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TRIGGERED HIGH MASS STAR FORMATION

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ABSTRACT

Triggered star formation is not a new idea — it's been around for at least the last 30 years. Although it has never disappeared from the scene, it seems to be enjoying something of a renaissance in recent years, in both observational and theoretical studies. Here we give a brief discussion of the background of triggered star formation, describe some of our own recent observational efforts in this regard, and briefly mention some initial conclusions that may be drawn.

Key words : Stars: formation – Stars: early-type – ISM: HII regions

I. A BRIEF BACKGROUND ON TRIGGERED STAR FORMATION

A chief requiste of star formation is the presence of a large amount of dense, self-gravitating gas. The study of star formation (in large part) is the investigation of how material (which may have been in a rather diffuse state in the interstellar medium) comes to collect itself into a dense, self-gravitating state, and from there proceeds to collapse and form stars.

"Triggered" star formation is understood to mean the situation in which there is some particular event which initiates the star formation process. In this sense, it is subtly different from "regular" star formation, which (in this view) would be seen to proceed by "normal" processes, without the need for some external triggering event. In this sense, triggered star formation might be viewed as a particular *mode* of star formation.

There are at least three distinct means of triggering the star formation process. These are: the direct compression of pre-existing molecular condensations, cloud-cloud collisions, and the accumulation of gas into a ridge or shell that then collapses into star-forming cores. In the first and third cases, the triggering event can come from the expansion of an HII region (e.g., Elmegreen & Lada 1977) or of a supernova remnant (e.g., van Till, Loren & Davis 1975). The third case, also known as the "collect and collapse" process, will be the focus of this presentation.

An excellent review of all three means of triggering star formation is found in Elmegreen (1998).

II. THE COLLECT AND COLLAPSE MODEL

The collect and collapse model was developed by Elmegreen & Lada in 1977, at least in part motivated by sequential bursts of star formation that were seen along the galactic plane by Ambartsumian (1955) and Blaauw (1964). The model proposed was sometimes referred to as the "burning cigar" model, with the image being of a cylindrical cloud with the star formation gradually eating its way into the cloud much as a cigar smolders.

I will certainly defer to others who were involved at the time, or who may have a better historical perspective than I do. But it seems to me that the collect and collapse model (undeservedly) languished for about a decade, in part because of this image of the "burning cigar." In particular, in the late 1970s and early 1980s we had the idea that massive stars formed near the surface of clouds (quite consistent with the cigar image) while by the 1990s the view had changed, with the realization that in general massive stars form deep within molecular clouds — somewhat at odds with the cigar image. Although a number of seminal works were done in the 1990s (e.g., Whitworth et al. 1994), it is only recently that theoretical interest has been rekindled in this model (e.g., Hosokawa & Inutsika 2005, 2006 and Dale, Bonnell & Whitworth 2007).

III. OBSERVATIONAL PROGRAMS

A major observational campaign to test the collect and collapse model has been started at the Observatoire de Marseille under the leadership of Lise Deharveng and Annie Zavagno. They have defined a sample of 19 candidates for this mode of star formation by locating isolated, spherical HII regions with infrared point sources located at their perimeters (Deharveng et al. 2005). With the advent of Spitzer (in particular the GLIMPSE project) they have found many more (and even better) candidates. A small subset of the Deharveng et al. (2005) sample is shown in Figure 1.

