Triggered star formation in a turbulent ISM
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Spiral arm triggering of star formation

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Abstract. We present numerical simulations of the passage of clumpy gas through a galactic spiral shock, the subsequent formation of giant molecular clouds (GMCs) and the triggering of star formation. The spiral shock forms dense clouds while dissipating kinetic energy, producing regions that are locally gravitationally bound and collapse to form stars. In addition to triggering the star formation process, the clumpy gas passing through the shock naturally generates the observed velocity dispersion size relation of molecular clouds. In this scenario, the internal motions of GMCs need not be turbulent in nature. The coupling of the clouds' internal kinematics to their externally triggered formation removes the need for the clouds to be self-gravitating. Globally unbound molecular clouds provides a simple explanation of the low efficiency of star formation. While dense regions in the shock become bound and collapse to form stars, the majority of the gas disperses as it leaves the spiral arm.

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1. Introduction

Star formation has long been known to occur primarily in the spiral arms of disc galaxies (Baade 1963). Spiral arms are denoted by the presence of young stars, HII regions, dust and giant molecular clouds, all signatures of the star formation process (Elmegreen & Elmegreen 1983; Ferguson *et al.* 1998). What is still unclear is the exact role of the spiral arms in inducing the star formation. Is it simply that the higher surface density due to the orbit crossing is sufficient to initiate star formation, as in a Schmidt law, or do the spiral arms play a more active role? Roberts (1969) first suggested that the spiral shock that occurs as the gas flows through the potential minima triggers the star formation process in spiral galaxies. Shock dissipation of excess kinetic energy can result in the formation of bound structures which then collapse to form stars.

Giant molecular clouds (GMCs) are observed to contain highly supersonic motions and a wealth of structure on all length scales (Larson 1981; Blitz & Williams 1999). The supersonic motions are generally thought to be 'turbulent' in nature and to be the cause of the density structure in GMCs (Mac Low & Klessen 2004; Elmegreen & Scalo 2004). We propose an alternative scenario whereby it is the passage of the clumpy interstellar medium through a galactic spiral shock that not only produces the dense environment in which molecular clouds form (Cowie 1981; Elmegreen 1991), but also gives rise at the same time to their supersonic internal motions (Bonnell *et al.* 2006).

2. Global Simulations

Recent global simulations of non-self gravitating gas dynamics in spiral galaxies (Dobbs, Bonnell & Pringle 2006) show that the spiral shocks can account for the formation of molecular gas from cold ($T \lesssim 100$ K) atomic gas and generate the large scale distribution of molecular clouds in spiral arms. Structures in the spiral arms arise due to the shocks that tend to gather material together on converging orbits. Thus, structures grow in time

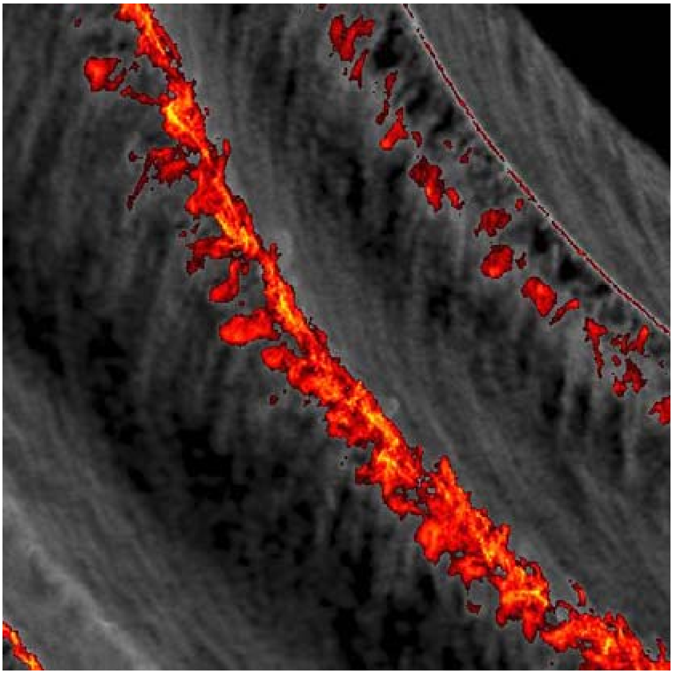

Figure 1. The formation of molecular clouds is shown as the gas passes through a spiral shock (Dobbs *et al.* 2006). Note the spurs and feathering that appear as the dense clumps are sheared away upon leaving the spiral arm.

