Triggered star formation in a turbulent ISM
Proceedings IAU Symposium No. 237, 2006
B. G. Elmegreen & J. Palouš, eds.

doi:10.1017/S1743921307001639

Simulations of ionisation triggering

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Abstract. We review recent pilot simulations that incorporate feedback from ionising radiation in SPH calculations of star forming clouds. In the case that the ionising radiation source is located within the star forming cloud, the inhomogeneity of the cloud significantly modifies the way that feedback operates compared with spherically symmetric cloud models. Inflow/outflow behaviour develops, combining accretion down dense filaments and thermally driven outflows that can remove many times the binding energy of the parent cloud. If the ionising source is located external to the cloud, we find evidence for triggered star formation but conclude that it is hard to find unambiguous observational signatures that would distinguish "triggered" stars from those created spontaneously.

1. Introduction

The thermal feedback of energy into the ISM via the ionising radiation field of OB stars raises a number of (currently unsolved) questions. An obvious issue is whether the effect of such feedback is net positive or negative (i.e. star formation promoting or disrupting) and how this affects the *efficiency* of star formation. If one decides that the star formation promoting aspect is important, one has then to ask what are the observational signatures of triggered star formation. Another aspect of the problem concerns how the sculpting of the local star forming cloud by ionisation feedback affects the escape of ionising radiation into the larger scale ISM and thus whether star formation is a plausible energy source for sustaining the thermal balance of the warm ionised medium in galaxies.

Historically, there have been two approaches to the numerical study of ionisation feedback. One involves hydrodynamic simulations in smoothly stratified media (Yorke *et al.* 1989; Franco *et al.* 1990; Garcia-Segura and Franco 1996). The other consists of radiative transfer in a realistically clumpy/fractal medium (i.e. with no hydrodynamics: Hobson and Padman 1993; Witt and Gordon 1996; Rollig *et al.* 2002). Evidently one wishes to combine the virtues of both approaches and instead model the hydrodynamic evolution in a realistically clumpy medium.

Such an ambitious task requires considerable simplification of the radiative transfer – specifically neglect of the diffuse field of ionising radiation due to recombinations to the ground state – so that through this 'on the spot' approximation one can compute the instantaneous Stromgren volume (region within which the number of recombinations per second equals the input ionising photon production rate). Determination of this Stromgren volume involves the computation of a recombination integral ($\propto \int n^2 r^2 dr$), a task that is trivial in a grid based code but which requires some thought in a Lagrangian method like SPH. Recently both Dale *et al.* (2005, 2006) and Gritschneder *et al.* (2006) have built on the original scheme of Kessel-Deynet & Burkert (2000) so as to use SPH neighbour lists to compute the recombination integral via jumping along a chain of

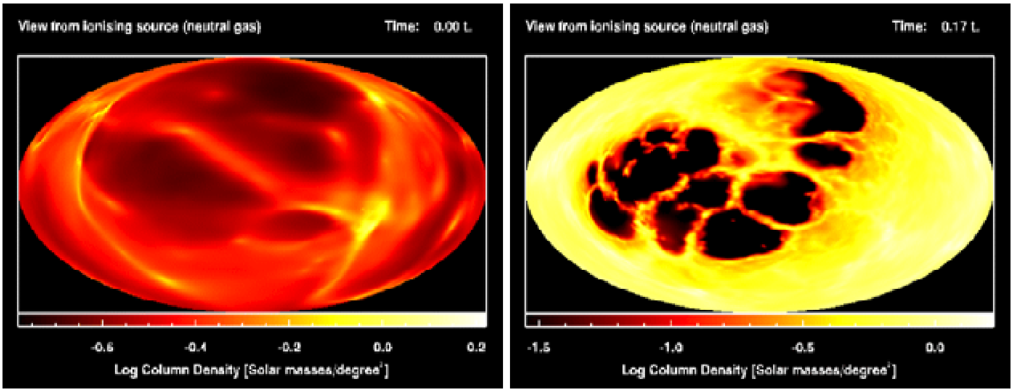

Figure 1. Column density map of sky seen from source: prior to switch on of ionising radiation (left panel) and after sculpting by ionising radiation (right panel).

particles leading to the central star. Once the Stromgren volume is determined in this way, the temperature therein is set to 10^4K. This approach works well in simple geometries and is currently being tested against full Monte Carlo radiative transfer codes in the case of the complex filamentary density fields encountered in realistic hydrodynamic simulations of turbulent molecular clouds (Ercolano *et al.* in prep.).

