Induced Star Formation around Young HII regions : a detailed study of the Trifid nebula

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There is large observational evidence that triggered modes of star formation may be important at the Galactic scale. Large-scale surveys suggest that HII regions are efficient in spreading star formation and producing high-/intermediate-mass objects but the details of the mechanisms are not well constrained, so that the role of HII regions in triggering SF is still questioned. We present here an observational study of the Trifid nebula, a young HII region, and its protostellar population. in relation with the parental cloud. Several massive protostellar cores (60 to 200 $M_{\odot}$) are detected, which harbour intermediate-mass objects. We find direct evidence that several of the cores are experiencing shock conditions which probably caused their gravitational collapse.

Keywords: ISM : HII regions, clouds; stars; Stars : formation

1 HII regions in the Galaxy

There is large observational evidence that HII regions play an important role in spreading Star Formation throughout the Galaxy. In the solar neighborhood, most of the embedded young stellar clusters are adjacent to HII regions excited by older stars and/or clusters. This is the case of Orion and other well-known regions such as the Rosette nebula, the W3/W4/W5 complex or M17.

Several systematic studies based on IRAS data [14,3] have shown that the dense condensations at the border of HII regions are common sites of Star Formation. The ysos identified in these clouds are, on average, one order of magnitude more massive than their counterparts in dark clouds. These studies were biased towards luminous sources; moreover, the poor angular resolution a priori excluded the youngest HII regions, whose nebular emission may dominate the ysos emission. Because of these instrumental limitations, the low-mass objects remained out of reach until the advent of SPITZER. Another consequence is that most of the studies were restricted to evolved regions, which have already reached sizes of tens of parcsecs. Under such conditions, the cometary globules are exposed to reduced ionizing and UV radiation fields, so that the radiation impact on the dynamics is then limited. In parallel to these large surveys, only very few detail studies of Cometary Globules have been carried out until now [2,11], so that the cloud physical properties are not well characterized. On the theoretical side, numerical modelling has allowed to get a clear view of the evolution of these structures exposed to the strong ionizing radiation of the nebula, in good agreement with the observations[9,10].

The possibility of triggering star formation in the environment of HII regions has long attracted the attention of theoreticians[4,16]. Several models have been proposed and revisited since (see Whitworth and Deharveng for a review). However, it is still not clear today if triggering is important in all star forming regions (SFRs) and which triggering mode is efficient. It is therefore not surprising that the properties of the protostellar population that forms in the vicinity of an HII region, its relation to the parental cloud, are not well understood.

It is in this context that we decided to start a systematic study of a young HII region, close enough to allow a complete census of the young stellar and protostellar population: the Trifid nebula (M20). The emission of the nebula and its environment were systematically observed from centimeter to optical wavelengths. The free-free radiation of the nebular gas and in the ionization fronts was observed with the VLA. The cold dust and gas emission was observed at IRAM, SEST and CSO. The emission of the Photon-Dominated Regions was observed with the instruments onboard ISO. Such a large database is necessary to disentangle the various processes at work in and around the HII region.

2 The Trifid at large-scale

The Trifid nebula (Fig. 1) is located in the Sagittarius arm of the Galaxy at a distance of 1.7 kpc, close to the young supernova remnant W28SNR and other massive SFRs. The nebula is rather compact, with a diameter of 3.5 pc, which allows a comprehensive study of the HII region and the parental molecular cloud. Subsequently, the measured electron density in the nebular gas is high ($100 - 200\,\mathrm{cm}^{-3}$). The spectral type is still somewhat debated, O7.5 III or O7 V, but the Lyman-c photon rate is well characterized : $\dot{N}_L = 10^{49}\,\mathrm{s}^{-1}$. The exciting star of the nebula (HD 164492A) is accompanied by a cluster of five objects (components B to F), some of which are still surrounded by their protostellar disks, undergoing heavy photoevaporation[7], which suggests a young evolutionary age for the nebula. Indeed, numerical modelling of cometary globules at the border of the Trifid indicate a dynamical age of 0.3 Myr[8].