through multiple spiral arm passages. These structures present in the spiral arms are also found to form the spurs and feathering in the interarm region as they are sheared by the divergent orbits when leaving the spiral arms (Dobbs & Bonnell 2006a). The high gas densities that result from the high Mach number shocks are sufficient for rapid formation of H_2 gas and thus of giant molecular clouds. If, in contrast, the gas is warm ($T \geqslant 1000$ K) when it enters the shock, then H_2 formation cannot occur due to the lower gas densities in the shock. In this model, molecular clouds are limited to spiral arms as it is only there that the gas is sufficiently dense to form molecules. These clouds need not be self-gravitating as their formation is independent of self-gravity. The velocity dispersion in the gas also undergoes periodic bursts during the spiral arm passage as the clumpy shock drives supersonic random motions into the gas (see below). Such bursts in the internal gas motions are likely to be observable and would give support for a spiral shock origin of giant molecular clouds and the triggering of star formation.

3. Triggering of Star Formation in the Spiral Shock

In simulations where self-gravity is included, the passage of gas through a spiral shock can result in the triggering of star formation (Bonnell *et al.* 2006). The evolution, over 34 million years, of 10^6 M$_\odot$ of gas passing through the spiral potential is shown in Figure 3. The initially clumpy, low density gas ($\rho \approx 0.01$ M$_\odot$pc^{-3}) is compressed by the spiral shock as it leaves the minimum of the potential. The shock forms some very dense ($> 10^3$ M$_\odot$pc^{-3}) regions, which become gravitationally bound and thus collapse to form regions of star formation. Further accretion onto these regions, modeled with sink-particles in SPH (Bate *et al.* 1995), raises their masses to that of typical stellar clusters (10^2 to 10^4 M$_\odot$). Star formation occurs within 2×10^6 years after molecular cloud densities are

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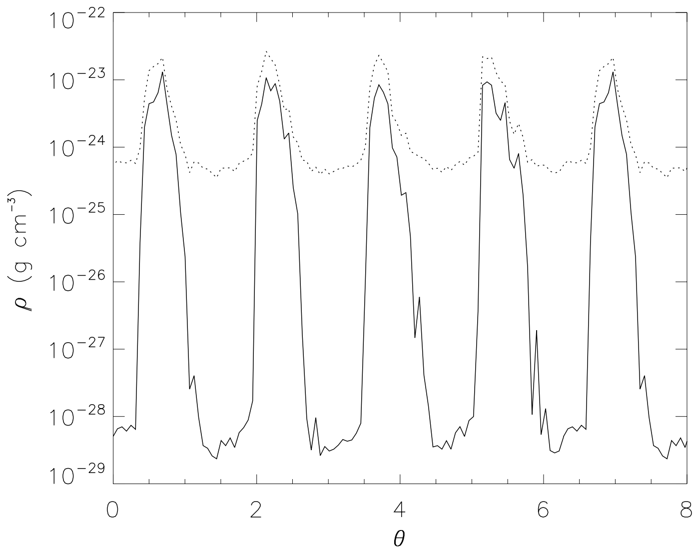

Figure 2. The total gas (dotted) and H_2 (solid) gas densities are plotted against azimuth for an annulus at 5 kpc. The gas is averaged over cells of 50 pc in size (from Dobbs *et al.* 2006). Molecular gas is almost exclusively contained.

reached. The total spiral arm passage lasts for $\approx 2 \times 10^7$ years. The gas remains globally unbound throughout the simulation and re-expands in the post-shock region. The star formation efficiency is of order 10 % and should be taken as an upper limit in the absence of any form of stellar feedback.