Here I will report briefly on two projects that use SPH with ionisation feedback included and which explore the effect of radiation from an OB star that is respectively internal (Dale *et al.* 2005) and external (Dale *et al.* 2006) to a star forming cloud. It should be stressed that in neither case has it been possible to explore parameter space and thus at this stage, the conclusions from these pilot studies are mainly qualitative.

2. Internal ionising source

In this case, the OB star is formed at the intersection of a set of dense filaments, and thus the 'sky' as 'seen' from the star is highly inhomogeneous even at the outset of the simulations, there being order of magnitude variations in column density and even larger variations in local density. Once the ionising source is switched on, the density contrasts are exacerbated: ionising radiation can propagate readily through lower density regions where the recombination timescale is long, and pressure gradients in the photoionised gas then drive outflows which reduce the density yet further (see Figure 1). On the other hand, ionising radiation can scarcely penetrate the dense filamentary structures where the recombination timescale is short. Thus an 'inflow-outflow' situation develops: material continues to be channeled onto the central star and yet there are also several regions of loosely collimated yet vigorous outflows. [Indeed, the mass flow rates and opening angles are compatible with the properties of some of the outflows observed in regions of high mass star formation (Churchwell 1997), implying that at least some of these may be environmentally collimated structures. Evidently, the simulations cannot reproduce highly collimated or bipolar structures, which instead demand a, presumably disc related, collimation mechanism close to the star. See Shepherd *et al.* 1997, Beuther *et al.* 2002.]

The present simulations evidence both positive and negative feedback effects. The mass flow rate down the filaments is reduced compared with a control simulation without feedback and yet is not halted in the higher density simulations. At the same time, lateral expansion of hot gas in the outflow channels compresses the gas in the filaments and induces extra star formation which is not occurring in the control simulation. Due

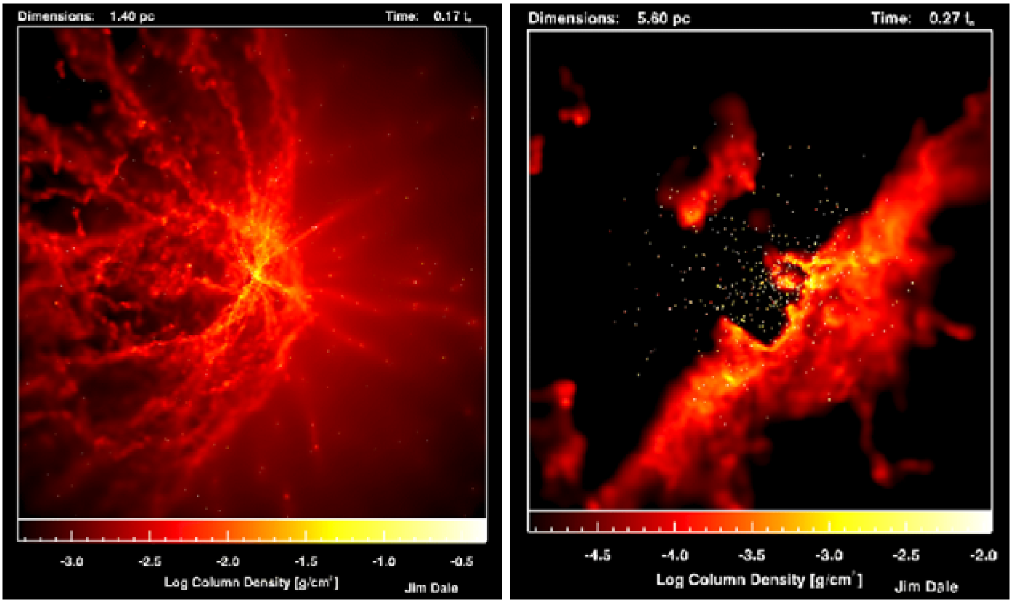

Figure 2. Column density map of high density ($\langle n \rangle \sim 10^4$ cm^{-3} run: left panel) and low density ($\langle n \rangle \sim 10^3$ cm^{-3} run: right panel) after $\sim 2 \times 10^5$ and $\sim 5 \times 10^5$ years respectively.

to limited numerical resolution of the induced star formation, it is not currently possible to assess whether the *net* effect of feedback is positive or negative.

