Indication of Star Formation Trigger on Cold Clouds†

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Abstract

We investigated the role of trigger mechanisms in the low mass star formation process. Star bearing and pre-protostellar cloud cores were searched as very cold objects of the ISO Serendipity Survey. We compared the distribution of cold starless cores VCCs to the distribution of FIR loops found on IRAS images. The distribution of VCCs follows the large scale ISM density distribution described by the FIR loops. Assuming that the 30pc-200pc scale trigger effects are reflected in the loop/shell structures, this result suggest a link between these effects and the VCCs.
KEYWORDS: *ISM: clouds – dust, extinction – ISM: molecules – Infrared: ISM: continuum – Surveys*

1. Introduction

Our galaxy forms stars on a low enough rate to allow the existence of 10% ISM in spite of the fact that high fraction of the ISM is stored in Jeans unstable clouds. As a solution for the Zuckerman-Evans (1974) paradox, all sorts of support mechanisms were introduced in the 70s. This led to the magnetic field regulated star formation theory. Numerical simulations late last century showed that magnetic braking is not an important support for interstellar cloud cores. Recent observational and modelling evidence suggests that actually there is no need for support since the clouds indeed collapse almost on free-fall time scale. This lowers the importance of star formation trigger mechanisms. Ten years ago those were still thought to be responsible for setting the location and/or timing and/or efficiency of star formation.

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One of the major unknown factors in theories of star formation is a detailed observational determination of the initial conditions of the collapse phase that forms a protostar. The pre-protostellar (or prestellar for short) core phase (Ward-Thompson et al. 1994) is believed to be the stage of star formation that precedes the formation of a protostar and hence should represent observationally the initial conditions of protostellar collapse. Some recent observations have even indicated that the Initial Mass Function (IMF) of stars may be determined before the protostellar collapse phase (see eg. Motte et al. 2001). It is thus important to know whether trigger plays an important role in the early (collapse) phase of cloud core evolution, prior to star formation.

Tracing trigger in the galactic ISM we use large FIR structures seen widely on IRAS FIR images. We compiled the first catalogue of FIR Loops which will be briefly discussed here. It is important to check the distribution of gravitationally bound starless cloud cores i.e. pre-protostellar cores whether it follows the large scale ISM density distribution. One has to collect a statistical sample of cloud cores well sampling both the on-loop and off-loop class. We then compare the physical parameters of both classes. Comparing the numbers in the two classes already allows us to draw a statement on the trigger effect of the process responsible for the creation of the loops. We evaluate the ISO Serendipity Survey (ISOSS) data which cover 15% of the sky with serendipitous slews observed at 170 μm with the ISOPHOT camera (Lemke et al. 1996) in board of ISO. We will discuss the parameters of ISOSS cores and their relation to the FIR loops.

2. What we know on low mass star formation

2.1. Tracers and efficiency

We outline important aspects of low mass star formation research, and give observational examples. First of all we list the most common indicators of recent low mass star formation. Various observational and theoretical results on the efficiency of star formation are also given below. Our selection of examples of low mass star formation is biased towards cases where trigger is apparent or expected. The trigger is considered strong when the star formation efficiency is increased.

Tracers of (low mass) star formation:

- Hα emission line stars. Star formation in the L134 complex: few$\times 10^6$ years old Hα stars around L1780, whose formation may be triggered by winds from the Sco-Cen-Lup association (Martin & Kun 1996).

- IRAS point sources as YSOs. Selection criteria were given by eg. Emerson (1987), statistical study of the "whole" IRAS Point Source Catalog was carried out by Prusti et al. (1992). Apparently the YSO distribution is not random.
- NIR point sources with $> 3\%$ NIR excess (Lada 1992)
- bipolar molecular outflows (Bally, 1982, Sato & Fukui 1989)
- cold molecular cloud cores as NH_3 (1,1) density peaks. The most cited NH_3 survey for dense cores in dark clouds (Benson & Myers 1989) indicates a physical association of young type IRAS sources and $T_{kin} \approx 10\,\mathrm{K}$ cold, and $n(\mathrm{H_2}) > 10^4 \mathrm{cm}^{-3}$ dense cloud cores.
- very cold, $T_d \approx 10\,\mathrm{K}$ dust, found in cloud cores eg. in B35 by Lada et al. (1981) and in L1172 by Ladd et al. (1991).