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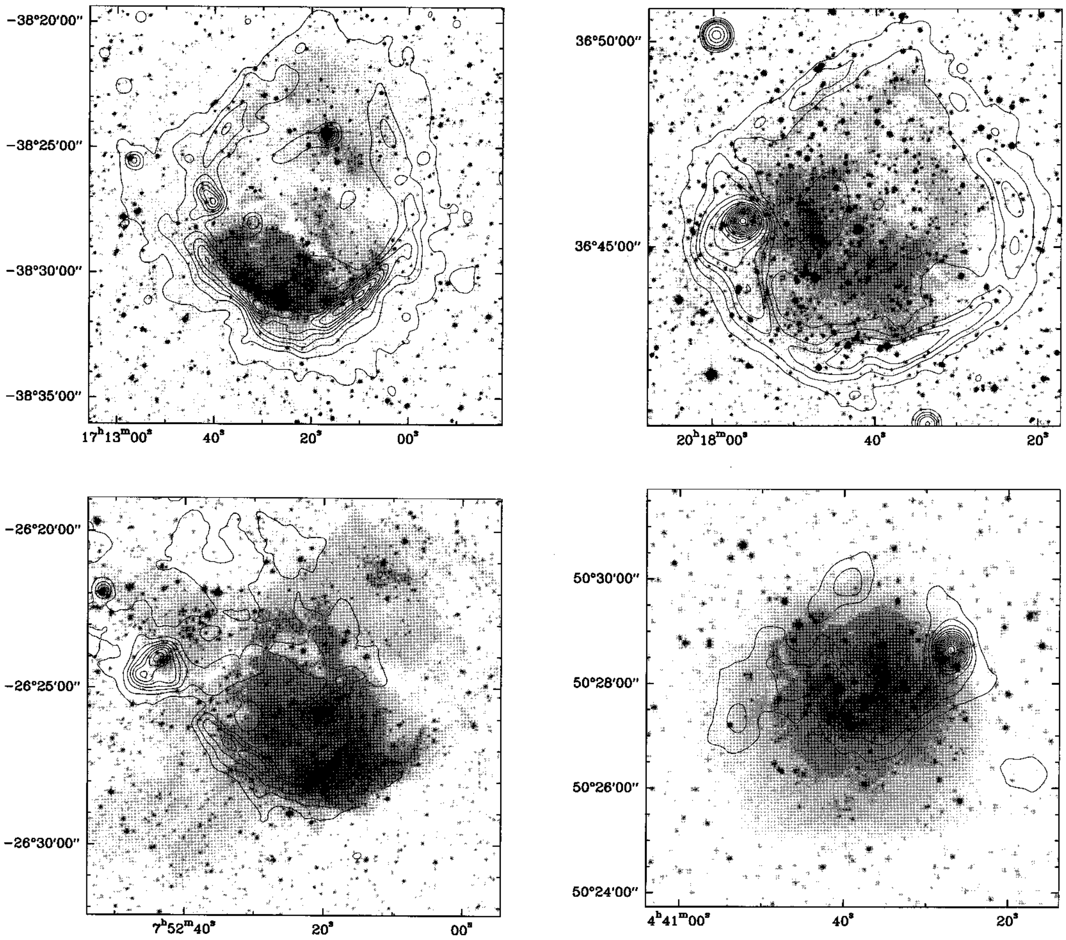

Fig. 1.— Shown are four candidate regions to test the collect and collapse model; they are part of the sample of 19 sources proposed by Deharveng et al.(2005). Thre grey-scale shows the Digital Sky Survey image while the overlaid contours are the 21 μm emission as seen by *MSX*. The collected gas layer is evident in all cases, as are compact sources which are candidate formation sites for massive stars or massive star clusters. As expected for a statistically significant sample, in some cases (above) the collected layer is seen projected at the edge of the HII region, in other cases (below) the collected layers are projected onto the HII region.

IV. RADIO CONTRIBUTIONS TO THE OBSERVATIONAL STUDIES

To complement the optical and infrared studies, we have made both single-dish and interferometric observations of a number of the candidate regions.

Using the Very Large Array, we searched a subsample of the Deharveng et al. sample for thermal ammonia emission, and for water and 44 GHz methanol masers. Somewhat surprisingly, we detected emission in only one source of our sub-sample. The large number of non-detections is interesting, because this methanol maser is fairly common in high mass star forming regions, and water masers are nearly ubiquitous in such regions. The lack of ammonia emission clearly indicates that no hot molecular cores are associated with these star formation sites. The lack of these traditional tracers may indicate fundamental differences in the collect and collapse star formation process compared to other, more common, star formation modes.

Using the Mopra telescope, we mapped a different (southern) sub-sample in various CO isotopomers. The Mopra telescope was recently equipped with an extremely flexible back-end spectrometer (called MOPS) which is capable of providing up to 16 simultaneous spectral windows (see Figure 2). In all the sources observed we found evidence for shells of molecular gas surrounding the HII region. The analysis of these data is underway, and we hope to soon have estimates for the column densities of the swept-up layers. We are also planning follow-up observations at the sites of the densest gas, to search for other tracers of recent high mass star formation.