Another noteworthy aspect of this inflow/outflow behaviour is that it is possible for the cluster to absorb a quantity of thermal and kinetic energy that far exceeds the cluster binding energy – and yet, under some circumstances, for the cluster to remain bound. This is simply because a relatively small mass fraction is expelled at ~10 km/s, i.e. at several times the escape velocity of the cluster. This result therefore demonstrates that simple criteria based on binding energy may be misleading when assessing the ultimate state (boundedness) of a cluster.

The results are evidently sensitive to mean density (contrast panels of Figure 2, which differ by only an order of magnitude in mean density). Although feedback is much more effective in the low density case (and, in fact, has halted accretion on to the OB star and unbound the cluster), this trend is *less* strong than it would be in the case of equivalent clusters with spherically symmetric density fields. [The spherically symmetric version of the left hand panel would result in essentially no impact from ionising radiation, since the HII region would in this case be confined by ram pressure to deep in the cluster core. In the spherically symmetric version of the low density run, however, the gas would have been completely cleared from the image shown in the right hand panel of Figure 2.]

A final point concerns the escape of ionising radiation. Even in the high density simulation (left hand panel of Figure 2), it is found that around 20% of the ionising photons can escape (along low density channels), whereas none would have escaped in the spherically symmetric equivalent cluster. Lesch *et al.* (1997) estimate that 15 – 20% of the ionising radiation from OB stars would need to escape from their natal regions in order to sustain the thermal state of the diffuse ionised gas in the Galaxy. The simulations demonstrate that, owing to the inhomogeneity of realistic star forming clouds, such escape fractions are credible even when the mean density of star forming clouds is very high ($\sim 10^4$ cm^{-3}).

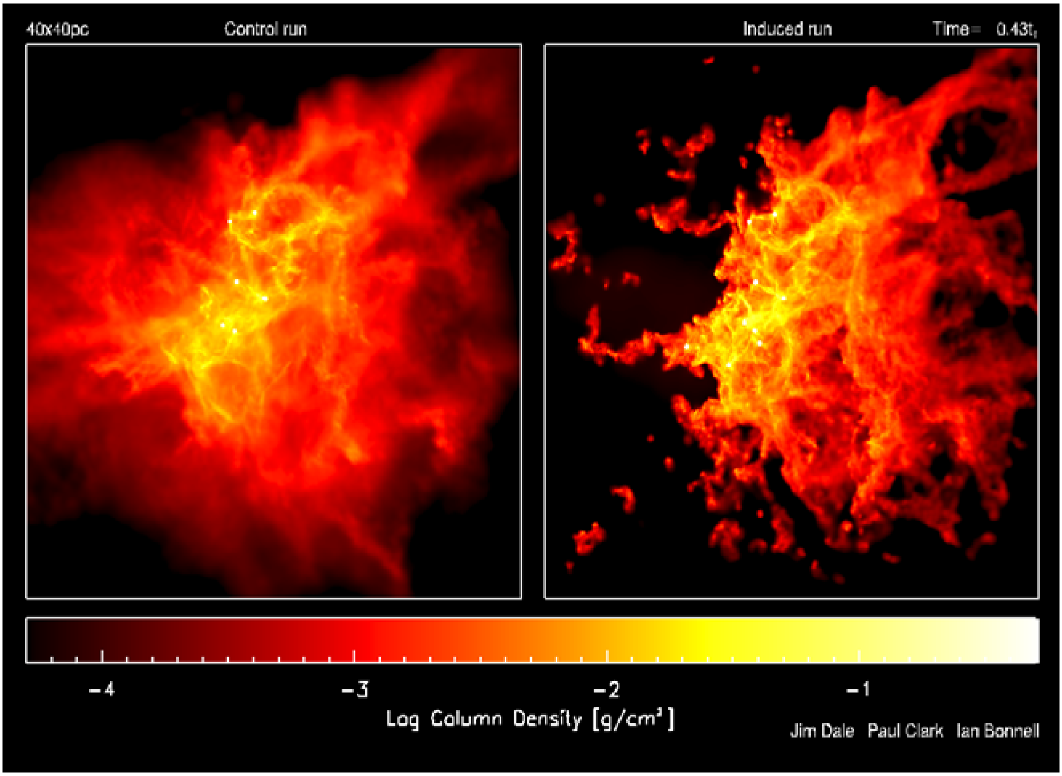

Figure 3. Comparison of the gas distribution in a run subject to external ionisation feedback (right hand panel) with a control run (left panel).

