin, 1985). In the case of Orion, as prototype of massive star forming region, Walmsley et al. (1999) showed that the [SiII] emission comes mainly from the PDR and not from the HII region or the ionization front region.

We try to determine the origin of the emission observed towards the globule. It is difficult to draw any definite conclusion because of the lack of angular resolution, hence of information about the spatial distribution of the emission. Also, 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 1.3mm; they indicate an average visual extinction $\mathrm{A_v} = 20$ across the globule (see Sect. 6). The values of the interstellar extinction tabulated by Mathis (1990) allow to estimate the opacity of the globule at 35μm : $\tau_{35} \simeq 0.08$. Therefore *the globule is mainly transparent at this wavelength.*

For the physical conditions encountered in the PDR of TC2, the model of Wolfire, Tielens & Hollenbach (1990) predicts a typical value of 0.015 for the ([SiII] 34.8/[OI] 63) ratio whereas the observed ratio is 0.5. Assuming 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 $[\mathrm{Si}]/[\mathrm{H}] \simeq 2.3 \times 10^{-5}$, i.e. 0.6 times the solar elemental silicon abundance ($\sim 3.6 \times 10^{-5}$). This is unrealistically high as observations in other HII regions like Orion indicate that about 90% of Silicon is tied up in dust grains (Walmsely et al. 1999), a value also similar to that found in diffuse interstellar clouds, Therefore, the PDR of TC2 alone can not account for the measured [SiII] flux.

Indeed, the SWS spectra show that the [SiII] 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 [SiII] radiation and it is illuminated mostly on its rear side, one would rather expect a flux $\approx$ one third of that detected in the Central beam, i.e. $\sim 3 \times 10^{-19}\mathrm{W\,cm^{-2}}$. This is much less than the flux detected. This reinforces our previous conclusion about the origin of the [SiII] line.

Assuming the flux variation between the Central and Northern position is due to the variation of PDR filling factor in the SWS beam, one can derive an estimate of the relative contribution of the PDR and the HII region. The emitted flux is then 2.2×10^{-19} and $7.4 \times 10^{-19}\mathrm{W\,cm^{-2}}$ for the PDR and the HII respectively; the emission of the PDR is somewhat dominated by the contribution of the HII in the SWS beam. The model of Wolfire, Tielens & Hollenbach (1990) is then consistent with a gas phase abundance of 6×10^{-6}, i.e. 17% the solar abundance. This value is much more compatible with the determinations obtained in other HII regions. Nevetherless, we stress again that new observations with a better SNR are required to determine more precisely the silicon abundance in the PDR and the HII region.

6. The Dust Continuum Emission

6.1. Warm Dust in the PDR : zone III

In this paragraph, we analyse the continuum emission detected with the SWS in the range $2-45\mu$m. The full spectra obtained at the three positions are shown in Fig. 11. The continuum emission becomes significant longwards of $30\,\mu$m in all the positions. We have fit the continuum using a black-body modified by a power law $\tau_\nu \propto \nu^\beta$. 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 $\mathrm{N(H)} = 1.7 \times 10^{21}\,\mathrm{cm^{-2}}$. Adopting the standard reddening law yields $\mathrm{N(H)} = 2.9 \times 10^{21}\,\mathrm{cm^{-2}}$. 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 43-48K, and hydrogen column densities of $(1-4) \times 10^{21}\,\mathrm{cm^{-2}}$.

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 fit with similar parameters and assuming a smaller column density of warm dust (N(H) $\simeq 0.9 \times 10^{21}$ cm^{-2}) at about the same temperature. The fits are shown superposed on the spectra in Fig. 11. They succeed rather well in reproducing the continuum flux longwards of 30μm.

It is therefore possible to explain the observed continuum emission by a warm dust layer at about 46 K and a column density $\simeq 2-3\times 10^{21}$ cm^{-2}. As we show below, such parameters also allow 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 30μm. The continuum emission shortwards of 30μm is almost identical at the Northern and central positions. It is somewhat weaker in the South.

The continuum emission is maximum between 15 and 30μm. Our CVF map of the continuum emission in the range $13-15\mu$m brings some more information on the distribution and the nature of this hot dust component. The continuum emission at 15μm revealed from our spectral decomposition is shown in Fig. 7. The map shows a good spatial correlation with the 7.7μm band and the photoionized envelope. The continuum is brightest in the PDR. It is shifted outwards 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 like what was observed in other PDRs (Abergel et al. 2002) and in cirrus clouds (Miville-Deschênes 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 [NeII] 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 30m 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 $\approx 12'' \times 32''$ (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 $\kappa_{250} = 0.1\,cm^2\,g^{-1}$, 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 $n(H_2) = 3 \times 10^5\,cm^{-3}$ for the core.