The low-density gas emission was mapped in the millimeter lines of CO and its isotopes (^{13}CO, C^{18}O) at the IRAM 30m telescope and at the CSO over an area of 20' by 30'. At the distance of the Trifid, the beam size of $10''$ corresponds to a linear size of 0.1 pc. We detected hardly any neutral gas inside the HII region, apart from tiny photoionized globules. The line profiles are characterized by a broad plateau covering a velocity range of $80\,\mathrm{km\,s}^{-1}$. On top of this plateau are detected narrower components (typically $1 - 3\,\mathrm{km\,s}^{-1}$ wide). The high-velocity components (up to $40\,\mathrm{km\,s}^{-1}$ with respect to the cloud velocity) are distributed in thin sheets of gas blown away from the nebula. The narrow components arise from denser regions, in particular the dust lanes. These are detected in absorption against the optical nebula, which means they are located on the front side of the ionized gas; it allows to derive the kinematical structure of the Trifid (see Fig. 2). Based on CS and C^{18}O line analysis, the typical H_2 density of these components is $\sim 5\times 10^3\,\mathrm{cm}^{-3}$ and the gas column density is $N(H_2) \sim 5\times 10^{21}\,\mathrm{cm}^{-2}$. It implies a thickness of 0.3 pc, comparable to the transverse size (in the plane of the sky). In other words, the gas around the nebula is distributed in filaments. The size of these filaments ranges from $1 - 2$ pc, for the lanes, up to 10 pc for gas in the filament on the Western side of the nebula. On the front side, the gas exhibit a much more fragmented appearance than what is derived from the optical. The lanes appear to have been accelerated to $\approx 10\,\mathrm{km\,s}^{-1}$ with respect to the ambient cloud, and they undergo strong velocity gradients, of several $\mathrm{km\,s}^{-1}\,\mathrm{pc}^{-1}$.

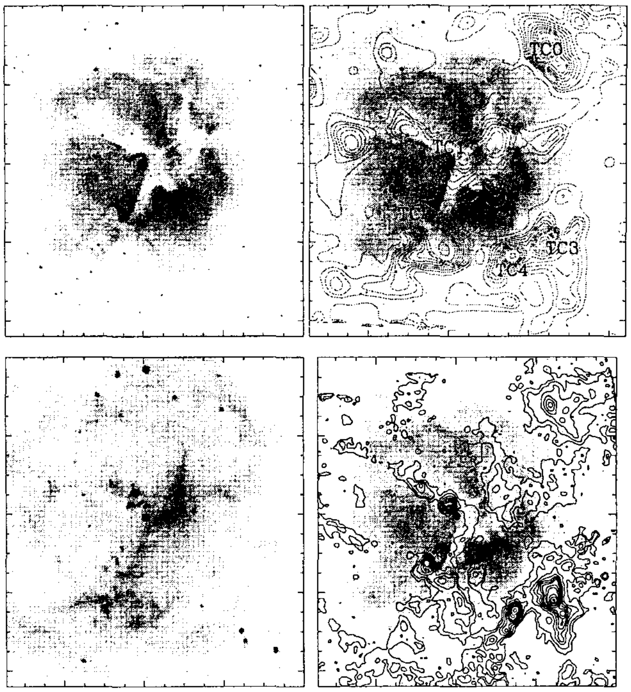

Figure 1: The Trifid nebula : (up. left) in the optical ($H\alpha$); (low left) at 11.5μm seen with ISOCAM; (up. right) in the $HCO^+ J = 1 \rightarrow 0$ line seen with the SEST; (low. right) at 1.3mm with the IRAM 30m telescope. Location of the protostellar sources TC1-TC4 is indicated in the HCO+ emission map.

3 Massive Protostellar Cores

The cold dust emission was mapped at 1.3mm with the MPIfR-37 channel bolometer array over an area of 15' by 30' (Fig. 3). Our sensitivity was good enough to detect the extended emission from the gas filaments and fragments inside these filaments. Seven condensations were identified in total : TC0N, TC0,1,2,..,5. Whereas five condensations are directly exposed to the influence of the nebula (TC0,..,4), two others are more distant but still associated with the parental molecular cloud.

Four of them (TC0N, TC0, TC3, TC5) are identified in the Western filament with masses ranging from about $200\,M_\odot$ up to $800\,M_\odot$. The fragments have a typical size of 1.5 pc and are equally separated by 10^{19} cm(3.3 pc). This value is in very good agreement with the most unstable mode that propagates in a purely hydrodynamically supported filament[12]. The mass of the fragments is being accreted from the filament itself, as suggested by the velocity field obtained in the CS $J = 2 \rightarrow 1$ line, that shows the molecular gas of the filament flowing onto the massive fragments. The total mass of the filament and the fragments are very similar ($\sim 2000\,M_\odot$). The condensations TC1-2 are located in the dust lanes at the border of the HII region, i.e. they are directly exposed to the high-energy radiation of the nebula. They have smaller sizes ($\sim$ 0.3 pc) and masses ($\sim 60\,M_\odot$). Molecular line observations have allowed to derive the condensation structure to 6" resolution and showed that a radiatively-driven shock propagates inside the condensations, whereas a Photon-Dominated Region has formed below the surface[8]. The filament associated with TC4 appears to be fragmented in at least three condensations.

