Are turbulent spheres suitable initial conditions for star-forming clouds?

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September 2014

ABSTRACT
To date, most numerical simulations of molecular clouds, and star formation within them, assume a uniform density sphere or box with an imposed turbulent velocity field. In this work, we select molecular clouds from galactic scale simulations as initial conditions, increase their resolution, and re-simulate them using the SPH code Gadget2. Our approach provides clouds with morphologies, internal structures, and kinematics that constitute more consistent and realistic initial conditions for simulations of star formation. We perform comparisons between molecular clouds derived from a galactic simulation, and spheres of turbulent gas of similar dimensions, mass and velocity dispersion. We focus on properties of the clouds such as their density, velocity structure and star formation rate. We find that the inherited velocity structure of the galactic clouds has a significant impact on the star formation rate and evolution of the cloud. Our results indicate that, although we can follow the time evolution of star formation in any simulated cloud, capturing the entire history is difficult as we ignore any star formation that might have occurred before initialisation. Overall, the turbulent spheres do not match the complexity of the galactic clouds.

Key words: galaxies: star formation – ISM: clouds – hydrodynamics – turbulence – gravitation

1 INTRODUCTION
One of the limitations of simulating star formation in molecular clouds is the choice of initial conditions. If excluding entirely arbitrary conditions, this leaves a limited number of geometries. Many studies assume a uniform sphere (e.g. Bate et al. 2002; Clark & Bonnell 2006; Bate 2009; Clark et al. 2011; Girichidis et al. 2011; Federrath et al. 2014), or a periodic box (e.g. Gammie & Ostriker 1996; Offner et al. 2009; Padoan & Nordlund 2011; Federrath & Klessen 2012; Myers et al. 2013) as initial setups. Other studies use colliding flows as an attempt to model the large-scale origin of molecular clouds (e.g. Heitsch et al. 2006; Vázquez-Semadeni et al. 2006; Hennebelle et al. 2008; Banerjee et al. 2009; Ntormousi et al. 2011; Clark et al. 2012; Walch et al. 2012) model clouds as fractal structures, although their main focus is on examining the propagation of HII regions into structured clouds (see also Gritschner et al. 2009). Most simulations adopt an imposed turbulent velocity field to model the dynamics of the inter-stellar medium (ISM).

With all these approaches, there are concerns about how the initial conditions affect the results, such as the evolution of the cloud, the resulting density and velocity structure and the star formation rate. One alternative way to select initial conditions is to use clouds extracted from full-scale galaxy simulations. This is the approach we take in this Letter, where we extract clouds from Dobbs & Pringle (2013), and Dobbs 2014 (submitted). Because these clouds in the galactic simulations have a limited number of particles, we resimulate the extracted clouds with higher resolution. We compare our results to the more typical approach of simulating an initially uniform sphere subject to a turbulent velocity field. Our Letter is organised as follows: In Section 2 we briefly explain the details of simulations. In Section 3 we discuss the density structure and star formation rate in both the galactic clouds and the turbulent spheres. Finally, in Section 4 we summarise our main findings.

2 DETAILS OF SIMULATIONS
Our starting ground is the galaxy simulation described in Dobbs & Pringle (2013) and shown in Figure 1. This simulation includes self gravity, ISM cooling and heating...
and stellar feedback. The particle mass in the galaxy simulation is 312.5 $M_\odot$, and the giant molecular clouds (GMCs) contain $\sim 10^4$ particles. We extract these clouds by selecting a box of gas ($L \sim 100$ pc) which includes the cloud, and increase the resolution by a factor of $N$. To do so, we split each particle $N$ times, distributing $N-1$ new particles according to the SPH kernel (as shown on the bottom left box in Figure 1). The velocities are kept the same as the original particle, to conserve energy and momentum. Although observed clouds are very cold, $T \sim 10$ K, we performed isothermal simulations with 50 K which ensures that the Jeans mass is well resolved $\text{Bate} \& \text{Burkert} \ (1997)$, (see also $\text{Federrath} \text{et al.} \ (2011, 2014)$ for more recent studies). We also ran simulations with 20 K though (not shown), which gave similar overall results.

In Figure 1 we show the galactic simulation at 250 Myr from which we have selected two clouds, one inside a spiral arm (Cloud A), and the other in an inter-arm region (Cloud B), both with an approximate radius of 100 pc. We show these two clouds in the two onsets of Figure 1, with the original and increased resolution. To compare these models, we have created two turbulent spheres of 100 pc radius (Spheres A and B), with similar virial parameters (as defined in $\text{Dobbs et al.} \ (2011)$) to Clouds A and B ($\alpha \sim 1$ and $\alpha \sim 2$ respectively). The two clouds are both found to exhibit a velocity dispersion relation of $\sigma \propto r^{1/2}$ (in accordance with observed and other simulated clouds, e.g. $\text{Roman-Duval et al.} \ (2011)$ $\text{Federrath et al.} \ (2011)$), so we set up the spheres with a velocity power spectrum of $P \propto k^{-4}$ to give a similar scaling relation $\text{Myers} \& \text{Gammie} \ (1999)$. The masses and amplitudes of the velocities are scaled to give similar kinetic and gravitational energies and virial parameters to Clouds A and B.