6.4. The Spectral Energy Distribution

The spectral energy distribution of the globule between 45 and 197μm was obtained by subtracting the emission of the reference position to the LWS spectrum taken towards TC2. The size of the emitting region encompassed by the LWS beam is $\approx 45''$, based on the ISOCAM 12μm image and the cold dust millimeter emission (Fig. 3). We measured the 1.3mm continuum filling the LWS beam solid angle in order to constrain the fit to the cold dust component. It was found to be $\simeq 0.83$ Jy. The spectral energy distribution is shown in Fig. 12. The emission could be satisfactorily fit 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 [CII] 158μm and the [OI] lines. The warm layer detected with the LWS also accounts for the mid-infrared continuum emission detected with the SWS longwards of 30μm. 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 : $I_{IR} = 0.21\,erg\,s^{-1}\,cm^{-2}\,sr^{-1}$. The temperature and the infrared luminosity of the warm layer are those expected for a PDR exposed to a FUV field $G_0 = 1000$. This is consistent with the intensity of the far-infrared [OI] and [CII] lines as observed with LWS (see above Sect. 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 far-infrared line ratios (Sect. 5.3), we estimate the thickness of the PDR $\simeq 1.0 \times 10^{17}$ 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 UV radiation field. Hence, it seems a good reasonable approximation to adopt 22 K as temperature of the dust core traced by the 1.3mm continuum emission in order to the 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 ($\sim 80''$). 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 = 0.68 Jy. Adopting a uniform dust temperature $T_d = 22\,K$, we obtain the average gas column density over the globule : $2.3 \times 10^{22}\,cm^{-2}$, 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 ($\sim 5\%$) which lies in the atomic surface layers, exposed to the strong FUV field of the stars exciting the Trifid. The ratio of the atomic and 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 place 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 Sect. 8.2.

7. The Molecular Condensation : zone IV

7.1. The 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 $\mathrm{km\,s^{-1}}$ that correspond to various physical regions in the molecular cloud containing the HII region (Lefloch et al. 2002). 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 C^{18}O. The spatial distribution of the kinetic components shows that the emission of TC2 peaks at $v_{lsr} = 7.7\,\mathrm{km\,s^{-1}}$ (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 ~ 30 K for the $J = 2 \rightarrow 1$ and $J = 1 \rightarrow 0$ transitions and 15 K for $J = 3 \rightarrow 2$ one.

We have tried to constrain the temperature and density distribution in the globule by modelling 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 Radiatively-Driven Implosion, is small, of the order of $1\,\mathrm{km\,s^{-1}}$ (see Sect. 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 all the globule, with typical brightness (antenna) temperatures of 13 K and 12.5 K for the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions respectively (Fig. 13). The C^{18}O $J = 1 \rightarrow 0$ has a main-beam brightness temperature of 2.3 K. From the ratio of the ^{13}CO/C^{18}O $J = 1 \rightarrow 0$ brightness temperatures (= 5.7) and assuming a standard relative abundance of 8, we derive the ^{13}CO line opacity $\tau^{10} \simeq 0.7$. 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 $\tau^{13} = 0.7$ 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) $\simeq 4 \times 10^{16}\,cm^{-2}$. Adopting a standard abundance [^{13}CO]/[H_2] $= 1.6 \times 10^{-6}$, we infer the total gas column density N(H_2) $= 2.5 \times 10^{22}\,cm^{-2}$ 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. The dense core

All the molecular lines observed towards the center of the globule peak at $v_{lsr} = 7.7\,km\,s^{-1}$ 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 $\sim$ 4 K (4.3 K and 4.0 K for the $J = 2 \rightarrow 1$ and the $J = 3 \rightarrow 2$ lines respectively) at the position ($72''$, $-135''$). The CS $J = 2 \rightarrow 1$ transition traces a region approximately circular with a typical size of 5×10^{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 which 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 (Fig. 14) : the central CS core. The core is slightly elongated in the North-South direction. Its dimensions (beam-deconvolved) are 5.2×10^{17} cm by 6.7×10^{17} cm, very similar to the size of the the CS $J = 2 \rightarrow 1$ emitting region. Hence both lines are probing the same region. As can be seen in Fig. 15, there is no evidence of a velocity shift in the CS $J = 2 \rightarrow 1$ emission peak along the major axis. The same results holds for the the $J = 3 \rightarrow 2$ transition and the HCO^+ line. This indicates that the molecular gas of the globule, in particular the dense core, is in a quiescent stage.

