Triggered Star Formation in a Turbulent ISM
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Anatomy of the S255–S257 complex - triggered high-mass star formation

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Abstract. We present a multi-wavelength (NIR to radio) and multi-scale (1 AU to 10 pc) study of the S255–S257 complex of young high-mass (proto)stars. The complex consists of two evolved HII regions and a molecular gas filament in which new generations of high mass stars form. Four distinct regions are identified within this dusty filament: a young NIR/optical source cluster, a massive protostar binary, a (sub)millimetre continuum and molecular clump in global collapse and a reservoir of cold gas. Interestingly, the massive binary protostellar system is detected through methanol maser and mid-IR emission at the interface between the NIR cluster and the cold gas filament. The collapsing clump is located to the north of the NIR cluster and hosts a young high-mass star associated with an outflow that is observed in mid-IR, methanol maser and radio emission. We interpret this anatomy as the possible result of triggered star formation, starting with the formation of two HII regions, followed by the compression of a molecular gas filament in which a first generation of high-mass stars forms (the NIR cluster), which then triggers the formation of high mass protostars in its near environment (the massive protostellar binary). The global collapse of the northern clump might be due to both the expansion of the HII regions that squashes the filament. In conclusion, we witness the formation of four generations of clusters of high-mass stars in S255–S257.

Keywords. stars: formation, ISM: clouds, HII regions, methods: data analysis

1. Introduction

S255–S257 belongs to the large complex of HII regions, S254, S255, S256, S257, S258, at a distance of 2.4-2.6 kpc (Fig. 1a). These five HII regions are powered by young high-mass stars and clusters of stars. S254 is the most extended HII region. S256 and S258 are still relatively small in extent, and S258 is isolated from the other bubbles of ionized gas. Interestingly, a luminous IR source is observed in between S255 and S257 (e.g. Howard *et al.* 1997). It is surrounded by a cluster of young stars with hundreds of T-Tauri, class I and class II objects (Ojha *et al.* 2006). The NIR source is also associated with a methanol maser that is a signpost of high-mass protostars (Minier *et al.* 2001). A second high-mass young stellar object (HMYSOs) is identified north of the NIR source cluster. It exhibits radio continuum emission that is the signature of an ultra-compact HII (UC HII) region (Kurtz *et al.* 1994).

With signatures of HMYSOs at various stages, the S255–S257 complex is an ideal laboratory to explore possible triggers of star formation. The following section describes

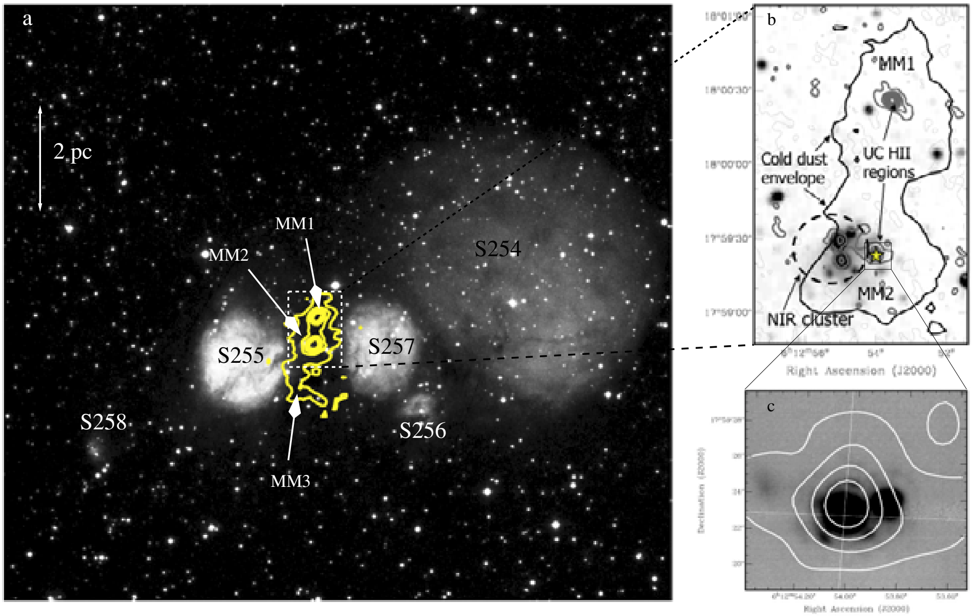

Figure 1. a. Cold dust continuum emission at 1.2 mm (contours) overlaid on the DSS optical image of the S254-S258 HII regions. b. Close-up of MM1 and MM2. Dust emission at 450-μm (single black contour), radio-continuum emission at 15 GHz (grey contours) overlaid on the J-band 2MASS image. The methanol maser site is indicated by a star. c. Close-up of MM2/methanol maser source. Radio-continuum emission overlaid on 18-μm mid-IR emission from hot dust.

the anatomy of the molecular cloud that is squeezed in between S255 and S257, from cloud scale (1 pc) down to protostar scale (1 AU).

