Triggered Star Formation in a Turbulent ISM
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Footprints of triggering in large area surveys of the nearby ISM and YSOs

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Abstract. Our goal is to evaluate the role of triggering effects on the star formation and early stellar evolution by presenting a statistically large sample of cloud and low-mass YSO data. We conducted large area surveys (ranging from 400 square-degree to 10800 square-degree) in optical, NIR and FIR. The distribution of the ISM and low-mass YSOs were surveyed. A relative excess was found statistically in the number of dense and cold core bearing clouds and low mass YSOs in the direction of the FIR loop shells indicating a possible excess in their formation.

Keywords. stars: early-type, stars: formation, stars: statistics, ISM: bubbles, ISM: clouds, ISM: dust, extinction, Galaxy: structure

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1. Introduction

Do we need more motivation for a study of triggered low mass star formation than a better understanding of the formation of our Solar System? We may assume that the formation of the Solar System was triggered by massive stars – based on abundance anomalies of short-lived radio isotopes in meteorites Lee, Papanastassiou & Wasserburg (1977), Cameron & Truran (1977). Either the pre-solar nebula was contaminated by various isotopes including Al^{26} at the time of a close-by supernova explosion, or the YSO disk of the young Sun was "doped" by these radioactive isotopes originating from the atmosphere of a nearby ($d \approx 0.2\,\mathrm{pc}$) red supergiant according to Chevalier (2000). The probability of the latter close-massive-star scenario is small but perhaps not negligible. But since massive stars form in associations, it is very likely that other, not so close, but massive YSO members of the association triggered the formation of the proto-Sun by their radiation, stellar and/or supernova winds (see also Hester *et al.* 2004).

The nearby low mass star forming regions are considered as examples for ISM-external effect interactions: Star formation in the outer regions of the ρOph cloud could be triggered by the same event that initiated star formation in Upper Sco (Wilking *et al.* 2005). The dense filamentary structures of the Taurus clouds were produced by large-scale colliding HI streams (Ballesteros-Paredes *et al.* 1999). Cloud collapse is likely triggered by an HII region in the Horsehead nebula, B33 (Ward-Thompson *et al.* 2006).

The low-density intercloud medium is the result of turbulence and overlapping supernova remnants. Clouds are at least partly turbulence-resulted fractals, and as such are also highly clustered, making the mean free path for ionizing photons at least twice as large as in the 'standard cloud' model (Elmegreen 1998). That means however, that a large fraction of dense ISM (i.e. clouds) is affected by either SN or ionizing photons from mid-plane HII regions with a large free path. A large free path means most photons can travel nearly to the next HII region (Elmegreen, 1998). The trigger (by radiation, wind, shock fronts) is then evidently present for a considerable (if not overwhelming) mass fraction of the cold neutral ISM in the Galactic disk.

The footprints of triggered star formation should be observed also in the distribution of few Myrs old YSOs, since those can still be found near their birthplaces.

What is the role of triggering in the formation of low mass stars? The answer is searched in 3 steps:

(1) We study the structure of low and intermediate mass clouds in the obvious presence and assumed absence of external effects.

(2) We survey the distribution of cold dense ISM to locate the interfaces between the very low density intercloud medium, and the dense ISM.

(3) We study the distribution of low mass YSOs, and try to relate their distribution to that of the ISM.

2. Surveys and results

Kiss *et al.* (2006a) performed an unbiased survey of a 256 square-degree area in Cepheus exploring the ISM distribution, cloud and star formation based on optical and NIR data. The nearby ($d \approx 300\,\mathrm{pc}$) Cepheus Flare GMC (Hubble 1934, Lebrun 1986) is known as a site of low- and intermediate-mass star formation with over 200 clouds and with a total ISM mass of $2 \times 10^5 \mathrm{M}_\odot$, of which only 20% is in the form of dark ($\mathrm{A}_V > 2.0\,\mathrm{mag}$) clouds (Kiss *et al.* 2006a). The observed projected axis ratios b/a (see Fig. 5) of our clouds correspond to near-prolate 3d shapes (see Jones & Basu 2002). This would be consistent with their formation from large-scale external forcing. While the ISM distribution in the central part of the Cepheus Flare reminds us of turbulent model images (see e.g. examples in this volume), there are high pressure events acting at its outskirts.

The eastern side of the Cepheus Flare GMC is bordered by the Cepheus Flare shell (Olano *et al.* 2006), an expanding shell enclosing an old supernova bubble (Grenier *et al.* 1989) with a radius $r = 50\,\mathrm{pc}$, expansion velocity $v = 4$ km s^{-1} and estimated age $t > 10^6$ yr. The southern border is however “guarded” by an expanding HI shell and FIR loop GIRL G109+11 (Kiss *et al.* 2004). Most of the opaque ($\mathrm{A}_V > 5\,\mathrm{mag}$) clouds were found in the loop-boundary area, i.e. 70% (19 out of 27) of these clouds are located at 20% of the total area. Most of the star formation occurs in these clouds as seen from the distribution of Hα, and infrared excess point sources. The immediate conclusion is that an effect results in cloud restructuring and star formation at the GMC-intercloud surface. A straightforward explanation is triggering by slow shock fronts ($v \approx 10$ km s^{-1}) which travel into the Cepheus Flare GMC. Clouds in the walls of the voids are exposed to external pressure and radiation. Triggering by a slow increase in external pressure has been recently discussed by Lesaffre *et al.* (2006). Radiation-driven implosion may result triggered star formation in bright-rimmed clouds as seen e.g. in recent observations by Urquhart *et al.* (2006) and modeling by Miao *et al.* (2006).