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 : $\Delta v = 1.3\,\mathrm{km\,s^{-1}}$. In the central position we find a density $n(\mathrm{H_2}) = 2.0 \times 10^5\,\mathrm{cm^{-3}}$ and a column density $\mathrm{N(CS)} = 1.8 \times 10^{13}\,\mathrm{cm^{-2}}$. The line opacities are relatively low, with $\tau^{21} = 0.42$ and $\tau^{32} = 0.70$. Similar densities are obtained around the center ($\sim 2 \times 10^5\,\mathrm{cm^{-3}}$) and at the brightness peak, 15″ South of the center. At this position, we find $\mathrm{N(CS)} = 3.0 \times 10^{13}\,\mathrm{cm^{-2}}$. Hence, from the H_2 core density and the beam size, we find a core mass $\sim 28\,M_\odot$, in good agreement with the dust estimate. Adopting a typical abundance $[\mathrm{CS}]/[\mathrm{H_2}] = 5 \times 10^{-10}$, we estimate the size of the CS emitting region $\ell = 3.0 \times 10^{17}$ cm. This value is consistent with the the size HPFW derived from the maps of velocity-integrated emission at 3 and 2mm.

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 $\mathrm{n(H_2)} = 2 - 3 \times 10^5\,\mathrm{cm^{-3}}$ surrounded by an envelope slightly warmer in the outer layers, at a temperature $\mathrm{T} \sim 30\,\mathrm{K}$, and density of about $3 \times 10^4\,\mathrm{cm^{-3}}$.

8. Radiatively-Driven Implosion of TC2

We have recalled briefly in the Introduction 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 :
a) $\gamma = \eta\alpha n_e R_g / c_i$: 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 Ly-c photons are consumed in the ionized gas layer surrounding the neutral condensation (see also Sect. 4.1).
b) $\delta = n_e / n(H)$: 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 ($n(\mathrm{H_2}) = 10^4\,\mathrm{cm^{-3}}$) and the molecular gas traced by ^{13}CO ($n(\mathrm{H_2}) = 3 \times 10^4\,\mathrm{cm^{-3}}$). Hence, we estimate that δ lies in the range $0.03 - 0.09$. The values of δ and γ 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 a D-critical I-front preceded by a shock front. In their study, LL94 showed that the morphology, the 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 δ and γ.

A direct estimate of the total (ram + thermal) external pressure at the surface of the cloud yields : $P_i/k_B = 2.11 \times 2n_eT_e = 4.2 \times 10^7\,\mathrm{K\,cm^{-3}}$. We can estimate the inner pressure from the kinematic motions as measured by the the linewidth of the ^{13}CO and CS transitions : $\Delta v = 1.4\,\mathrm{km\,s^{-1}}$. We find a kinetic pressure $P_k/k_B = 2.3 \times 10^6\,\mathrm{K\,cm^{-3}}$. 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 (Sect. 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 $7.7\,\mathrm{km\,s^{-1}}$, we detect a second component at "blue" velocities shifted by $0.7\,\mathrm{km\,s^{-1}}$.

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 towards the ionized gas in the HII region. The low SNR of the spectrum prevents from leading any quantitative analysis.

This component is not related with prostostellar activity. First, the blueshifted component is detected *only* at the border of the globule. There is no evidence of a blueshifted component towards the dust emission peak $15''$ South (more than 2×10^4 AU away from the border of the globule) where the protostar is expected to be found (see Sect. 8.2). Second, the blueshifted component is kinematically separated from the main body gas emission and it does not exhibit the typical "wing" profile of molecular outflows. Third, there is no evidence for an additional, redshifted, component which 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 kinematical signature of the PDR.* It is completely unresolved by the 30m telescope. However, since the far-infrared 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 modelling of a photoionized globule presented in LL94. The simulation was done for ionization parameters similar to TC2 : $\Delta = 0.1$ and $\Gamma = 10$ (Δ and Γ are the initial values of the parameters δ and γ). 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 (Figure 4 in LL94), we find the best match for an age comprised between 0.13 Myr 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 $\tau \simeq 0.15$ Myr. The numerical modelling indicates that the amplitude of the secondary kinematic component at such early photoionization stages is typically $1-2\,\mathrm{km\,s^{-1}}$ (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 $0.7\,\mathrm{km\,s^{-1}}$ 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 : $k \simeq 2$. The radius of the *scaled* (simulated) globule is then $\sim 6\times10^{17}$ cm whereas we measured 4.0×10^{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. The HH 399 jet

The first evidences of ongoing star formation in TC2 were presented by CL98, based on a [SII] image of the HH399 jet running out of the bright rim of TC2. The jet has been studied in the optical by Rosado et al. (1999) and CL98. 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 μJy beam^{-1}). We take $0.85''$ ($\approx 2 \times 10^{16}$ 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 $1.0 - 1.5 \times 10^3$ 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 3×10^3 cm^{-3} and 8×10^3 cm^{-3} respectively. This could be due to clumpiness in the jet structure. This can be also explained by our assumption on the geometry of the jet, apart from the uncertainties in the 3.6cm flux (the noise is $\sim 15 - 20$ μJy beam^{-1}). For instance, assuming a jet diameter ten times less would yield an electron density of 3×10^3 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 μJy beam^{-1}, we obtain a total flux $S_j =$ 0.36 mJy for the jet, and an average emissivity EM $= 8.8 \times 10^3$ pc cm^{-6}. The recombination rate per surface unit of the jet is 7.3×10^9 cm^{-2} s^{-1}. This is only half the ionizing flux impinging on the globule, as estimated in Sect. 3.1. Hence, there are enough Ly-c photons to maintain the jet fully ionized once it propagates out of the globule. HH399 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 which would be the counterpart to the optical jet but did not find any evidence of such a phenomenon. This is probably because of the unfavourable orientation of the jet, very close to the plane of the sky (Rosado et al. 1999 estimate an inclination lower than 4 deg). 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 10^5 yr. If this age is correct, it means that star formation began approximatly at the time when the ionizing star HD 164492A turned on and ignited the nebula.

