*Triggered star formation in a turbulent ISM*
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# Triggered formation and collapse of molecular cloud cores

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**Abstract.** First I discuss the dynamics of core formation in two scenarios relevant to triggered star formation, namely the fragmentation of shock-compressed layers created by colliding turbulent flows and the fragmentation of shells swept up by expanding nebulae. Second I discuss the influence of thermodynamics on the core mass spectrum, on determining which cores are 'pre-stellar' (i.e. destined to spawn stars) and on the minimum mass for a pre-stellar core. Third, I discuss the properties of pre-existing cores whose collapse has been triggered by an increase in external pressure, and compare the results with observations of collapsing pre-stellar cores and evaporating gaseous globules (EGGs).

**Keywords.** Stars: formation, ISM: clouds, ISM: bubbles, instabilities, turbulence.

## 1. Introduction

Triggered star formation has several advantages over spontaneous star formation. First it is much easier to understand how nature co-ordinates the approximately coeval formation of stars over an extended region, to form a cluster, if there is a trigger involved. Second, it is much easier to understand why star formation is so patchy, on a galactic scale, if there is a trigger involved. Thirdly it is easier to understand the multiplicity of stars and the great diversity of their properties (separations, eccentricities, mass-ratios), if there is a trigger involved. In spontaneous star formation the approach to instability is normally quite quasistatic, and consequently the material has rather alot of time to organise its subsequent collapse onto a single focus. Triggered star formation tends to bypass the linear stages of instability and launch material directly into the non-linear stages of collapse; the material therefore retains a memory of the asymmetries and substructures generated in its previous history, and can then amplify them gravitationally to produce multiple systems. Other evidence for triggered star formation can be found in the patterns of sequential self-propagating star formation, and in the prodigious bursts of star formation observed in interacting and merging galaxies.

In this contribution I concentrate on three aspects of triggered star formation: (i) the basic dynamics of core formation due to triggered gravitational fragmentation (Sections 2 and 3); (ii) the influence of thermodynamics on the mass function of cores in a turbulent medium (Section 4), on the threshold which must be passed for cores to collapse and form stars (Section 5), and on the minimum mass for a prestellar core (Section 6); and (iii) the evolution, and observable features, of pre-existing cores whose collapse is triggered by a sudden increase in pressure (Section 7), and the fate of pre-existing cores which are overrun by an HII Region (Section 8).

## 2. Fragmentation of shock-compressed layers created by colliding turbulent flows

In a turbulent medium, pre-stellar cores are created wherever two turbulent flows having sufficient density and column-density collide with sufficient ram-pressure to form a self-gravitating condensation. The simplest generic model of this process involves two flows having density $\rho_0$ colliding at relative speed $v_0$ to produce a plane-parallel layer, in which the effective isothermal sound speed is $a_{\rm S}$ and the density is $\rho_{\rm S} \simeq \rho_0 (v_0/a_{\rm S})^2$. Eventually the layer becomes massive enough to fragment gravitationally. If we model a proto-fragment as a disc with radius $r$ (in the plane of the layer) and half-thickness $z$ (perpendicular to the plane of the layer), then the time at which fragmentation becomes non-linear, and the mean initial mass, radius and half-thickness of the resulting fragments, are given by

$$\begin{aligned} t_{\rm FRAG} &\sim \left(\frac{a_{\rm S}}{G\,\rho_0\,v_0}\right), & m_{\rm FRAG} &\sim \left(\frac{a_{\rm S}^7}{G^3\,\rho_0\,v_0}\right), \\ r_{\rm FRAG} &\sim \left(\frac{a_{\rm S}^3}{G\,\rho_0\,v_0}\right), & z_{\rm FRAG} &\sim \left(\frac{a_{\rm S}^5}{G\,\rho_0\,v_0^3}\right) \end{aligned} \tag{2.1}$$

(Whitworth *et al.*, 1994). We stress that the mean fragment mass is not simply the standard Jeans mass evaluated at the shocked density $\rho_{\rm S}$ and sound speed $a_{\rm S}$. This is because at its inception a fragment is flattened: its thickness is determined by ram-pressure, and self-gravity only dominates in the directions parallel to the plane of the layer. The initial aspect ratio of a fragment is effectively equal to the Mach number, $\mathcal{M}$, of the shock bounding the layer, $r_{\rm FRAG}/z_{\rm FRAG} \sim v_0/a_{\rm S} \sim \mathcal{M}$.