Cloud-intercloud interfaces could be found e.g. locating expanding HI shells, of which more than 700 were cataloged by Ehlerova (see also in this volume). The voids however do not always expand, and even when they do, the expansion velocity may decrease to a few km s^{-1} as the expanding shell is aging.

We wanted to search for the cloud-intercloud interfaces without a restriction on the kinematics. The column density of the dusty ISM is seen in the FIR optical depths. With this in mind, the ISSA IRAS all-sky 60μm and 100$\,\mu$m surface brightness data were examined and 462 loops were located (Kiss *et al.* 2004 and Könyves *et al.* 2006). Loops are at least 60 percent complete arcs, where an excess 100$\,\mu$m surface brightness occurs over the central parts of at least 3 times the local surface brightness fluctuation level. The

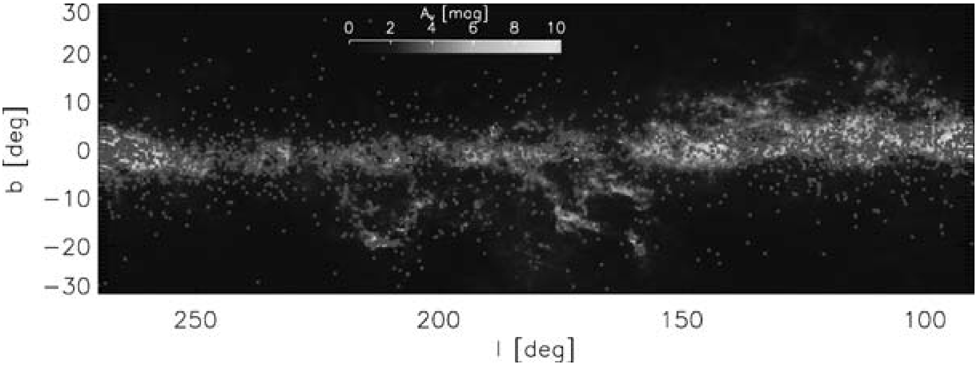

Figure 1. Reddening by Schlegel in the outer galaxy, with CTT candidate point sources over-plotted, marked with (red) dots.

FIR colour of the loops is the same as the cirrus, with a local hydrogen column density excess of 10% in average over their surroundings. The loops appear as typical structure of galactic cirrus in the few pc to a few times 10 pc scale. Large chains and super-loops are seen. Most of our FIR defined loops can be identified on NIR reddening maps as well.

How do the distribution of low mass YSOs compare to the pattern drawn by the projected image of interfaces of the dense cloudy ISM and the low density intercloud medium? We tested it in the outer galaxy ($-30 < b < 30$, $90 < l < 270$). The ISM column density, as derived from the IRAS based FIR optical depth (Schlegel *et al.* 1998) is shown in Figure 1 with all 2MASS point sources over-plotted which have classical TTauri-like (CTT) NIR colours and a good photometry.

A remarkable correlation is seen between the CTT number density and reddening in Orion, i.e. the CTTs follow the loop structure. A careful statistical comparison of the CTT distribution and FIR loops showed that the on-loop CTT number density $N(\mathrm{CTT})$ is highly non-random, where $N(\mathrm{CTT})$ is the number of CTTs seen projected on the loop shell divided by the loop shell area. In order to account for the ISM column density variations we divided $N(\mathrm{CTT})$ by the average NIR based A_V extinction of the loop shell. The observed average $N(\mathrm{CTT})/A_V$ value of 0.2 is far from the results of our Monte Carlo simulations. That we understand as a statistically proved excess star formation on the shells. This suggests triggered star formation. Further details are given in Kiss, Tóth & Elmegreen 2006).

3. Conclusion and outlook

Triggering mechanisms, which may induce, hasten or at least modify the low mass star formation process, are well known. We pointed out that cloud restructuring and YSO distribution indicate an overall importance of triggering in low mass star formation. The low mass clouds do form spontaneously and some of them would indeed condense in gravitationally bound cores. However the opaque, and thus well cooling, and so easily unstable cores form more likely at the outskirts of GMCs (Cepheus) or in filaments (Taurus, Ophiuchus). Those are the locations where the clouds are well exposed to external effects, and triggering acts. It would be important to have an all-sky deep and unbiased census of the nearby low mass young and very young stars. Recent surveys by ISO or Spitzer confined the search for the low mass YSOs to a few star forming regions only.

The ASTRO-F (Akari) (see e.g. Shibai 2005) is in duty scanning the sky like IRAS (Beichman *et al.* 1988) did, but with more spectral filters with at least a factor of 10 better sensitivity and resolution. We expect to see a new all-sky catalogue of infrared point sources. As a part of the Star Formation Mission Programme also the question of low mass star formation triggering will be revisited.

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Discussion

SHORE: (1.) Is it possible (plausible) that the star forming clouds may be compressed (pre-existing) clouds while the other lower density regions may be formed by dynamics and thermal instability (transient) effects along the shell? (2.) this problem is another reason for going to a LOFAR/SKA type survey – to look at these objects at low frequency.

TOTH: In my view, pre-existing clouds are being re-structured by external effects which turn those to star-forming regions faster on the shells or loops than the clouds would evolve in a spontaneous process inside the relaxed regions. Without being exposed to winds and ionising radiation of the inter-GMC space, low mass star formation is slower and so less effective in the clouds. High resolution (below 0.1 pc) large area surveys of the diffuse ISM will help us understand the physics of transient density fluctuations and their relation to virialized clouds.