9.2. The 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} respectively at a level of 3σ and 4.5σ 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 broad band filters, there is no evidence of point-source emission in the globule. This indicates that the powering source of HH399 is a much less luminous and massive object than the protostar detected in Southwestern molecular cloud (Lefloch & Cernicharo 2000). A close inspection of the continuum emission between 13 and 15μm in the globule however reveals a local maximum of compact, unresolved, emission at $\Delta\alpha = +70''$, $\Delta\delta = -124''$. This source is spatially separated from the PDR, though close to it ($\approx 7''$). 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 HH399 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 : $L_{max} = 1200\,L_\odot$. This value is typical of intermediate-mass protostars but we stress again that the actual luminosity could be lower.

9.3. The 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, which is affected by the FUV field, and not the dense core where the material is being accreted. An important paramater 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) :

$$\dot{M} = 14 \left(\frac{\Phi_i}{10^7\,\mathrm{cm^{-2}\,s^{-1}}} \right)^{1/2} \left(\frac{R_g}{1\,\mathrm{pc}} \right)^{3/2} M_\odot\,\mathrm{Myr^{-1}} \qquad (2)$$

For TC2, we estimate a present mass-loss rate of $34\,M_\odot\,\mathrm{Myr}^{-1}$. 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 $\tau_g = M/\dot{M} \simeq 1.9\,\mathrm{Myr}$. 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 10^5 yr (André et al. 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 10^5 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 HII region ($n_e \sim 50 - 100\,\mathrm{cm}^{-3}$). 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, $n(H_2) = 3 \times 10^5\,\mathrm{cm}^{-3}$), of small dimensions surrounded by a lower-density envelope ($n(H_2) = 3 \times 10^4\,\mathrm{cm}^{-3}$). Its mass ($\simeq 63\,M_\odot$) 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 $1.4\times10^{10}\,\mathrm{cm^{-2}\,s^{-1}}$; it creates an ionization front and a photoevaporated envelope of density $1-2\times10^{3}\,\mathrm{cm^{-3}}$ at the surface of the globule.

The PDR is traced by the emission of the PAHs bands at 6.2, 7.7, 8.6 and 11.3μm. 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 11.3μm band drops outside of the PDR in the photoionized layers, as a consequence of the ionization of the PAHs. The 7.7μm band is still detected in the photoionized envelope of the globule, though at a weaker level. Despite the high visual extinction of the globule, the 7.7μm 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 which precedes the ionization front as a shock moving into the globule. The relative projected velocity is weak, $\approx 0.7\,\mathrm{km\,s^{-1}}$. Comparison with models of photoionized globules (LL94) indicates that TC2 has been exposed to the ionizing radiation for 3×10^{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 far-infrared 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 $G_0 \simeq 1000$. The PDR has a typical column density of $2\times10^{21}\,\mathrm{cm^{-2}}$ and a molecular hydrogen density $\simeq 10^{4}\,\mathrm{cm^{-3}}$. The FUV field heats the dust to a temperature $\simeq 46$ K whereas the average gas temperature is found close to 300 K. The emission of the [SiII] 34.8μm line in the PDR can be accounted for by assuming a silicon gas phase abundance of 6×10^{-6}, i.e. $\simeq$ 17% 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 $\leq 500\,L_\odot$. 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 10^{5} yr, which suggests that star formation in TC2 probably started in the large burst which 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. LFR is grateful to CONACyT, Mexico, for its support. This research made use of SIMBAD.

REFERENCES

Abergel, A., Bernard, J.P., Boulanger, F., et al. , 2002, A&A, in press

Allamandola, L.J., Hudgins, D.M., Sandford, S.A., 1999, ApJ, 511, L115

André, P., Ward-Thompson, D., Barsony, M., 2000, in Protostar & Planets IV,

Bachiller, R., 1996, Ann. Rev. Astrom. Astrophys., 34, 111

Bakes, E.L.O., Tielens, A.G.G.M., 1994, ApJ, 427, 822

Bakes, E.L.O., Tielens, A.G.G.M., 1998, ApJ, 499, 258

Bertoldi, F., 1989, ApJ, 346, 735

Bertoldi, F., McKee, C.F., 1990, ApJ, 354, 529

Boulanger, F., Boissel, P., Cesarsky, D., Ryter, C., 1998, A&A, 339, 194

Cernicharo, J., Bachiller, R., Duvert, G., Gonzalez-Alfonso, E., Gómez-Gonzalez, J., 1992, A&A, 261, 589

Cernicharo, J., Lefloch, B., García-Lopez, R.J., & Esteban, C., 1997, in "Low Mass Star Formation from Infall to Outflow", pg 8, IAU182, ed. F. Malbet & A. Castets.