These results have been confirmed by numerical simulations (Whitworth *et al.* 1995). In reality, the layer fragments initially into filaments, and then into cores along the filaments, but it is still the case that the separation between neighbouring filaments, and the separation between cores along a filament, are both $\sim 2r_{\rm FRAG}$.

We note also that $a_{\rm S}$ must be defined to represent all contributions to the velocity dispersion of the shocked gas – i.e. thermal motions plus all non-thermal motions which are on sufficiently small scales (i.e. $< r_{\rm FRAG}$) to contribute to resisting self-gravity. Non-thermal motions on larger scales contribute to fragmentation by creating sub-structure in the shocked gas which then acts to seed fragmentation.

## 3. Fragmentation of shells swept up by expanding nebulae

A similar mechanism for creating pre-stellar cores involves gravitational fragmentation of a shell swept up by an expanding nebula, i.e. an HII Region (HIIR), a stellar-wind bubble (SWB), or a supernova remnant (SNR). This mechanism is fundamental to the process of sequential self-propagating star formation (Elmegreen & Lada 1977), whereby the massive stars in one generation trigger the formation of the next generation through the compressive action of the HIIRs, SWBs and SNRs which they excite. The phenomenology of shell fragmentation is very similar to that of layer fragmentation, basically because in both cases ram-pressure plays a key role. Indeed, it is the fundamental role of ram-pressure which distinguishes triggered star formation from spontaneous star formation. Again, the fragments are, at their inception, flattened disc-like objects, with an aspect ratio of order the Mach number of the shock bounding the shell on its outer edge. Again the shell fragments first into filaments, and then into cores along the filaments.

As an example, we consider the case of a shell at the edge of a SWB created by a stellar wind with mechanical luminosity $L_{\rm WIND}$ blowing into a medium with density $\rho_0$. The time at which the shell starts to undergo non-linear fragmentation, the radius of the shell at this juncture, the mean mass of the resulting fragments, their mean radius and their mean half-thickness (i.e. the half-thickness of the shell) are given by

$$\begin{aligned} t_{\rm FRAG} &\sim \left(\frac{a_{\rm S}^5}{G^5\,\rho_0^4\,L_{\rm WIND}}\right)^{1/8}, \qquad & R_{\rm FRAG} &\sim \left(\frac{a_{\rm S}^3\,L_{\rm WIND}}{G^3\,\rho_0^4}\right)^{1/8}, \\ m_{\rm FRAG} &\sim \left(\frac{a_{\rm S}^{29}}{G^{13}\,\rho_0^4\,L_{\rm WIND}}\right)^{1/8}, & & \\ r_{\rm FRAG} &\sim \left(\frac{a_{\rm S}^{13}}{G^5\,\rho_0^4\,L_{\rm WIND}}\right)^{1/8}, & z_{\rm FRAG} &\sim \left(\frac{a_{\rm S}^{23}}{G^7\,\rho_0^4\,L_{\rm WIND}^3}\right)^{1/8} \end{aligned} \tag{3.1}$$

(Whitworth & Francis 2002). Here $a_{\rm S}$ is the effective sound speed in the shocked gas of the shell.

## 4. The core mass function

If we consider a large region of the interstellar medium, i.e. sufficiently large that the overall rate of star formation is a small perturbation to the overall ensemble of cores, there is presumably an approximate statistical equilibrium, in which small cores merge to form larger cores and large cores break up into smaller cores. If the cores subscribe to Larson-type scaling relations,

$$R \propto M^{\alpha}\,, \qquad \sigma \;\propto\; M^{\beta}\,, \tag{4.1}$$

(where $M$, $R$, $\sigma$ are the mass, radius and internal velocity dispersion of a core; Larson 1981), and if their mass spectrum is a power law,

$$\frac{d\mathcal{N}}{dM} \propto M^{-\gamma}\,, \tag{4.2}$$

then – by implication – there is an inertial range over which the dynamical processes which merge and break up cores are self-similar. Under this circumstance, the amount of mass in equal logarithmic mass intervals (which is proportional to $M^{2-\gamma}$) must be proportional to the dynamical timescale ($t_{\rm DYN} \sim R/\sigma \propto M^{\alpha-\beta}$), and so