The star forming clouds that form in the spiral shocks are generally unbound and thus disperse once they leave the spiral arm. Numerical simulations of unbound clouds (Clark & Bonnell 2004; Clark *et al.* 2005) have recently shown that they can form local subregions which are gravitationally unstable and thus form stars. In contrast, the bulk of the cloud does not become bound and thus disperses without entering into the star formation process. The resultant star formation efficiencies are of order 10 per cent, even without the presence of the divergent flows of gas leaving a spiral arm. In fact, arbitrarily low star formation efficiencies are possible with relatively small deviations from bound conditions. This then offers a simple physical mechanism to explain the low star formation efficiency in our Galaxy.

3.1. *The Generation of the Internal Velocity Dispersion*

In addition to triggering star formation, we must be able to explain the origin of the internal velocity dispersion and how it depends on the size of the region considered (Larson 1981; Heyer & Brunt 2004). The evolution of the velocity dispersion as a function of the size of the region considered is shown in Figure 4 (from Bonnell *et al.* 2006). The initially low velocity dispersion, of order the sound speed $v_s \approx 0.6$ km/s, increases as the gas passes through the spiral shock. At the same time, the velocity dispersion increases more on larger scales, producing a $v_{\rm disp} \propto R^{0.5}$ velocity dispersion size-scale relation. The basic idea is that when structure exists in the pre-shocked gas, the stopping point of a particular clump depends on the density of gas with which it interacts. Thus some regions will penetrate further into the shock, broadening it and leaving it with a remnant velocity dispersion in the shock direction. Smaller scale regions in the shock are likely to have