Cernicharo, J., Lefloch, B., Cox, P., Cesarsky, D., Esteban, C., Yusef-Zadeh, F., Méndez, D.I., Acosta-Pulido, J., García-Lopez, R.J., Heras, A., 1998, Science, 282, 462 (CL98)

Cernicharo, J., Noriega-Crespo, A., Cesarsky, D., Lefloch, B., Gonzalez-Alfonso, E., Najarro, F., Dartois, E., Cabrit, S., 2000, Science, 288, 649

Cesarsky, C.J., Abergel, A., Agnese, P., 1996, A&A, 315, L32

Chaisson, E.J., Willson, R.F., 1975, ApJ, 199, 647

Clegg, P.E., Ade, P.A.R., Armand, C., et al., 1996, A&A, 315, L38

Crete, E., Giard, M., Joblin, M., Vauglin, I., Leger, A., Rouan, D., 1999, A&A, 352, 277 de Graauw, T., Haser, L.N., Beintema, D.A., et al., 1996, A&A, 315, L49

Dartois, E., d'Hendecourt, L., 1997, A&A, 323, 534

Dinerstein, H.L., Lester, D.F., Werner, M.W., 1985, ApJ, 291, 561

Elmegreen, B.G., Lada, C.J., 1977, ApJ, 214, 725

Gry, C., Swinyard, B., Harwood, A., et al., 2001, in "LWS - The Long-Wavelength Spectrometer", ISO Handbook Volume IV (LWS), SAI/99-077/Dc, Eds. T.G. Müller & J. Blommaert

Habing, H.J., 1968, Bull. Astr. Inst. Netherlands, 19, 421

Heiles, C., 1994, ApJ, 436, 720

Hildebrand, R.H., 1983, QJRAS, 24, 267

Hollenbach, D.J., Takahashi, T., Tielens, A.G.G.M., 1991, ApJ, 377, 192

Joblin, C., Tielens, A.G.G.M., Geballe, T.R., Wooden, D.H., 1996, ApJ, 460, L119

Kaufman, M.K., Wolfire, M.G., Hollenbach, D.J., Luhmna, M.L., 1999, ApJ, 527, 795 (K99)

Kessler, M.F., Steinz, J.A., Anderegg, M.E., 1996, A&A, 315, L27

Leech, K., de Graauw, T., van den Ancker, M., et al., 2001, in " SWS - The Short-Wavelength Spectrometer", ISO Handbook Volume VI (SWS), SAI/2000-008/Dc, Eds, K. Leech, T.G. Müller & J. Blommaert

Lefloch, B., Lazareff, B., 1994, A&A, 289, 559 (LL94)

Lefloch, B., Lazareff, B., 1995, A&A, 301, 522

Lefloch, B., Lazareff, B., Castets, A., 1997, A&A, 324, 249

Lefloch, B., Castets, A., Cernicharo, J., Loinard, L., 1998, ApJ, 1998, 504, L109

Lefloch, B., Cernicharo, J., 2000, ApJ, 545, 340

Lefloch, B., Cernicharo, J., Cesarsky, D., Demyk, K., Miville-Deschênes, M.A., and Rodriguez, L.F., 2001, A&A, 368, L13

Lefloch, B., Pardo, J.R., Cernicharo, J., 2002, in prep.

Lester, D.F., Dinerstein, H.L., Werner, M.W., Watson, D.M., Genzel, R.L., 1983, ApJ, 271, 618

Lester, D.F., Dinerstein, H.L., Werner, M.W., Watson, D.M., Genzel, R., and Storey, J.W.V., 1987, ApJ, 320, 573

Lynds, B., Canzian, B.J., and O'Neil, E.J. Jr., 1985, ApJ, 288, 164

Mathis, J.S., 1990, ARA&A, 28, 37

Mauersberger, R., Guélin, M., Martin-Pintado, J., Thum C., Cernicharo, J., Hein, H., Navarro, S., 1989, A&ASupp. Series, 79, 217

Miville-Deschênes, M.A, Boulanger, F., Abergel, A., Bernard, J.P. , 2000, A&AS, 146, 519

Miville-Deschênes, M.A, Boulanger, F., Joncas, G., Falgarone, E., 2002, A&A, 381, 209