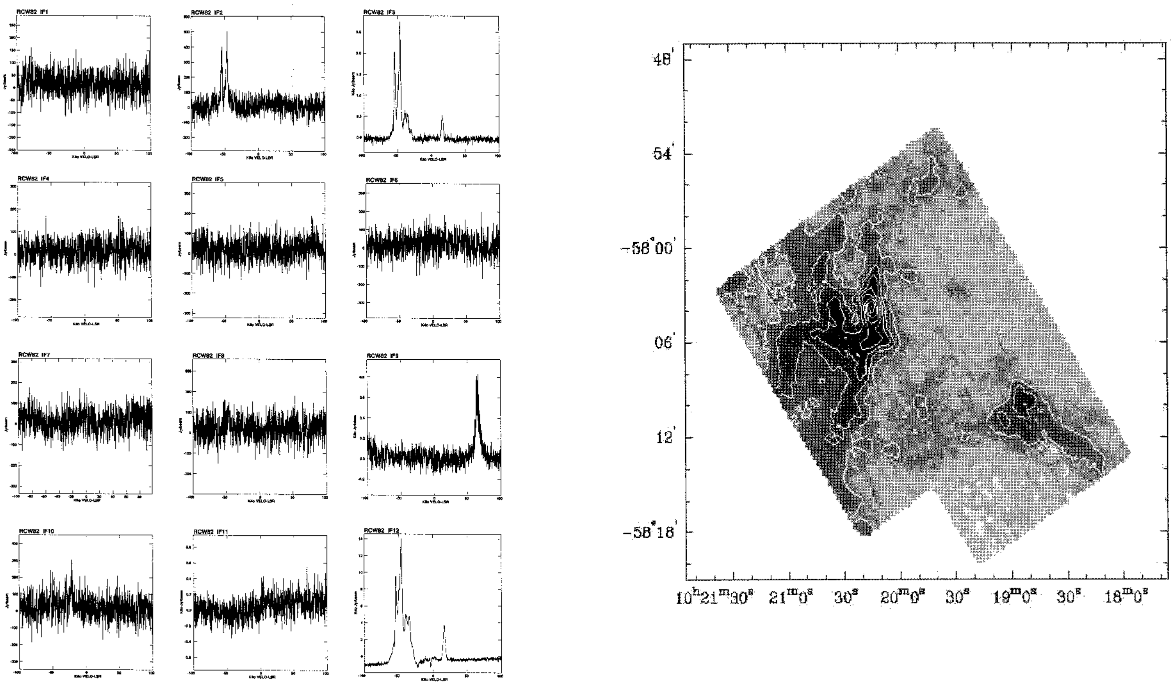

Fig. 2.— Shown at left are the 12 simultaneous spectral bands observed with the MOPS spectrometer at Mopra. Clear detections are made of CO, ^{12}CO, and C^{18}O, which were mapped by the On-The-Fly technique. The MOPS spectrometer is capabable of observing up to 16 spectral bands simultaneously. Shown at right is the CO (1–0) map of Dutra 45. Collected CO layers are seen at both the left and the right side of the map; the HII region occupies the vacant, central region.

V. CONCLUDING COMMENTS

The observational campaign undertaken by the Marseille group and their collaborators is very much a work in progress. Nevertheless, enough results are in to mention some preliminary findings. Further details may be found in Zavagno et al. (2006, 2007) and Deharveng et al. (2006).

First, the collect and collapse process *does* seem to be at work, at least in a number of carefully selected HII regions. Whether it is a common mode of star formation is still undetermined. Simulations by Hosokawa & Inutsuka (2005) suggest that it may be, but as yet there is no observational basis for this claim.

Second, the collect and collapse process seems to form *massive* stars. In the sample so far studied, the second-generation stars (or clusters) that have formed all have an O-type star, and several are in the O5-O6 range. I would certainly not claim that the collect and collapse process *always* results in massive second-generation stars, but clearly the present sample tends to support this idea.

In cases where clump masses have been determined, they are *massive clumps*. Typical masses are in the range of 10^2 – 10^3 M$_\odot$. In some cases, the clumps are seen to host young massive clusters. The fact that in several cases (e.g., Sh 104, see Deharveng et al. 2003) the clumps are quite regularly spaced around the expanding HII region also supports the idea of swept-up interstellar gas, rather than chance condensations in the surroundings of the HII region.

Third, the star formation efficiency seems to be fairly high with the collect and collapse process. In the Sh 104, Sh 212, and the RCW 79 regions, for example, the star formation efficiency ranges from 14% to over 30%. This is consistent with other research, which suggests that star formation efficiencies in *clumps* are generally somewhat higher than star formation efficiencies for an entire *cloud.*

Fourth, the lack of traditional high-mass star formation tracers in a number of sources — particularly water masers and hot molecular cores — is suggestive that the collect and collapse process may have some distinct differences from other, more common, high-mass star formation mechanisms. In particular, these star formation sites appear to be less deeply-embedded than is often the case.

The results being obtained for the Deharveng et al. sample are very promising, and should greatly facilitate further theoretical developments in the area of the collect and collapse model in particular, and triggered star formation in general.

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