$$\gamma \;\simeq\; 2 - \alpha + \beta\,. \tag{4.3}$$

In high-mass cores ($M > {\rm M}_\odot$), $\sigma$ is dominated by non-thermal motions, $\alpha \simeq 0.5$ and $\beta \simeq 0.25$, so $\gamma \simeq 1.75$, which is essentially what is observed for more diffuse cores and clumps in molecular clouds (e.g. Williams *et al.* 1994). In low-mass cores ($M < {\rm M}_\odot$), $\sigma$ is dominated by thermal motions, $\alpha \simeq 1$ and $\beta \simeq 0$, so $\gamma \simeq 1$, which is significantly flatter. Therefore there should be a knee in the core mass function around ${\rm M}_\odot$, *and* the cores below the knee should contribute rather little to the total mass in cores. This knee may be partly responsible for the peak in the core mass function around ${\rm M}_\odot$ (e.g. Nutter & Ward-Thompson 2006), and hence for the peak in the initial mass function (IMF) around $0.3\,{\rm M}_\odot$ (e.g. Kroupa 2002; Chabrier 2003). However, we should stress that the theory we have presented above is for the mass function of all cores, and most of these cores are presumed to be transient rather than pre-stellar. It is not clear how this mass function would map into the mass function for pre-stellar cores — for example, if it were subjected to a sudden increase in ambient pressure.

## 5. A pressure threshold for creating prestellar cores

One possibility is that pre-stellar cores are those which are both gravitationally bound *and* sufficiently dense for the gas to couple thermally to the dust (and thereby to avail itself of broadband cooling). The second condition requires that the timescale on which the gas couples to the dust, $t_{\rm COUPLE}$, is less than the freefall time, $t_{\rm FF}$. Since we are here concerned with triggered star formation, these timescales should be evaluated at the density, $\rho_{\rm S}$ and sound speed, $a_{\rm S}$, in a shock-compressed layer or shell:

$$t_{\rm COUPLE} \;\simeq\; \frac{(2\pi)^{1/2}\,r_{\rm D}\,\rho_{\rm D}\,f(a_{\rm S})}{Z_{\rm D}\,\rho_{\rm S}\,a_{\rm S}} \;\lesssim\; t_{\rm FF} \;=\; \left(\frac{3\,\pi}{32\,G\,\rho_{\rm S}}\right)^{1/2}. \tag{5.1}$$

Here $r_{\rm D}$ and $\rho_{\rm D}$ are the radius and internal density of a representative dust grain, and $Z_{\rm D}$ is the fraction by mass in dust. $f(a_{\rm S})$ is the thermal accommodation coefficient for a gas particle ($H_2$ molecule) striking a dust grain; for simplicity, we set $f(a_{\rm S})$ to unity, which is a reasonable assumption for gas kinetic temperatures $T \lesssim 100\,{\rm K}$ ($a_{\rm S} \lesssim 0.6\,{\rm km\,s^{-1}}$). Condition (5.1) then reduces to a condition on the ram pressure creating the layer or shell,

$$P_{\rm RAM} \;\equiv\; \rho_0\,v_0^2 \;\simeq\; \rho_{\rm S}\,a_{\rm S}^2 \;\gtrsim\; P_{\rm COUPLE} \;\simeq\; \frac{64\,G}{3}\left(\frac{r_{\rm D}\,\rho_{\rm D}}{Z_{\rm D}}\right)^2 \tag{5.2}$$

In contemporary, local star formation regions, $r_{\rm D} \sim 10^{-5}\,{\rm cm}$, $\rho_{\rm D} \sim 3\,{\rm g\,cm^{-3}}$ and $Z_{\rm D} \sim 10^{-2}$, so $P_{\rm COUPLE} \sim 10^5\,{\rm cm^{-3}\,K}\,k_{\rm B} \sim 1.4\times10^{-21}\,({\rm g\,cm^{-3}})\,({\rm km\,s^{-1}})^2$. The corresponding surface-density is $\Sigma_{\rm COUPLE} \sim (P_{\rm COUPLE}/G)^{1/2} \sim 1.4\times10^{-2}\,{\rm g\,cm^{-2}} \sim 60\,{\rm M_\odot\,pc^{-2}}$, or equivalently $N_{\rm COUPLE} \sim 4\times10^{21}\,{\rm H_2\,cm^{-2}}$. These values are compatible with conditions in observed regions of star formation.