Panagia, N., 1973, AJ, 78, 929

Puget, J.L., Léger, A., 1989, Ann.Rev. A&A, 27, 161

Reipurth, B., 1983, A&A, 117, 183

Reipurth, B., Bally, B., Fesen, R.A., Devine, D., 1998, Nature, 396, 343

Rho, J., Corcoran, M.F., Chu, Y.H., Reach, W.T., 2001, ApJ, 562, 446

Rosado, M., Esteban. C., Lefloch, B., Cernicharo, J., García-López, R.J., 1999, AJ, 118, 2962

Rubin, R.H., 1985, ApJSupp. 57, 349

Rubin, R.H., 1989, ApJSupp. 69, 897

Rubin, R.H., Simpson, J.P., Haas, M., Erickson, E.F.,1991, ApJ, 374, 564

Rubin, R.H., Simpson, J.P., Lord, S.D., Colgan, S.W.J., Erickson, E.F., Haas, M.R., 1994, ApJ, 420, 772

Salama, A., 2000, in "ISO Beyond Point Sources : Studies of Extended Infrared Emission", Madrid, Spain, ESASP-455

Simpson, J.P., Colgan, S.W.J., Rubin, R.H., Erickson, E.F., Haas, M.R., 1995, ApJ, 444, 721

Spitzer, L., 1978, *Physical Processes in the Interstellar Medium*, (New-York : Wiley), 107

Sugitani, K., Fukui, Y., Ogura, K., 1991, ApJSupp, 77, 59

Tielens, A.G.G.M., Hollenbach, D., 1985, ApJ, 291, 722

Vastel, C., Spaans, M., Ceccarelli, C., Tielens, A.G.G.M., Caux, E., 2001, A&A, 376, 1064

Verstraete, L., Puget, J.L., Falgarone, E., Drapatz, S., Wright, C.M., Timmermann, R., 1996, A&A, 315, 337

Walborn, N.R., 1973, AJ, 78, 1067

Walmsley,C.M., Pineau des Forêts, G., Flower, D.R., 1999, A&A, 342, 542

White, G.J., Nelson, R.P., Holland, W.S., et al., 1999, A&A, 342, 233

Whitworth, A.P., Bhattal, A.S., Chapman, S.J., 1994, MNRAS, 268, 291

Wolfire, M.G., Hollenbach, D., Tielens, A.G.G.M., 1989, ApJ, 344, 770

Wolfire, M.G., Tielens, A.G.G.M., Hollenbach, D., 1990, ApJ, 358, 116

Fig. 1 – Schematic drawing of the TC2 region : (I) the HII region between the exciting star (HD 164492A) and the bright-rimmed globule; (II) the ionization front (IF) and the expanding envelope of photoionized gas around the globule; (III) the Photon-Dominated Region (PDR) and the shock ahead of the IF; (IV) the molecular core of TC2.

Fig. 2 – [Hα] image of the Trifid Nebula observed with the NOT telescope (CL98). 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.

Fig. 3 – Thermal dust emission of TC2 observed at 1.25mm with the MPIfR 19 channel bolometer array (thin white contours) superposed on the optical [SII] emission of the region. Contours range from 10% to 90% of the peak flux (160 mJy/11$''$ beam). In thick white contours, we have superposed the mid-IR emission, as observed with the ISOCAM LW10 filter ($8 - 15\mu$m). First contour and interval are 160 and 20 MJy/sr respectively. In thin black contours is superposed the 3.6cm free-free emission observed at the VLA. Contours are 0.4, 0.8, 1.1, 1.5, 1.9 mJy/beam.

Fig. 4 – Magnified View of TC2 as observed in the [SII] lines $6717, 6731\AA$. The white circle marks the TC2 region encompassed with the LWS beam. The rectangles mark the regions observed with ISO/SWS, and delineate the aperture of the detector (band 4). The center of the SWS fields are marked by stars.

Fig. 5 – (a) Contour map of the free-free emission at 20 cm obtained with the VLA (CL98), superposed on the optical [SII] image of the globule. First contour and contour interval are 1.5×10^{-2} and 2.5×10^{-3} Jy/beam respectively.
b) Contour map of the free-free emission at 3.6 cm obtained with the VLA, superposed on an [SII] image of the head of bright-rimmed globule TC2 (greyscale). The first contour and contour interval are 4×10^{-5} and 2×10^{-5} Jy/beam respectively.

Fig. 6 – Fine structure atomic and ionic lines detected at the three positions observed with ISO/SWS and at the two positions observed with ISO/LWS.

Fig. 7 – Mid-infrared emission as detected with the CVF in the PAH bands at 6.2, 7.7, 8.6 and 11.3μm (greyscale and contours), in the [NeII] 12.7 μm (with the PAH 12.7μm band) and the [NeIII] 15.5 μm line and in the continuum between 13 and 15μm (greyscale). We have superposed (contours) the PAH 11.3μm band emission on the panels of the 12.7 μm, [NeIII], and $13 - 15\mu m$ emissions. The location of the spectra shown in Fig. 9 is marked with white squares.