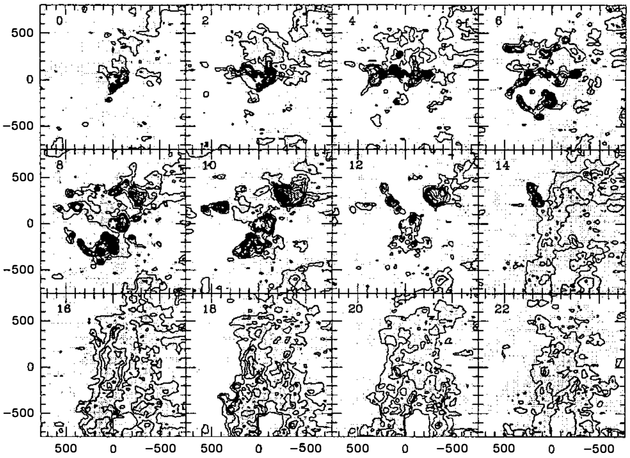

Figure 2: Map of the CO $J = 3 \rightarrow 2$ emission integrated per velocity channels observed at the CSO. Channel velocity is indicated in the upper right corner. A white star marks the position of the exciting star of the nebula.

The two other condensations have smaller masses ($\sim 10\,M_\odot$). The distribution of the dense gas and its kinematics are consistent with condensations forming **from** the fragmentation of the filament, compressed by the shock preceding the ionization front[6].

Several cores could be identified in the most massive condensations (TC1-5), which appear strongly peaked (Fig. 3). The cores are compact, with sizes of 0.1 – 0.2 pc. We focus here on the brightest cores identified in each condensation. TC0N and TC0 differ somewhat from the rest of the sample in that their flux distribution is much shallower and does not present any strong peak. Comparison with the $12\mu m$ maps obtained ISOCAM shows that only two sources (TC4-5) exhibit a counterpart in the mid-IR, indicating all the millimeter sources to be deeply embedded. Indeed, the Spectral Energy Distribution obtained with ISO for some of them (TC2,4,5) indicates dust temperatures of $15-20$ K and dust column densities of a few 10^{23} cm^{-2}. The core properties are summarized in Table 1. They are massive ($M = 20 - 200\,M_\odot$) and their luminosity is typical of intermediate-mass objects.

Detailed studies of the molecular content of TC1-5 have confirmed the protostellar nature of these cores[6,8] : evidences of outflowing gas were discovered in all the cores. TC2 is somewhat an exception as the outflow is oriented almost in the plane of the sky, so that the wings were too weak to be detected at the IRAM 30m telescope. However, the source powers the splendid HH399 photoionized jet[13]. The various molecular tracers observed (HCO^+,CS,SiO) show bright lines, comparable to those detected in the Orion protostellar cores, once scaled at the same distance[6]. The ratio of their millimeter to bolometric luminosity is found large, with values typical of "Class 0" protostars, i.e. all the protostars are very young, still in the phase of accreting the bulk of mass from their parental envelope. The cores TC3-4-5 appear to be very dense, with densities $n(H_2) = (1-5)\times 10^6$ cm^{-3} at the emission peak, and in the envelope ($n(H_2) = (2-4)\times 10^5$ cm^{-3}). The line profiles of the high-density gas tracers (CS, SiO) are characterized by bipolar wings

Table 1: Physical properties of the protostellar cores detected around the Trifid nebula. In the last column is given the flux scaled at the distance of the nearest SF complexes (ρ Oph and Taurus; 160 pc). We adopt a dust temperature of 20 K and a dust spectral index of 2 (derived from the SED obtained with ISO/LWS). A dust absorption coefficient $\kappa = 0.1\,\mathrm{cm^2\,g^{-1}}$ at 250μm was assumed. We follow the convention $a(b) = a \times 10^b$

Source	$S_{1.3}^{peak}$ (Jy)	$S_{1.3}^{int}$ (Jy)	M_t ($M_\odot$)	N_H ($\mathrm{cm^{-2}}$)	L_{bol} (L_{bol})	S^* (Jy)
TC0	0.10	0.70	46	1.0(23)	-	
TC1	0.16	0.20	23	1.7(23)	-	16
TC2	0.15	0.18	27	1.6(23)	500-1200	15
TC3	0.39	0.92	90	3.7(23)	-	39
TC4	0.29	0.60	58	2.8(23)	520-2400	29
TC5	1.03	2.0	200	1.0(24)	3900	-

that reach velocities up to $30\,\mathrm{km\,s^{-1}}$ with respect to the ambient gas for some of these sources. The outflow properties could be derived in the case of TC3-4-5 and are found consistent with those powered by intermediate-mass protostars[15]. TC1 and TC2 exhibit similar properties : their peak density, as derived from CS, is less (typically $2 - 4 \times 10^5\,\mathrm{cm^{-3}}$), as well as their mean envelope density ($\sim 2 \times 10^4\,\mathrm{cm^{-3}}$). The TC1 and TC2 protostars are detected in condensations less massive and less dense than the TC3-4-5 sources. As such, they are a good illustrative case of star formation going on at the same time as the protostellar envelope is photoevaporated. We did not find any strong evidence the star formation process was triggered by the radiatively-driven implosion of the condensations[8]; observations at a better angular resolution would help ascertain this conclusion. The gas properties of TC0 are rather similar to those of TC1-2. The core does not exhibit any sign of gravitational collapse : it appears to be still in a quiescent stage while it is hit by the ionization front of the HII region.

