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Formation of Star-Forming Clouds from the Magnetised, Diffuse Interstellar Medium

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Molecular clouds, the birthplaces of stars in galaxies, form dynamically from the diffuse atomic gas of the interstellar medium (ISM). The ISM is also threaded by magnetic fields which have a large impact on its dynamics. In particular, star forming regions must be magnetically *super-critical* in order to accommodate gas clumps which can collapse under their own weight. Based on a parameter study of three dimensional magneto-hydrodynamical (MHD) simulations, we show that the long-standing problem of how such supercritical regions are generated is still an open issue.

1 Introduction

Present day stars form within the densest regions of molecular clouds (MCs) and giant molecular clouds (GMCs), in gravitationally unstable cores and clumps. Our common understanding is that those MCs and GMCs form from the diffuse, atomic (HI) gas within timescales of less than 10 Myr^1 . The generation of filaments and substructures within GMCs is primarily controlled by magnetic fields and turbulence⁴. In particular, magnetic fields are an elemental part of the interstellar medium^{5,6} which have a large impact on the dynamics of the ISM on various spatial scales⁷ as the magnetic energy density is comparable to the thermal energy density of the ISM⁸.

One long-standing issue is the formation of supercritical clumps and cores. Similarly to thermal pressure, magnetic fields prevent contraction of otherwise (thermally) self-gravitating gas clumps if the magnetic fields are strong enough. Therefore, gaseous overdensities must be magnetically *supercritical*, quantified by the mass-to-flux ratio, μ , to collapse and to subsequently allow the formation of stars.

Already in 1956, Mestel & Spitzer realised that molecular clouds should be magnetically *subcritical* assuming field strengths that correspond to the equipartition of magnetic and kinetic energy density within the ISM⁹. To generate supercritical cloud cores out of those subcritical conditions, they suggested that the non-perfect coupling between charged particles and neutrals, i.e. the ambipolar diffusion (AD) drift, could locally increase the mass-to-flux ratio which allows the cloud to break up and to form stars. For a long time this was the standard theory of star formation out of the magnetised ISM^{2,10}. In this fairly static “standard model” of magnetically-supported, AD-mediated supercritical cores, low-mass stars would form by the slow gravitational contraction of isolated cores containing a very small fraction of the clouds’ mass. This picture would also account for the very low observed global star formation efficiency (SFE) of giant molecular clouds^{11,12}. The slow contraction results from the typical timescale for ambipolar diffusion, t_{AD} , which is an order of magnitude larger than the free-fall time, t_{ff} , of individual cloud cores (their ratio is about $t_{AD}/t_{ff} \approx 10(x_e/10^{-7})$, where x_e is the ionisation fraction). On the

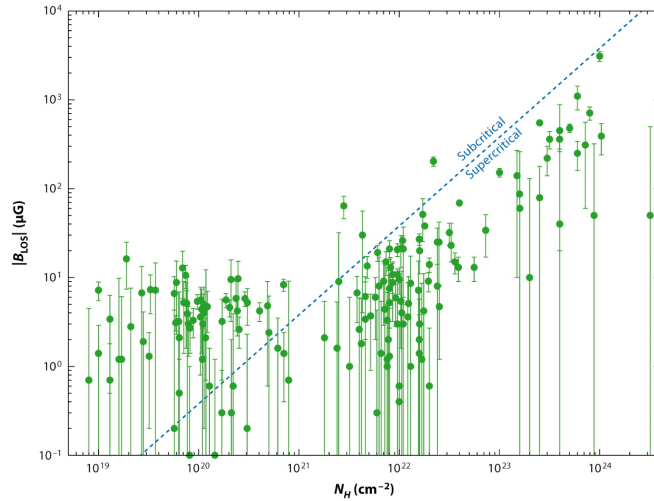


Figure 1. These observational data summarise the main motivation for our proposed study: How do subcritical (HI) clouds become supercritical (H₂) clouds? Our previous studies have shown that it is everything but trivial to build up supercritical clouds out of the magnetised interstellar medium, because the mass-to-flux ratio is fairly well conserved, even in the presence of ambipolar diffusion and enhanced non-ideal MHD setups^{26,27}. [From Crutcher (2012)⁵].

other hand, rather recent observations by Crutcher (2009)¹³ of individual cloud cores including Zeeman measurements to determine their magnetic field distribution indicate that idealised models of ambipolar-diffusion driven star formation are unlikely to be operative. In idealised models with ordered background magnetic fields, efficient ambipolar diffusion would lead to a local increase of the mass-to-flux ratio towards the centre of cloud cores which is not seen in their observed sample¹³ (but see also Bertram *et al.* (2012)¹⁴ on the difficulty to interpret those observations).