## 6. The minimum mass for a pre-stellar core (opacity-limited primary fragmentation)

Since the geometry of triggered fragmentation, and the expression for the typical fragment mass, are different from those that obtain in hierarchical three-dimensional fragmentation, it is appropriate to revisit the question of the minimum mass of a pre-stellar core, as determined by the requirement that a core can only undergo *Primary Fragmentation* if it is able to keep cool by radiating away the thermal energy delivered by compression. (*Secondary Fragmentation* may occur at higher densities due to the dissociation of $H_2$.) If we simply require that the radiative luminosity be greater than the rate of $PdV$ heating of the gas in the condensing fragment, there is an upper limit on the flux of matter flowing into the shock-compressed layer or shell,

$$\rho_0\,v_0 \;\lesssim\; \dot{\Sigma}_{\rm MAX} \;\sim\; \frac{4\,\pi^2\,\bar{m}^4\,a_{\rm S}^6}{15\,c^2\,h^3}\,, \tag{6.1}$$

and the expression for the minimum mass is essentially the same as for hierarchical 3-D fragmentation,

$$M_{\rm MIN} \;\simeq\; \frac{(30)^{1/2}}{\pi^3}\,\frac{m_{\rm PLANCK}^3}{\bar{m}^2} \times \left(\frac{a_{\rm S}}{c}\right)^{1/2} \tag{6.2}$$

(Whitworth & Stamatellos 2006). Here $m_{\rm PLANCK} = (hc/G)^{1/2} \simeq 5.5\times10^{-5}\,{\rm g}$, $\bar{m}$ is the mean gas-particle mass, $c$ is the speed of light, $h$ is Planck's constant and $G$ is the gravitational constant. We note (i) that the part of the above expression preceding '×' is essentially the Chandrasekhar mass (the maximum mass for a non-rotating white dwarf),

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and (ii) that $M_{\rm MIN}$ depends very weakly on temperature ($\propto T^{1/4}$), as noted by Rees (1976), but quite strongly on the mean gas-particle mass ($\propto \bar{m}^{-9/4}$). For contemporary local star formation in gas with $\bar{m} \simeq 4 \times 10^{-24}$ g and $T \sim 10$ K, Eqn. (6.2) gives $M_{\rm MIN} \sim 0.001\,{\rm M}_\odot$.

In reality the situation is likely to be more complicated. In particular, a core condensing out of a shock-compressed layer (or shell) grows by accreting the material which continues to flow into the layer. Consequently its final mass is larger than its initial mass. Moreover, it must now not only radiate away the $PdV$ heating due to internal contraction, but also the energy dissipated by the accreting material. When this is taken into account in a 2-D semi-analytic model (still with $\bar{m} \simeq 4 \times 10^{-24}$ g and $T \sim 10$ K), the minimum mass becomes $0.0027\,{\rm M}_\odot$ (Boyd & Whitworth 2005). In the limiting case, the proto-fragment starts off with a mass of $0.0011\,{\rm M}_\odot$ but then more than doubles this by accretion, as it condenses out.

## 7. Triggered core collapse

Another way in which star formation can be triggered is if a pre-existing core (which would otherwise disperse or persist in a state of approximate hydrostatic equilibrium) experiences a sudden increase in external pressure which causes it to collapse.

### 7.1. *Velocity fields and accretion rates*

Hennebelle *et al.* (2003) have simulated the response of a stable non-rotating isothermal core to a sudden increase in external pressure. A compression wave propagates into the core setting up an inward velocity field very similar to those which have been inferred from asymmetric line profiles in pre-stellar cores like L1544 (Tafalla *et al.* 1998). When the compression wave reaches the centre, a protostar forms. The accretion rate is initially high, due to the compression wave, but then it declines. Consequently the Class 0 phase is shorter than the Class I phase, in accordance with the observational statistics. We note that this mode of star formation is 'outside-in', in direct contrast to the standard 'inside-out' model involving a singular isothermal sphere.

### 7.2. *Disc fragmentation and multiplicity*

Hennebelle *et al.* (2004) have simulated the response of a stable rotating core to a sudden increase in external pressure. Again a compression wave propagates into the core triggering the formation of a primary protostar at the centre. However, most of the material has too much angular momentum to accrete directly onto the primary protostar and therefore forms a massive accretion disc around the primary protostar. This disc then fragments to produce one or two companions to the primary protostar. Fragmentation occurs because the compression wave deposits material onto the outer parts of the disc more rapidly than the existing disc is able to stabilise itself by redistributing angular momentum through gravitational torques. As a result, the outer parts of the disc become strongly Toomre unstable. The prediction that a single core spawns only a small number of protostars accords with the observed statistics of binary systems (McDonald & Clarke 1995, Goodwin & Kroupa 2005, Hubber & Whitworth 2005).