Fig. 8 – CVF Emission in the range $5 - 16\mu$m at a few positions towards TC2. The locations are marked in the lower right panel of Fig. 2d. *(a)* and *(b)* : photoionized region (positions A and B respectively). *(c)* and *(d)* : photon-dominated region (at C and D resp.); *(e)* : reference position (position E); *(f)* : core of TC2 (position F). In panels *a)-d)*, we have superposed (thin contour) the

spectrum of the reference position scaled to match the intensity of the 7.7μm band.

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). The flux scale of the spectra in the core of TC2 and in the absorbed PDR has been divided by 2.0

Fig. 10 – Large-Velocity Gradient analysis of the [OI] lines observed with the LWS. Isoflux contours in the temperature-density diagram for the [OI] 63μm (solid) and 145μm (dashed). for three oxygen column densities. For each line, we have also indicated the upper and lower limits at 20%.

Fig. 11 – Mid-Infrared emission observed between 2 and 45μm with the Short Wavelength Spectrometer onboard ISO, towards 3 positions centered respectively on the PDR of TC2 at the offset position $\Delta\alpha = +71''\quad\Delta\delta = -120''$ (central panel), the main body of the globule (lower panel) and the bright rim and the HII region (upper panel) The thin line draws the fit to the SED.

Fig. 12 – Spectral Energy Distribution of TC2 after subtracting the extended emission of the nebula. We have indicated (square) the 1250 μm flux (integrated over the ISO/LWS beam). We show in dashed the fits to the warm and cold dust component. The fit to the whole emission is indicated by the solid line.

Fig. 13 – Montage of the molecular lines detected in the core of TC2. The line fluxes are given in the antenna temperature scale. The dashed line indicates the systemic velocity of the dense core $\mathrm{v_{lsr}} = 7.7\,\mathrm{km\,s^{-1}}$.

Fig. 14 – Contour maps of the velocity-integrated emission $\mathrm{HCO^+}J = 1 \rightarrow 0$, CS $J = 2 \rightarrow 1$, $^{12}\mathrm{CO}J = 1 \rightarrow 0$, $^{12}\mathrm{CO}J = 2 \rightarrow 1$, CS $J = 3 \rightarrow 2$ and $^{12}\mathrm{CO}J = 2 \rightarrow 1$. The emission was integrated between 5 and $10\,\mathrm{km\,s^{-1}}$. Contours range 0.1, 0.2... to 0.9 times the emission peak. The contours are superposed on a 1.3mm continuum emission map of the globule.

Fig. 15 – Molecular gas emission in the CS $J = 2 \rightarrow 1$ and $\mathrm{HCO^+}J = 1 \rightarrow 0$ lines in a cut across the Photon-Dominated Region in North-South direction. The dashed lines indicate the systemic velocity of the main body gas in TC2 ($\mathrm{v_{lsr}} = 7.7\,\mathrm{km\,s^{-1}}$) and of the second kinematic component detected in the PDR ($\mathrm{v_{lsr}} = 7.0\,\mathrm{km\,s^{-1}}$).

Fig. 16 – VLA emission at 3.6cm (contours) superposed on the continuum emission between 13 and 15μm as observed with the CVF.

Table 1: List of Observations.

Zone	Instrument	Observations	Wavelength	Figures
I (HII region),	VLA	Free-free radiation	3.6 cm, 20 cm	5a, 5b, 16
II (Bright Rim)	NOT	Hα, [SII]	Optical	2, 4
	SWS, CVF, LWS	Atomic Lines : [NeII], [NeIII], [SIII], [NIII], [OIII], [SiII], [CII]	$2.5 - 197\mu$m	6,7
	SWS	Continuum (dust)	$2.5 - 45\mu$m	11
III (PDR)	ISOCAM	LW10	$8 - 15\mu$m	3
	CVF	PAH bands	$5 - 17\mu$m	7,8
	SWS, LWS	Continuum (dust)	$2.5 - 197\mu$m	11, 12
	SWS, LWS	Atomic Lines : [OI], [CII], [SiII]	$2.5 - 197\mu$m	6,7
IV (Molecular Core)	LWS	Continuum (dust)	$45 - 197\mu$m	12
	IRAM-30m	Continuum (dust)	1.25mm	3
		CO, ^{13}CO, C^{18}O, HCO^{+}, SiO, CS	1-3mm	13, 14, 15
	CSO	CO	0.8mm	13

Table 2: Millimeter lines observed towards TC2 : frequency, telescope beamwidth and efficiency.

	Line	Frequency GHz	Beamwidth $''$	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

Table 3: Fine structure lines detected with the SWS. The fluxes are uncorrected for the mid-IR extinction.