2. Anatomy of S255–S257

2.1. *The molecular gas and dust filament*

Observations of S255-S257 were performed with Gemini-North in five mid-IR bands (Longmore *et al.* 2006), with JCMT/SCUBA at 450 and 850 μm and SEST/SIMBA at 1.2-mm (Minier *et al.* 2005), with the IRAM-30m in N_2H^+(1-0) and HCO^+(3-2) spectral lines, with the SEST in the ^{13}CO(1-0) line, with the VLA at 15, 22 and 43 GHz, and with the EVN and VLBA for imaging water and methanol masers (Goddi *et al.* 2006; Minier *et al.* 2001). Complementary data were extracted from the Digitized Sky Survey archives, the Spitzer/IRAC archives, 2MASS, MSX and IRAS IRSA image service, and the VLA and NVSS archives. This work also makes use of other observational results that were obtained in the 2.2-μm H_2 line by Miralles *et al.* (1997) and 44-GHz methanol masers by Kurtz *et al.* (2004).

The observations of cold dust and molecular gas emission reveal a ridge or a filament of dense gas that is squeezed in between S255 and S257 (Fig. 1a,b). It is part of a more extended molecular cloud that links the HII regions from the eastern S258 to the western S254 (Fig. 2a). The molecular gas ridge is observed by Spitzer/IRAC as a dark lane on the bright PAH emission at 8 μm that traces the interface between ionized gas in the HII regions and neutral gas in the cloud (Fig. 3).

Dense molecular clumps are identified in the ridge between S255 and S257. Two clumps are clearly observed in the cold dust emission. MM1 and MM2 present similar physical

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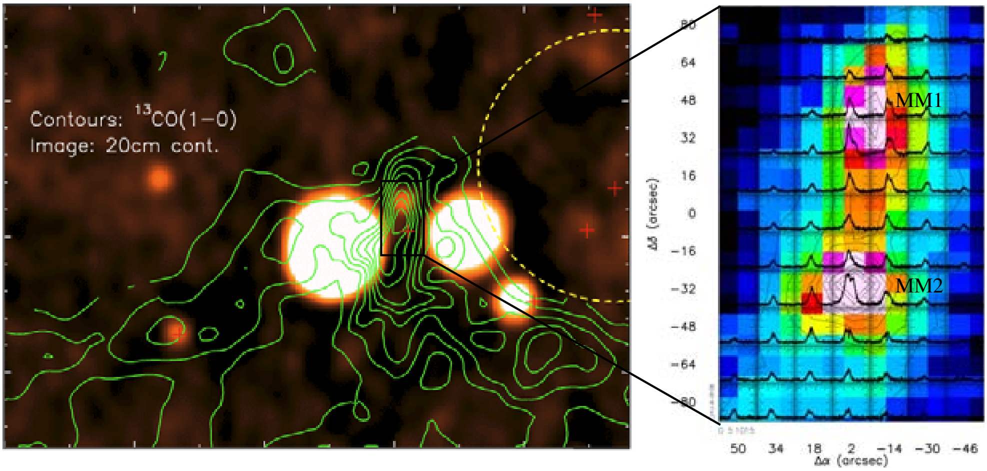

Figure 2. a. ^{13}CO(1-0) line emission (contour) overlaid on the NVSS radio-continuum image at 20 cm. b. Close-up of MM1 and MM2. HCO$^+$(3-2) line spectra overlaid on integrated-line emission.

conditions (see Minier *et al.* 2005). Their mass is $\sim$ 300 M$_\odot$ and their luminosity is $5 - 10 \times 10^4$ L$_\odot$ within $\sim$ 0.3 pc. These clumps are dense (10^5 cm^{-3}) and cold (40 K). They are also observed in HCO$^+$(3-2) (Fig. 2b) and N$_2$H$^+$(1-0). There is a third clump in the N$_2$H$^+$(1-0) emission map that is located in more diffuse dust emission (Fig. 1a).

2.2. *Dust clump MM1*

MM1 hosts a UCHII region at its center (Fig. 1b). The radio-continuum emission is extended in a NE-SW direction as well as the 44-GHz methanol masers (Kurtz *et al.* 2004). Spitzer/IRAC and Gemini-North images also reveal this elongated source. This morphology is likely that of an outflow and its heated-up cavity. At larger scales ($\sim$0.5 pc), MM1 exhibits spatially resolved signatures of infall in HCO$^+$(3-2), which suggest the global collapse of this clump (Fig. 2b; see Peretto *et al.* 2006 for a comprehensive study about global collapse signatures). Simple 1D radiative transfer calculations give an infall velocity of 0.7 km s^{-1}, that translates to a dynamical infall time of 10^5 yr, which is about the free-fall time for such a clump.