4 Triggered Star Formation around the Trifid

Analysis of the gas kinematics in the Western filament yields interesting constraints on the star formation that took place. A map of the $C^{18}O$ emission per velocity channels (Fig. 3) in the region near TC3 and TC4 shows that the emission from the cores is anticorrelated with the rest of the filament : there is a perfect match between the cores and the apparent "hole" in the filament. The emissions are separated by about $3\,\mathrm{km\,s^{-1}}$ (compare the panels at $v = 18\,\mathrm{km\,s^{-1}}$ and $v = 21\,\mathrm{km\,s^{-1}}$). This is a direct evidence that TC3 and TC4 are forming in **shocked** material of the filament. Dense molecular gas tracers such as CS, SiO, $H^{13}CO^+$ peak exactly at the same velocity despite their different optical depth, hence probing different gas layers. It is consistent with star formation occuring **after** the shock impact. In the opposite case, one would expect optically thin tracers to keep track of the initial velocity distribution in the inner core regions. A detailed analysis of TC5 has been carried out and leads to the conclusion that TC5, too, is forming inside a shocked core. The most plausible trigger would be W28SNR, at the border of which lies TC5. Interestingly, in the Western filament, the evidences of ongoing star formation are found only in the cores which show evidences of shock.

Numerical simulations of a filament impacted by an HII region[5] show that the timescales involved to form the first and the subsequent generation(s) of cores are always several times the crossing time of the filament : ≈ 1.5 Myr for the Western filament, much more than the age of the Trifid and W28SNR. The fragmentation of the filament is therefore related to some older event, and the protostellar cores were pre-existing the ignition of the nebula. The very short dynamical timescale of the cores ($\sim 10^4$ yr) is consistent with a very recent gravitational

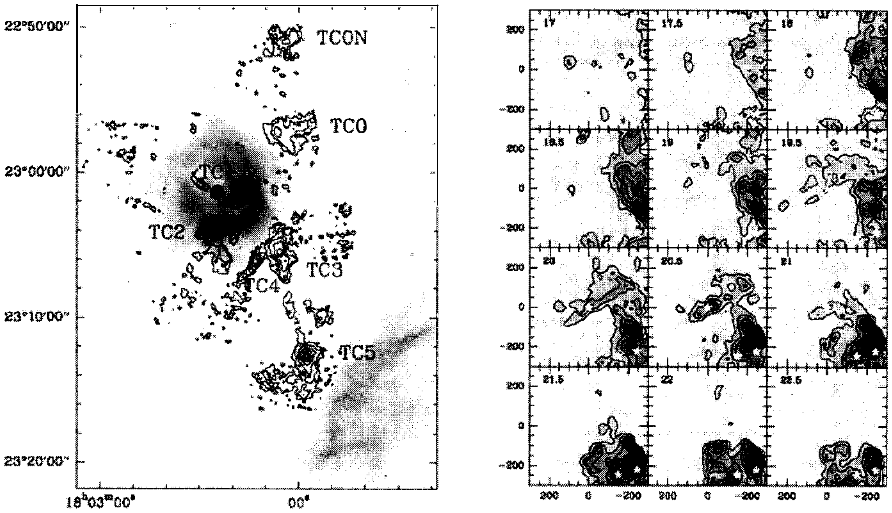

Figure 3: *(left)* 1.3mm dust emission map (contours) superposed on a 20cm VLA image of the region. *(right)* Map of the $C^{18}O$ $J = 1 \rightarrow 0$ emission per velocity channels on the Western side of the Trifid. White stars mark the position of HD 164492A, TC3 and TC4.

collapse, following immediately the shock compression of the cores.

The Trifid nebula is a good illustrative case of a young HII region formed in a dense cloud. The exciting star was born inside a web of filaments. The destabilization of these filaments has led to their fragmentation. The formation of new generation of stars in these fragments has been triggered by shock interaction with the ambient medium, probably the Trifid and/or W28SNR. High-angular resolution observations as well as numerical modelling should be undertaken to understand the peculiar kinematical structure of these cores, and how strongly it can affect the gravitational collapse and the source multiplicity.

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