## 8. EGGs and free-floating very low-mass stars

One way in which the external pressure acting on a pre-existing core might increase is if the core is overrun by an HII Region. An ionisation front then eats into the core, preceded by a shock front, which triggers collapse. The final mass of the protostar formed at the centre of the core is determined by a competition between collapse (initiated by the shock front) and photo-erosion (due to the ionisation following close behind). A simple, semi-analytic model (Whitworth & Zinnecker 2004) shows that the final stellar mass is given by

$$M_\star \sim 0.010\,\mathrm{M}_\odot \left(\frac{a_{\mathrm{I}}}{0.3\,\mathrm{km\,s^{-1}}}\right)^6 \left(\frac{\dot{\mathcal{N}}_{\mathrm{LyC}}}{10^{50}\,\mathrm{s^{-1}}}\right)^{-1/3} \left(\frac{n_{\mathrm{II}}}{10^3\,\mathrm{cm^{-3}}}\right)^{-1/3}, \tag{8.1}$$

where $a_{\mathrm{I}}$ is the isothermal sound speed in the neutral gas of the core, $\dot{\mathcal{N}}_{\mathrm{LyC}}$ is the output of ionising photons exciting the HII Region, and $n_{\mathrm{II}}$ is the number-density in the HII Region. Since the dependence on the parameters which might be expected to have a large range ($\dot{\mathcal{N}}_{\mathrm{LyC}}$ and $n_{\mathrm{II}}$) is weak, and the strong dependence is on a parameter ($a_{\mathrm{I}}$) which cannot vary much, this appears to be a rather robust mechanism for producing free-floating very low-mass stars (brown dwarfs and planetary-mass objects), in the sense of not requiring very special circumstances. Moreover, we are presumably observing it happening in the evaporating gaseous globules (EGGs) seen in M16 and other HII Regions (Hester *et al.* 1996). However, it is also an inefficient way to produce free-floating very low-mass stars, in the sense that only a small fraction of the initial core ends up in the protostar; most of it is photo-eroded. In addition, the mechanism cannot operate in star formation regions like Taurus, where there are no OB stars to excite an HII Region and yet plenty of very low-mass hydrogen-burning stars and brown dwarfs (Luhman 2004). Therefore photoerosion is probably not a major source of very low-mass stars.

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**Discussion**

KRUMHOLZ: How are MRI and accretion luminosity likely to change your results on disk fragmentation?

WHITWORTH: I don't think MRI will have an effect. When extra mass is dumped on the outer parts of the disc, instability develops on a dynamical time scale, whereas MRI takes longer to develop and transport angular momentum. However, we will not in the immediate future be able to simulate the MRI. I expect that the accretion luminosity will inhibit fragmentation in the inner disc, but in the outer disc proto-fragments can cool fast enough to condense out.

CLARK: For the core mass spectrum to map to the IMF, each core must contain only one star. If the cores are formed by turbulence, it is unlikely that the flows will deliver just one Jeans mass in the turbulent model, so do you feel the core IMF can ever be related to the star IMF.

WHITWORTH: In my picture, cores form by gravitational fragmentation of a shock-compressed layer or shell, and therefore by definition they contain a Jeans mass. However, they will not necessarily collapse to form just a few stars (e.g., a binary and a couple of ejecta), they may collapse and fragment further to produce a whole cluster of stars.

KROUPA: The idea that photoevaporation may lead to Brown dwarfs that otherwise would have become stars is interesting. In Kroupa *et al.*(2003) we played with this idea and found that a population of photo-evaporated Brown dwarfs would be "substantial" in globular clusters which presumably had 1000's of O stars. But would-be G dwarfs would also have been photo-evaporated to make K- or M- dwarfs, thereby changing the initial stellar mass function. Since globular clusters are found to have very similar IMFs for low-mass stars as the current Galactic field, which mostly stems from low mass clusters (Kroupa 1995, Lada & Lada 2003), this similarity would give constraints on this process.

WHITWORTH: I agree. Even in clusters including OB stars, it can only produce a few very low-mass stars. (Parenthetically, it seems to me that there is a big dynamic range between small cores which end up as EGGs and large cores which end up as bright rimmed clouds. What happens in between?)