2.3. *Dust clump MM2*

MM2 harbours a more complex structure with a NIR source cluster on its East side and neutral molecular gas on its West side (Fig 1b). MM2 hosts two well-developed UC HII regions that are associated with the cluster of NIR sources and a hyper-compact HII region that is coincident with the methanol and water maser source (Fig. 1b; Goddi *et al.* 2006). The NIR cluster is surrounded by a bubble of shocked H$_2$ gas (Miralles *et al.* 1997). The methanol maser is located within this H$_2$ bubble at the interface between the cluster and the neutral molecular gas. A signature of infall in HCO$^+$ is observed at this position (Fig. 2b). Finally, a massive protostellar binary is imaged at the position of the maser (Fig. 1c; Longmore *et al.* 2006).

3. Triggered star formation?

The anatomy study of the molecular gas filament between S255 and S257 reveals two new active sites of high-mass star formation: MM1 and MM2. MM1 is a cold molecular

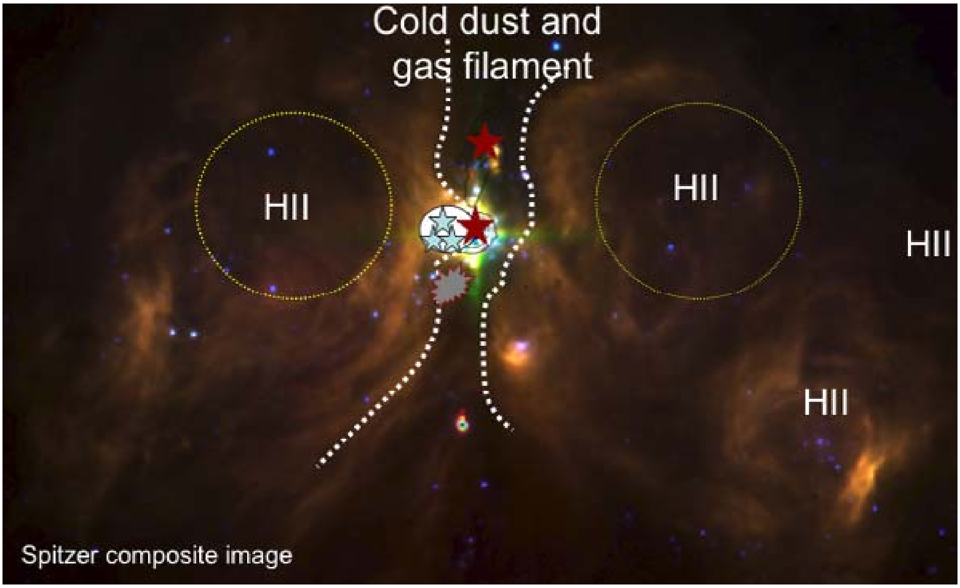

Figure 3. Spitzer composite image in three IRAC bands. Red stars show the position of high–mass protostars. White area and blue stars illustrate the B-star cluster and the H_2 bubble. The grey cloud symbol represents the MM3 cold gas reservoir.

cloud in global collapse. It hosts a high-mass protostar that ionizes its near environment and powers an outflow. It is not clear how the HII regions S255 and S257 have triggered its collapse because the infall time is not greater than the free-fall time of MM1. MM1 is probably a first-generation high-mass star-forming clump. MM2's history is much more complex. MM2 is surrounded by a cluster of low-mass YSOs. Two UCHII regions that are located East from MM2 emission peak are associated with optically visible high-mass stars (Howard *et al.* 1997). They might be part of the cluster. An HII region has developed around them as defined by the shocked H_2 bubble. Interestingly, a massive protostellar binary is born in the shocked interface. A possible interpretation is the formation of high-mass stars through a collect-and-collapse process after the fragmentation of the shocked gas around a HII region (Elmegreen 1998). The massive protostellar binary would therefore be the product of second-generation, triggered high-mass star formation. MM3 is a reservoir of pre-stellar gas that is not yet an active site of star formation.

In summary, this region contains a wide set of star formation mechanisms which might be necessary ingredients to form high-mass stars, such as large scale molecular cloud compression, early global collapse of clumps, or even small scale triggered star formation.

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Discussion

Bieging: Poster 84 shows largescale CO maps, which have a 2nd CO(3-2) and IR peak with no obvious triggering mechanism evident.

Minier: This is also shown in our ^{13}CO(1-0) map.

Zinnecker: You did not emphasize the presence of the embedded IR-cluster between the S255 and S257 HII regions with hundreds of low-mass stars! This very young cluster could have ejected the two B0-stars that power the S255 and S257 HII regions. These two B0-stars do not have a cospatial low-mass star clusters and were once considered evidence for isolated massive star formation (or bimodal star formation). Taken together with your new data, this region of star formation exhibits a rich variety of complex phenomena that may be characteristic of many other regions and star formation in general.

Minier: There is a poster by Ohja *et al.* that describes the low-mass star cluster in between S255 and S257. However, this cluster is relatively evolved, 1 Myr or so, and the massive protostars we identified cannot be part of it as they are too young. They must be second-generation stars, especially the massive binary associated with the methanol maser.