However, present-day models of star formation also account for the fact that molecular clouds are also pervaded by supersonic random motions, i.e. turbulence^{15,16}. Eventually, this resulted in a paradigm shift of the theory of star formation where magnetic fields only play a minor role and supersonic, super-Alfvénic turbulence controls the star formation efficiency within molecular clouds^{3,17}. As a consequence, the magnetic fields are expected to be highly disordered rather than being an ordered background field. Hence, idealised models of ambipolar diffusion drift should not apply¹⁸. Additionally, the AD characteristic timescale is expected to decrease in this case^{19,20} and other diffusive effects like turbulent reconnection might be operative²². Indeed, a number of studies have suggested that both MCs²³ and their clumps^{24,25} are close to being magnetically critical, with a moderate preference for being supercritical. Moreover, recent compilations of observational data show that cloud cores and clumps with column densities of $N \gtrsim 2 \times 10^{21} \text{ cm}^{-2}$ are essentially *all* supercritical (see Fig. 1).

Whether those supercritical cloud cores and clumps are the result of ambipolar diffusion together with random motions in the ISM is far from being certain and has to be investigated further. For instance, recently Heitsch & Hartmann (2014)²⁸ argued in their

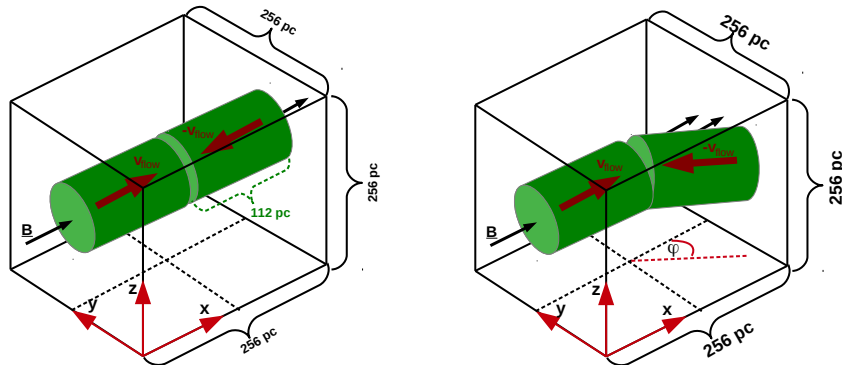


Figure 2. Setup of the initial conditions. *Left*: The well studied head-on collision where both flows are in the direction of the background magnetic field. *Right*: Flows with an inclination angle with respect to the background magnetic field. This setup resembles the impact of external driving of such flows (e.g. driving by SN blast waves). [From Körtgen & Banerjee (2015)²⁷].

parameter study that ambipolar diffusion in concert with turbulence is unlikely to control the formation of supercritical cores and hence star formation. They again propose an alternative scenario where large scale flows are the main driver to generate supercritical cores. This idea, where supercritical clouds could be assembled from large scale flows was already discussed in Mestel & Spitzer (1956)⁹ as an alternative to the AD-mediated scenario and to avoid the “magnetic flux problem”. But only in combination with supersonic turbulence this scenario becomes more feasible because gravitational fragmentation could be suppressed during the assembly of the clouds by those turbulent motions²⁹. This accumulation idea would also support a number of recent observations which show that magnetic fields are dynamically important on all scales in the Milky Way and other spiral galaxies^{30,7}. This is particularly evident from Fig. 1: The low column density HI gas is magnetically *subcritical*, whereas clouds which exceed columns of $N \gtrsim 2 \times 10^{21} \text{ cm}^{-2}$ are magnetically *supercritical*.