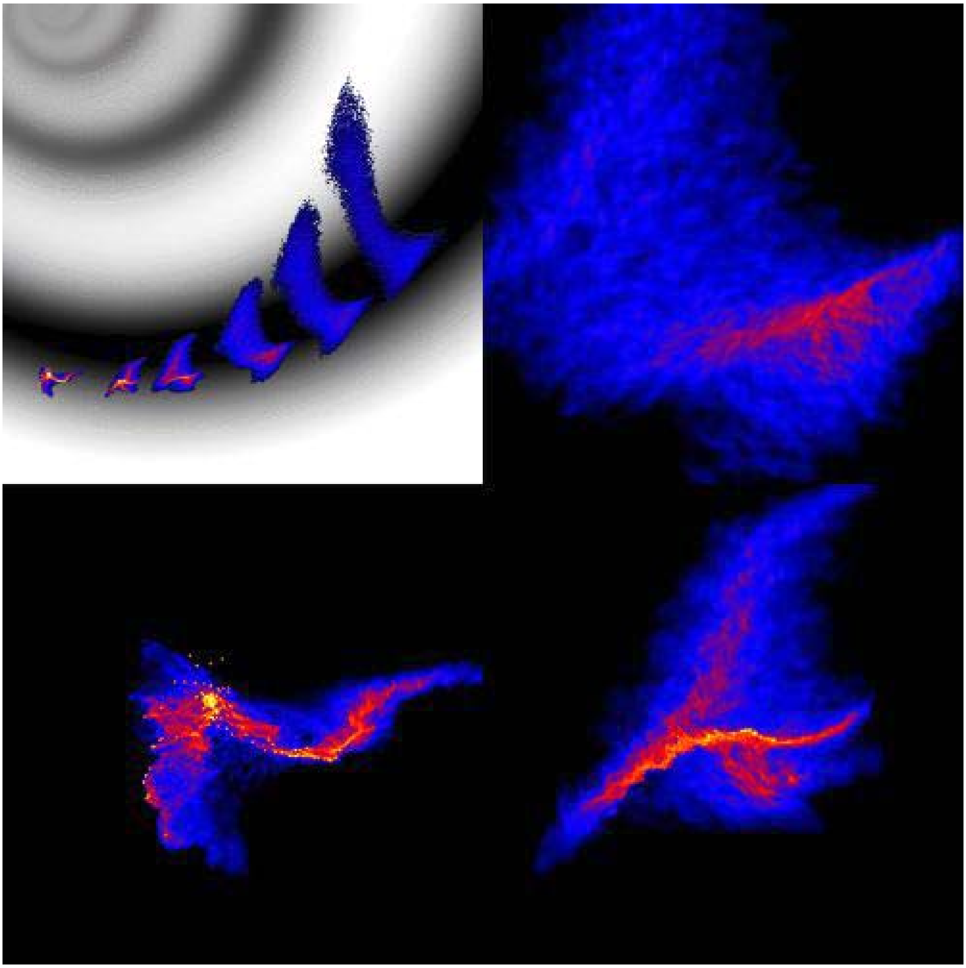

Figure 3. The evolution of cold interstellar gas through a spiral arm is shown relative to the spiral potential of the galaxy (upper left-panel). The minimum of the spiral potential is shown as black and the overall galactic potential is not shown for clarity. The 3 additional panels, arranged clockwise, show close-ups of the gas as it is compressed in the shock and subregions become self-gravitating. Gravitational collapse and star formation occurs within 2×10^6 years of the gas reaching molecular cloud densities. The cloud produces stars inefficiently as the gas is not globally bound.

more uniform momentum injection as well as encountering similar amounts of mass. This then results in small velocity dispersions. Larger regions will have less correlation in both the momentum injection and mass loading such that there will be a larger dispersion in the post-shock velocity. Any clumpy shock can induce such velocity dispersions. Thus the fractal nature of the ISM passing through a spiral shock is a straightforward explanation for how the velocity dispersion size relation arises in molecular clouds (Dobbs & Bonnell 2006b).

3.2. *The clump-mass spectrum*

Clumpy shocks may also be an important role in setting the clump-mass spectrum. Numerical simulations of colliding clumpy flows show that from an initial population of identical clumps, the shocked gas contains a spectrum of clump masses that is consistent

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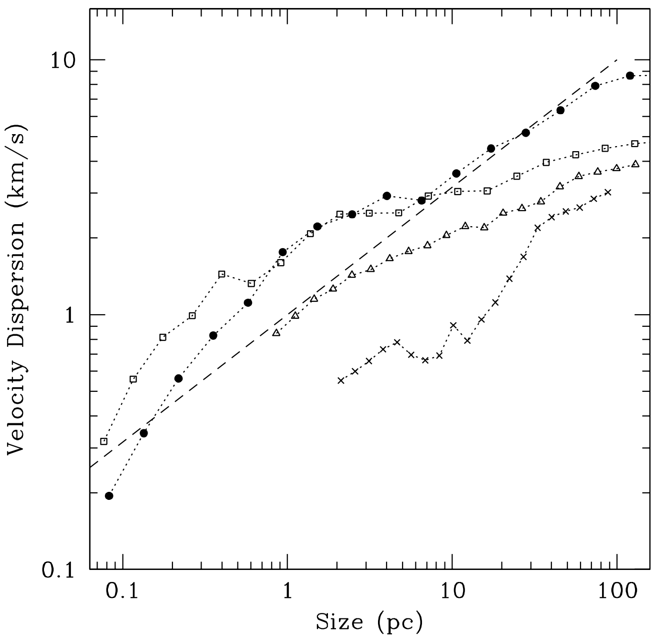

Figure 4. The velocity dispersion is plotted as a function of size at 5 different times during the passage of the gas through a spiral shock. The velocity dispersion is plotted at 4.2, 14, 18, 23, and 27×10^6 years after the start of the simulation. Star formation is initiated at $\approx 23 \times 10^6$ years. The dashed line indicates the Larson relation for molecular clouds where $\sigma \propto R^{-1/2}$ (Larson 1981; Heyer & Brunt 2004).