3. The external case

In the following simulations (Dale *et al.* 2006), an OB star is situated next to a turbulent molecular cloud which is initially globally unbound (initial ratio of kinetic to gravitational energy of ~2). The effect of the ionising source can be carefully assessed through comparison with a control simulation. As can be seen from the left hand panel, the control simulation forms some stars even though it is globally unbound: gas on initially convergent paths undergoes shock compression and dissipation of kinetic energy, producing the filaments in the core of the panel. Gas on initially divergent trajectories can (in the case of this unbound cloud) simply escape in all directions, generating the halo of diffuse gas in the left hand panel.

In the run with the ionising source (located at the middle of the left hand edge of the right hand panel in Figure 3), the gas distribution develops a clear asymmetry. To the right, initially outflowing gas streams freely outwards as before. To the left, however, gas initially flowing outwards has its flow velocity reversed by interaction with the ionising radiation field. When this swept up gas reaches the cloud core (i.e. the region where star formation was proceeding in the control run) it shocks and fragments. It would appear that feedback is triggering some star formation in the cloud (i.e. stars form which are not present in the control run). Analysis of the mass contained in the stars in both simulations shows that, as expected, the stars in the feedback run derive much of their mass from material that was previously outflowing towards the ionisation source. Thus, in a complex environment, these simulations manifest the "collect and collapse" idea first proposed by Elmegreen and Lada 1977 (see also Elmegreen *et al.* 1995 for application of these ideas to a clumpy medium).

Although feedback has triggered some star formation in this case, it turns out to be impossible to find observational diagnostics which distinguish the induced stars from those that would have formed anyway. For example, the two populations are co-spatial since, as noted above, the swept up material only fragments when it encounters dense counter-flowing gas in the core, which is any case the site for star formation. The complexity of the velocity field also removes kinematic signatures of induced star formation, i.e. the net momentum of the gas that fragments following the collision of the swept up gas and turbulent gas in the cluster core can be in either direction. This is because the r.m.s. velocity of the turbulence (a few km s^{-1}) is comparable to that of the swept up gas (which initially attains about 10 km s^{-1} but which is decelerated by mass loading as it ploughs into the cloud core).

The implication of this work is that it is very hard to identify which stars have formed from ionisation induced feedback and that one should therefore be careful about claims in the observational literature about the self-evident hallmarks of triggered star formation.

Finally it is worth asking whether, given that feedback appears to be triggering star formation in this run, one can argue against feedback being the mechanism by which the efficiency of star formation is reduced to observationally acceptable levels? Before discarding the notion that feedback can reduce the star formation efficiency, however, one should stress the fact that this simulation started with an unbound cloud, and so the ionising radiation field played the role of returning material to the cloud core which would otherwise have escaped. It is thus unsurprising that the star formation efficiency is, if anything, enhanced in this case. Further simulations are required in order to discover whether this remains the case if the cloud is bound initially.

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Discussion

DOPITA: A comment and a question: The stellar wind will make an enormous difference to your simulations compared to the photoionization-only simulation. A question: do you include the effect or radiation pressure on grains, which is very important near the stars?

de Gouveia Dal Pino: Just a quick comment (similar to the one made by M. Dopita): C. Melide, A. Raga and I have performed simulations including both the effects of an ionization front and or supersonic winds (or SNR shock fronts) and this later seems to have also relevant influence upon the overall system evolution.

Clarke: These particular simulations involve only ionising radiation feedback, which is already challenging in the context of fully self-gravitating turbulent hydrodynamic simulations. Work is well under way to add the capability to include stellar winds in such simulations. Radiation pressure on dust is of course the dominant feedback mechanism on the scale of individual stars (i.e. on the ∼100 A.U. scale) but is a secondary effect on the cluster scale. Supernova feedback is a potential factor in determining the initial conditions of our star forming clouds but, on the dynamical timescale on which star formation occurs in these simulations, there is of course insufficient time for the stars created in the simulations to undergo supernovae.

Krumholz: Have you tested against the Spitzer similarity solution, and if so, can you reproduce the result to ∼1%.

Clarke: Yes, agreement with the Spitzer solution is excellent. However, this is not the most challenging aspect of these simulations, which is instead the modeling of the thermal structure of the gas in the case that the gas is distributed in converging filaments. Here there are concerns that the SPH path finder can bias one towards denser regions of the flow, an aspect which we are pursuing through detailed comparison with Monte Carlo radiative transfer calculations.