Regulation of star formation - theory: Most of the molecular clouds in the Galaxy are Jeans' unstable, which results in a star-formation rate of $130 < SFE < 400\,\mathrm{M_\odot yr^{-1}}$ (see, e.g., Evans 1991). But this number is two orders of magnitude higher than the average Galactic star-formation rate over the last few Gyr (see, e.g., Scalo 1986). It was generally believed that magnetic fields play a crucial role in supporting the clouds (Mouschovias & Spitzer 1976; Nakano & Nakamura, 1978). A magnetized cloud is virial stable when $M_v > 10^3 \mathrm{M_\odot}$. As it has recently been claimed, magnetic brake (e.g. ambipolar diffusion) cannot prevent local collapse for much longer than the global free-fall time (Heitsch et al., 2001). Does turbulence control the star formation? Is there a still larger scale trigger? Radiation driven implosion (RDI) shapes the clouds: gas condensations in molecular clouds irradiated by an O star and the cloud will have a cometary shape after re-expansion in $\approx 10^6$years (recently e.g. Kessel-Deynet & Burkert, 2002).
Increased efficiency of star formation - observations: The star formation efficiency (SFE) seems to vary with time and location. Large variations of SFE were observed in L1630 where all the massive cores contain regions with densities of at least $10^5\,\mathrm{cm}^{-3}$. The cores with rich embedded clusters (with high SFE), tend to be larger (i.e. to have larger areas of detectable CS($J = 5 \rightarrow 4$) emission) than those without clusters and with low SFE (Lada et al., 1997). It is strange, however, that in the Rosette molecular cloud a majority (65%) of the high-mass ^{13}CO clumps ($M > 450\,\mathrm{M_\odot}$) are not associated with any embedded cluster. The cluster formation may be triggered by the ionization fronts from the nearby HII region associated with NGC 2244 (Phelps & Lada, 1997). The distribution of

YSOs or embedded like IRAS point sources of the Upper Cep-Cas follows a large loop shell (Pásztor et al., 1993) YSOs in L1251 indicate 5% SFE and an age gradient (Kun & Prusti 1993). A shock travelled through L1251 according to Tóth & Walmsley (1996). A few times 10^6 years old Hα stars around L1780 are related to a slowly expanding old SNR shell (Tóth et al., 1995; Martin & Kun, 1996). Cometary clouds RNO 6 and RNO 6NW with embedded IR point sources are cases of formation of intermediate mass stars triggered by RDI according to Bachiller et al. (2002). Star formation propagates with a speed of $1\,\mathrm{kms}^{-1}$, as it can be inferred from the average separation and age difference of aligned cores in the Eagle nebula. Cloud P contains "core b", "core a", and the NIR source P1, with an average projected separation of < 0.1 pc. These objects most likely correspond to a starless core, a Class 0 object, and a Class I object, respec-tively. The age difference is then roughly 10^5 yr. The apparent propagation speed is a little slower than the shock propagation speed of $1.3\,\mathrm{kms}^{-1}$ (White et al., 1999). Conclusion: O5 star is triggering star formation in Cloud P.

2.2. Cold interstellar matter

Star formation occurs in dense cores within molecular clouds (e.g. Williams et al., 2000), although study of such regions was hampered for many years by their very large optical depths at near-infrared and optical wavelengths. It is only since the opening up of the far-infrared and submillimetre regimes that astronomers have been able to study molecular clouds in detail. Density enhancements of the interstellar medium far enough from heat sources and sources of moment can cool efficiently, which leads to collapse. Detailed study of the cold and very cold phase ISM and many pre-stellar cores is central to our understanding of star formation.

Cold interstellar matter (CISM) was introduced in the three phase ISM model of McKee & Ostriker (1977) with density and temperature of $n(\mathrm{H}) = 42\mathrm{cm}^{-3}$ and $T_{kin} \leq 80$K and with a volume filling factor of $\approx 2\%$. The CISM as appears in FIR, is mostly cirrus. At high galactic latitudes it has a temperature of T_d =17.5K (Dwek et al., 1997; Lagache et al., 1998). The ISM gets very cold at shielded regions, efficiently cooled by FIR and mm-lines. It forms molecular clouds (T_{kin} =20K), and starless cloud cores (T_{kin} =10K). The dust is also cold in these clouds and cloud cores. Thus they may be located by excess of FIR relative to 60μm surface brightness. The dust temperature in the very cold ISM is $T_d \leq 15$K (Laureijs et al., 1991; Boulanger et al., 1998; Lagache et al., 1998). An example of FIR radiation of CISM in other galactic disks is given by Haas et al. (1998).

The dust radiation models account for FIR-NIR-optical-UV radiation (e.g. Desert et al., 1990). They assume three components: PAHs and VSGs ($a <$ 10nm, $\lambda \leq 60\mu$m) and large grains (inferred from optical). As simulations show, the heating-cooling instabilities in clouds may lead to collapse (Clarke & Pringle, 1997; Burkert & Lin, 2000). The very cold cloud cores are thought to be the results of such instabilities, and were found to be related to star formation.