with a Salpeter-like slope (Clark & Bonnell 2006). This clump mass spectrum arises due to the coagulation and fragmentation of the clumps in the shock, and is very similar to that observed in dense prestellar cores (Motte *et al.* 1998). The relation between this clump-mass spectrum and the stellar IMF is unclear as it arises independently of self-gravity and thus a one-to-one mapping of clump to stellar masses is unlikely. Instead, the produced clumps are likely to be a combination of unbound clumps that will not form stars and clumps that are very bound that will form multiple many stars.

4. Conclusions

The triggering of star formation by the passage of clumpy gas through a spiral arm can explain many of the observed properties of star forming regions. Molecular cloud formation occurs as long as the pre-shock gas is cold ($T \lesssim 100$ K). The shock forms dense structures in the gas which become locally bound and collapse to form stars. The clouds are globally unbound and thus disperse on timescales of 10^7 years, resulting in relatively low star formation efficiencies. In addition, the clumpy shock reproduces the observed kinematics of GMCs, the so-called 'Larson' relation. There is no need for any internal driving of the quasi-turbulent random motions. The internal structure of GMCs can also be understood as being a product of a clumpy shock and even the observed clump-mass spectrum in pre-stellar cores is reproduced. Finally, the clouds are sheared upon leaving the spiral arms, producing the spurs and feathering commonly observed in spiral galaxies.

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Discussion

PADOAN: Can you explain what you mean when you say that the motions set up by spiral waves do not generate turbulence? How can you avoid the cloud being turbulent once they are given a velocity dispersion by whatever mechanism?

BONNELL: At present there is no evidence of a turbulent cascade in the simulations but that instead the velocity dispersion is driven at all scales simultaneously. This is not to say that turbulence will not develop in real shocks but just that it is not in the simulations even though the primary kinetic property, the velocity - size scale relation, is attained.

VAZQUEZ-SEMADENI: One question and two comments. Question: In your clumpy simulations, are the clumps at the same temperature as the interclump medium? If so, they are overpressured, and should be dispersing, no? Comment 1: My impression is that the clumpiness you introduce is a substitute, in your isothermal assumption, of the softer than isothermal (even thermally bistable) actual behavior of the clouds. Comment 2: The isothermal assumption may be responsible for several of the effects you observe, in particular the unboundedness of the clouds (cooler clouds would be more bound) and of the very low vorticity of the flow: in the isothermal (or, in general, barotropic) flow, the baroclinic term, $\nabla P \times \nabla \rho$, which is an important source of vorticity, is forced to be zero.

BONNELL: In the single-phase simulations the clumps are unbounded and free to expand. They do so somewhat reducing the gas densities before entering the shock. The isothermal equation of state is an oversimplification of the physics but should not affect the boundedness of the clumps as this is primarily determined by the kinetic energy. I do agree that cooling will help introduce the types of structures we assume in our initial conditions.

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Block: A general question on longevity of the feathers, with particular application to NGC 2841 (e.g., Block & Elmegreen, Nature) which is optically flocculent with dense grand-design arms of dust observed at 2.1 μm.

Bonnell: The feathering, which develops in the interarm regions due to the shearing of the spurs, appears to last most of the way through the interarm region for a timescale of several 10's of Myrs.

E. Ostriker: I am concerned that in your global isothermal models, the pressure is too low by two orders of magnitude, and that as a consequence your spiral shocks are too strong, leading to unphysical clumping (without self-gravity).

Bonnell: In order to get H_2 formation, a gas temperature of 100K is required in our isothermal simulation. This implies that for these models to be correct requires the presence of cold HI gas or sufficiently fast cooling of the gas as it enters the shock (as reported by Glover & Mac Low 2006).