Line	Band	λ (μm)	Aperture ($'' \times ''$)	$F_\nu^{(0,+0)}$ W cm^{-2}	$F_\nu^{(0,+20)}$ W cm^{-2}	$F_\nu^{(0,-20)}$ W cm^{-2}
[NeII]	3A	12.8	14×27	$(7.5 \pm 0.7)(-19)$	$(9.0 \pm 0.9)(-19)$	$(8.4 \pm 0.8)(-18)$
[NeIII](^{a})	3A	15.5	14×27	$(6.9 \pm 0.7)(-19)$	$(9.0 \pm 0.9)(-19)$	-
[SIII]	3C	18.7	14×27	$(1.3 \pm 0.1)(-18)$	$(1.3 \pm 0.1)(-18)$	$(9.0 \pm 0.9)(-19)$
[SIII]	4	33.5	20×33	$(4.2 \pm 1.2)(-18)$	$(3.9 \pm 1.0)(-18)$	$(3.6 \pm 1.0)(-18)$
[SiII]	4	34.8	20×33	$(9.6 \pm 2.9)(-19)$	$(9.6 \pm 2.9)(-19)$	$(8.3 \pm 2.5)(-19)$

(^{a}) Unreliable due to large statistical errors.

Table 4: Fine structure atomic lines detected with the LWS.

Line	Band	Beam Size ($''$)	λ (μm)	F_ν^{On} W cm^{-2}	F_ν^{Off} W cm^{-2}	TC2 ("On" - "Off") W cm^{-2}
[OIII]	SW2	84	51.7	$(7.1 \pm 1.4)(-18)$	$(2.5 \pm 0.5)(-18)$	4.6 (-18)
[NIII]	SW2	84	57.2	$(4.9 \pm 1.0)(-18)$	$(2.2 \pm 0.4)(-18)$	2.7 (-18)
[OI]	SW3	86	63.3	$(9.8 \pm 2.0)(-18)$	$(2.6 \pm 0.5)(-18)$	7.2 (-18)
[OIII]	SW5	80	88.4	$(9.0 \pm 1.8)(-18)$	$(4.0 \pm 0.8)(-18)$	5.0 (-18)
[NII]	LW2	68	122.0	$(1.4 \pm 0.3)(-18)$	$(7.7 \pm 1.5)(-19)$	6.3 (-19)
[OI]	LW3	70	145.5	$(5.8 \pm 1.2)(-19)$	$(1.5 \pm 0.3)(-19)^*$	4.3 (-19)
[CII]	LW4	68	157.8	$(9.8 \pm 2.0)(-18)$	$(7.1 \pm 1.5)(-18)$	2.5 (-18)

Table 5: Physical Properties of TC2.

FUV Radiation Field (G_0)	1000
Infrared Luminosity	$1200\,L_\odot$
Total Mass ([a])	$63\,M_\odot$
Mean Radius R_g	4×10^{17} cm
Mean H_2 Column Density	$2.3 \times 10^{22}\,\mathrm{cm}^{-2}$
Core	
Dimensions (10^{17} cm)	3×8
Dust Temperature	22 K
Maximum H_2 Column density ([a])	$8.0 \times 10^{22}\,\mathrm{cm}^{-2}$
Mean H_2 Column density ([a])	$5.1 \times 10^{22}\,\mathrm{cm}^{-2}$
Mass	$27\,M_\odot$
H_2 Density	$3 \times 10^{5}\,\mathrm{cm}^{-3}$
Central source luminosity	$\leq 500\,L_\odot$
Molecular Envelope	
H_2 Density (^{13}CO)	$3.0 \times 10^{4}\,\mathrm{cm}^{-3}$
Gas Temperature	30 K
Photon-Dominated Region	
Thickness	1×10^{17} cm
Dust Temperature	46 K
Atomic Gas Temperature (OI)	300 K
Gas Column Density ([a])	$2.0 \times 10^{21}\,\mathrm{cm}^{-2}$
Oxygen Column Density	$7 \times 10^{17}\,\mathrm{cm}^{-2}$
Oxygen Abundance	3.0×10^{-4}
Carbon Column Density	$3 \times 10^{17}\,\mathrm{cm}^{-2}$
Carbon Abundance	1.4×10^{-4}
Density (H_2)	$1.0 - 6.0 \times 10^{4}\,\mathrm{cm}^{-3}$
Atomic Gas Mass (CII)	$3 - 4\,M_\odot$
Velocity field	Radiatively-Driven Implosion
Photoionized Envelope (Bright Rim)	
Thickness	$\sim 5 \times 10^{16}$ cm
Electron Density	$1.0 - 2.0 \times 10^{3}\,\mathrm{cm}^{-3}$

[a]from dust observations.

This figure "figure1.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208119v1

This figure "figure6.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208119v1

This figure "figure8.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208119v1

This figure "figure9.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208119v1

This figure "figure10.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208119v1

This figure "figure15.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208119v1