IRAS Loops in the 2nd Galactic Quadrant: In order to study the role of trigger in star formation we have carried out a search for interstellar bubble tracers i.e. loops. To achieve a high angular resolution we analysed IRAS maps instead of eg. HI surveys. Due to its low opacity the $100\,\mu$ radiation of dust is useful in a search for both diffuse and dense ISM. All IRAS ISSA maps of the 2nd galactic quadrant were searched for arc-shape bright regions. Our eye-biased search resulted over 150 loops (loop is a $> 60\%$ complete ring with significant surface brightness excess over its surroundings). These FIR loops bear point sources of all types. At intermediate galactic latitudes, the surface density of the TTau-like IRAS point sources is two times higher on the loops than elsewhere whereas the ISM column density is only 50% higher towards the loops than elsewhere (see Kiss et al. 2002).

3. ISO observations and data analysis

ISOSS: The coldest cloud cores are believed to be in the phase of thermal instability induced collapse, and will eventually form low mass stars. The most relevant recent survey to find these objects is the ISO Serendipity Survey (Bogun et al., 1996; Stickel et al., 1998; Tóth et al., 2000). Below we summarize what we have to know on ISOSS and the ISOSS very cold cores (VCCs).
ISOSS - the measurement: Slews between pointed observations of ISO were used to scan the sky with ISOPHOT's C200 array in a broad wavelength band centred at $170\,\mu$m. The slew paths are unpredictable and curved in order to avoid the forbidden regions near Sun and Earth.
ISOSS Calibration Accuracies (errorbars): Photometric accuracy of 30% can be achieved (Müller et al., 2002). Pointing $rms < 1$', rms reproducibility error is $< 15\%$ as measured at scan crossings (Stickel et al., 2000).

ISOSS very cold cores (VCC): Besides the ISOSS extragalactic point source catalogue (Stickel et al. 1998) the galactic FIR objects were also studied resulting a number of candidate pre-protostellar cores. Very cold (< 15K), fairly bright (> 6Jy) ISOSS/IRAS sources were located. Their optical associates on DSS2 are mostly opaque cloud cores in cloud complexes or in isolated dark clouds. There are associated NIR point sources seen usually around, but not "inside". As mm spectroscopy followups (CO, CS, NH_3 lines with Effelsberg-100m, Parkes-64m, IRAM-30m telescopes) revealed, these cold ISOSS sources are associated with dense parts of molecular clouds. In Chamaeleon (Tóth et al., 2000), the $I(170)$-excess clouds have $T_{\rm col}(\rm dust) < 14\,K$ with a 3% area filling factor. The $I(170)$ and $I(100)_{\rm cold}$ FIR surface brightnesses are well correlated, and $I(170)$ is correlated up to $A_V = 7\,$mag with the NIR based extinction. The very cold ISOSS sources were found to be cloud cores and thus were named as very cold cloud cores (VCCs). There are 14 VCCs with $T_d \approx 12$K in the Cepheus region. these VCCs are inside $A_{\rm V} > 3\,$mag dark clouds, and mostly associated with $T_{kin} \approx 10\,$K NH_3 cores.

4. Relating very cold cores to FIR loops

The distribution of VCCs, which are candidate pre-protostellar cores, is compared to the distribution of FIR loops (Kiss et al. 2002). The FIR loops are most likely projections of 3D bubble shells, as shown by a statistical investigation of the apparent shapes. These are the most prominent features of the nearby (2kpc) interstellar medium on 30–200 pc scales. Thus these shells are considered to be proper tracers of large scale trigger effects. The investigation is limited to the 2^{nd} galactic quadrant which is, however, the region with best sky coverage fraction in the ISOSS database. The resuls of the comparison are:

- 89 VCCs are inside the 2nd Galactic Quadrant
- the VCCs appear within $-40° < b < 30°$ (limited b range)
- the FIR loop shells cover 32% of total sky area within $-40° < b < 30°$
- 70 of the 89 VCCs (79%) are associated with loops, 34 are on loops
- only 6 VCCs are seen inside a loop and 2 VCCs are far from loops

We conclude that the formation of the ISOSS VCCs is likely triggered by the same physical processes which formed the large shells seen as FIR loops. Is it a weak trigger only i.e. modifying the location of otherwhise spontaneous star formation by moving the ISM into shells, or may the high pressure events directly trigger cloud collapses? Further investigation of individual VCCs may answer to this question.

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