We take Clouds A and B from a snapshot of the galactic simulation and although the original galactic simulation included the prior evolution of these clouds, it did not contain sink particles, or follow star formation in detail. We traced back the gas in Cloud A to a time of 240 Myr in order to follow the preceding stages of Cloud A’s evolution when the gas was less gravitationally bound (we call this model Early A). Lastly we wanted to test if the method of extracting galactic clouds is robust, given the large increase in resolution. Hence, we have selected a cloud in a spiral arm taken from a simulation by Dobbs 2014 (submitted), which models gas going through a spiral arm with a particle mass of 3.85 $M_\odot$ (Cloud C). For Cloud C, we only increase the resolution by a factor of $N = 30$. The main parameters of all the clouds are summarised in Table 1.

We follow the evolution of the clouds using the SPH code Gadget2 $\text{(Springel} \ (2005)$). Our simulations are isothermal with a temperature of 50 K. We include sink particles similar to $\text{Bate et al.} \ (1995)$ at densities of $\rho_{\text{sink}} = 1.6 \times 10^4$ cm$^{-3}$ with a sink radius $r_{\text{sink}} = 0.1$ pc using the implementation in $\text{Clark et al.} \ (2008)$ (based on $\text{Jappsen et al.} \ (2005)$). We run simulations of the GMCs for 16 Myr and the spheres for 24 Myr, which corresponds to at least 3 free fall times for all of the clouds. We do not include the galactic potential in our simulations (as described in $\text{Dobbs et al.} \ (2006)$). We tested its impact on Early A, the biggest cloud, with little effect: the rotational period of the galaxy ($\sim 220$ Myr) is much greater than the simulation time of our clouds, and the clouds do not traverse between the spiral arms and interarm regions in any of our calculations. The effect of both feedback and cooling are not included but will be investigated in future work.

### Table 1. Mass, radius, velocity dispersion, virial parameter and number of particles of each simulated cloud.

| Cloud        | Mass ($M_\odot$) | R (pc) | $\sigma$ (km/s) | $\alpha$ | Part # |
|--------------|------------------|-------|-----------------|----------|--------|
| Cloud A      | $4.3 \times 10^6$ | 100   | 8.75            | 2.07     | $9.6 \times 10^6$ |
| Sphere A     | $3.0 \times 10^6$ | 100   | 7.60            | 2.24     | $1.00 \times 10^7$ |
| Cloud B      | $2.6 \times 10^6$ | 100   | 5.17            | 1.18     | $1.01 \times 10^7$ |
| Sphere B     | $3.6 \times 10^6$ | 100   | 6.08            | 1.19     | $1.00 \times 10^7$ |
| Cloud C      | $1.4 \times 10^6$ | 100   | 7.80            | 5.02     | $1.09 \times 10^7$ |
| Early A      | $6.1 \times 10^6$ | 200   | 11.48           | 5.01     | $1.07 \times 10^7$ |

3 COMPARING THE EVOLUTION OF THE GALACTIC CLOUDS WITH THE TURBULENT SPHERES

We show the column density plots of the six clouds 5 Myr after the first star is formed in Figure 2 (except for Early A). In the galactic simulation Early A evolves into Cloud A after 10 Myr. Therefore, in Figure 2 we show Early A at 15 Myr, to compare it with Cloud A at 5 Myr. All clouds show a complex filamentary network and are highly structured, whether using the initial conditions from the galaxy, or the
Modelling molecular clouds from galactic simulations

Figure 2. Column density plots of the clouds 5 Myr after the first star is formed are shown except for Early A (which is shown at 15 Myr to compare it with Cloud A). The sink particles are represented by black dots. The galactic clouds show a variety of density configurations, with Cloud A showing a rather complex network of filaments, Cloud B and Early A being dominated by one main long dense filament, and Cloud C appearing as rather diffuse and barely substructured cloud. Sphere A and B are dominated by two dense filaments that coalesce in the centre of the cloud.

In Figure 3 we show the density PDF (Probability Density Function, see Vázquez-Semadeni (1994); Federrath et al. (2008)) for all the clouds. The PDFs show good agreement between the spheres and galactic GMCs. All PDFs are similar, except for Cloud C, which stands out for containing significantly less dense gas when compared to the other clouds. In the beginning of the simulation, the PDFs for the turbulent spheres are obviously narrower in comparison to the rest of the GMCs.

In Figure 3 we show the star formation rate defined as \( \text{SFR}(t) = \dot{M}_{\star}(t) \), where \( \dot{M}_{\star}(t) \) is the time derivative of the mass contained in sinks. We have used a timestep of 0.1 Myr. In the top panel we show the SFR of the galactic clouds. The star formation process is similar for A, B and Early A, starting almost from initialisation, as these clouds already have overdense regions. Once the initial star formation burst is over, the SFR decreases during the remainder of the simulation because there is less gas...
available (as it has been accreted by the sinks). For Cloud C, the star formation rate behaves differently - it increases slowly, and is significantly lower than the other clouds during most part of the simulation. On the bottom panel we show the SFR for clouds and spheres A and B. We have set the origin of time when the first sink is formed. The spheres need 6 - 7 Myr to create the first sink, and another 4 - 5 Myr to reach the peak of the SFR. At later times the SFRs are very similar for both the GMCs and the spheres. The total star formation efficiencies we obtain for all cases are high (~ 50%) compared with the observed ~ 5% (e.g. Bigiel et al. 2008; Evans et al. 2009). However, we have not included magnetic fields or feedback processes which likely reduce the efficiencies to similar values of other simulations in the literature ~ 10 – 20% (e.g. Price & Bate 2009; Dobbs et al. 2011; Federrath & Klessen 2012, 2013; Dale et al. 2014).

The global evolution of Cloud C is substantially different to the other clouds. We suspected this was a consequence of the large scale velocity field. We include a velocity map of Cloud C, Early A and Sphere B, 5 Myr after the first sink is created in Figure 3. For Sphere B, the velocity field mainly traces the gravitational collapse in the main filaments where star formation happens. The velocity field for Early A shows stronger rotation, but there is still convergence in the centre where stars are forming. Cloud C has also a peculiar velocity field also inherited from the galactic simulation. It has a strong pair of divergent flows in the northern and southern regions, which results in the disruption of the cloud, inhibiting star formation. To check whether the difference between Cloud C and the other examples was linked to how much we increase the resolution, we also selected another cloud from the spiral arm simulation of Dobbs 2014 (submitted). The SFR in this last example (not shown in Figure 3) was higher, and comparable to the other simulations. This confirms that the shear flows in Figure 3 are responsible for the difference in star formation rate for Cloud C. The effects of the different velocity fields are clearer when visualising the evolution of the clouds and spheres in a movie.

4 CONCLUSIONS

In this letter we performed numerical simulations of clouds that have been extracted from galactic simulations. We selected four clouds and modelled two turbulent spheres that resemble two of the galactic clouds. We explored the differences and similarities of using turbulent spheres and GMCs as initial conditions to model the star formation process. The main advantage of the GMCs compared to the turbulent spheres is that they provide a wider variety of morphologies and velocity structures which influence the clouds’ evolution and properties.

There are some clear similarities between the simulated GMCs and turbulent spheres, namely their PDFs and star formation rates or efficiencies. Although the initial PDFs of the spheres are narrower, they eventually become comparable to most of the GMCs at late times. The spheres also have comparable SFRs once they have evolved and formed dense areas able to produce stars. However the GMCs can evolve to show quite different behaviour from each other, and the spheres, dependent on their initial conditions. The velocity field from larger (galactic) scales affects the morphology, kinematics and can effect the star formation in those clouds. The influence of the inherited properties appears to have a greater impact on star formation than the virial parameter of the clouds. For instance, Cloud C and Early A have similar virial parameters, but the star formation rate of Early A is more comparable to the other models, whereas in Cloud C it is inhibited by the inherited shear flows. In essence, the spheres tend to be dominated by gravitational infall, whereas for the GMCs the large scale velocity field can be equally important. Our conclusions are in agreement with Federrath & Klessen (2012). They find that the compressive and solenoidal components of a turbulent velocity field (quantified by the mode mixture parameter $b$) have a large impact on star formation. This constitutes the main advantage of the GMCs, as creating such different environments which would be difficult to reproduce with turbulent spheres.

Another advantage with respect to turbulent spheres is that as well as modelling clouds in different environments (for example arm and inter-arm regions), we can also study different stages of their evolution. We found that Cloud A and Early A, which should be the same cloud, have different morphologies due to following sink particle creation in Early A. Our results are somewhat extreme, as we do not include feedback and the star formation rate in Early A is far too high. However this highlights that likely all simulations of isolated clouds will miss a previous star formation history. This problem can perhaps be lessened when using galactic simulations and tracing clouds back to earlier stages.
Figure 5. Projected velocity field (in white arrows) superposed on the column density maps for three studied clouds 5 Myr, after the first star is formed. In the sphere, the velocity field follows the direction of the gravitational collapse, and the highest velocities are in the vicinity of a filament. For Early A and Cloud C the velocities inherited from the galactic simulations are more important than those arising from the gravitational collapse (except in the densest areas). The shear flows that inhibit star formation in Cloud C are patent.

5 ACKNOWLEDGEMENTS

We thank an anonymous referee for suggestions which helped improve the paper, and Paul Clark for comments on an earlier draft. The calculations for this paper were performed on the University of Exeter Supercomputer, a DiRAC Facility jointly funded by STFC, the Large Facilities Capital Fund of BIS, and the University of Exeter. RRR, CLD and ADC acknowledge funding from the European Research Council for the FP7 ERC starting grant project LOCALSTAR. Fig. 1, Fig. 2 and Fig. 5 were produced using SPLASH (Price 2007).

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