In the presented numerical parameter study, we investigated the possibility of diffusion mediated generation of *supercritical* clouds showing that it is unlikely that such unstable clouds can be built up from *subcritical* HI-clouds.

2 Numerical Method and Initial Conditions

For these studies we used the FLASH adaptive mesh refinement (AMR) code³¹. In addition to the basic ideal MHD equations (for which we employ the Bouchut solver^{33,34}) we also used the *ambipolar diffusion* module developed by Duffin & Pudritz (2008)³⁵. Additionally, self-gravity as well as heating and cooling processes were included in those simulations. For the latter, we followed the treatment by Koyama & Inutsuka (2002)³⁶ (an analytic simplification of their detailed calculation in Refs. 37,39). To capture the build-up of self-gravitating cores within the molecular clouds we used *sink particles*⁴⁰ in addition to the Jeans refinement criterion (i.e. the Truelove criterion⁴¹). In particular the detailed

sink particle approach allows us to unambiguously identify supercritical, collapsing regions which are important for our studies quantifying the star formation ability from the magnetised ISM.

Our initial setups for those studies are similar to the ones described in Refs. 38, 39 (see also Fig. 2) where the build-up of molecular clouds is modelled by the collision of cylindrical streams of warm neutral HI gas (WNM). Each flow is $l = 112$ pc long and has a radius of $r = 64$ pc. The bulk flows are slightly supersonic with typical Mach numbers of $\mathcal{M}_f = 2$. On top of those bulk motions, a turbulent velocity field is superimposed which triggers initial instabilities like the non-linear thin-shell instability (NTSI)⁴² and subsequently leads to fragmentation of the cloud. The initially uniform magnetic field has a strength of $B = \{3, 4, 5\}$ μG corresponding to mass-to-flux ratios of $\mu/\mu_{crit} \approx 1, 0.7, 0.6$ if the critical value $\mu_{crit} \approx 0.13/\sqrt{G}$ is applied⁴³.

Furthermore, we also studied the impact of an oblique angle of the flows with respect to the background magnetic field (see right panel of Fig. 2). Those oblique flows are more realistic than the head-on flows and could be generated, for instance, by supernova shock waves and by the gravitational potential of spiral arms. The motion of the flow at an inclination with respect to the magnetic field results in enhanced magnetic diffusivity (by numerical diffusion^{44,45}). Again, those flows resemble streams of the WNM in a thermally bistable configuration⁴⁶. The flows are studied with different oblique angles, which are varied from 10° to 60° , different initial magnetic fields strengths and different strength of the initial turbulence ranging from subsonic to supersonic velocity fluctuations. For details on the numerical setup and our initial conditions see Körtgen & Banerjee (2015)²⁷.

3 Results

As can be seen from Fig. 3, the different initial field strengths have significant implications for the resulting dynamical behaviour of the molecular cloud. The main difference comes about in efficiency to form stars (or not). In the case of a rather weak background field of $3 \mu\text{G}$ supercritical star forming clumps can be generated whereas in the case of a slightly stronger, but more realistic, magnetic field star formation is fully suppressed. Note that, due to the oblique flows with an angle of 60° the effective mass-to-flux ratios are 0.73 in the $3 \mu\text{G}$ case and 0.44 in the $5 \mu\text{G}$ case. That means that both cases are initially subcritical, but only in the cases of the weak magnetic field locally supercritical clumps are assembled due to sufficient flux loss.

An interesting point is also the field morphology. In the weak magnetic field case the field structure in the dense regions is clearly separated from the large scale magnetic field, whereas in the strong field case the field morphology is almost unaffected compared to the initial configuration (see the blue stream lines of Fig. 3). From an observational point of view, the field structure and its dynamical importance within molecular clouds is still debated. On the one hand, some multi-scale polarisation data indicate that magnetic fields in GMCs are essentially just dragged in from larger scales and are dynamically important^{7,30}. On the other hand, Zeeman measurements of individual cloud cores together with analyses of numerical simulations indicate rather weak fields that might not be dynamically important^{13,47}. With our subsequent studies on cloud formation on cloud scales including a more detailed modelling of ambipolar diffusion we hope to clarify this issue.

In Fig. 4 we quantify the main results by means of histograms in the N - B -plane from

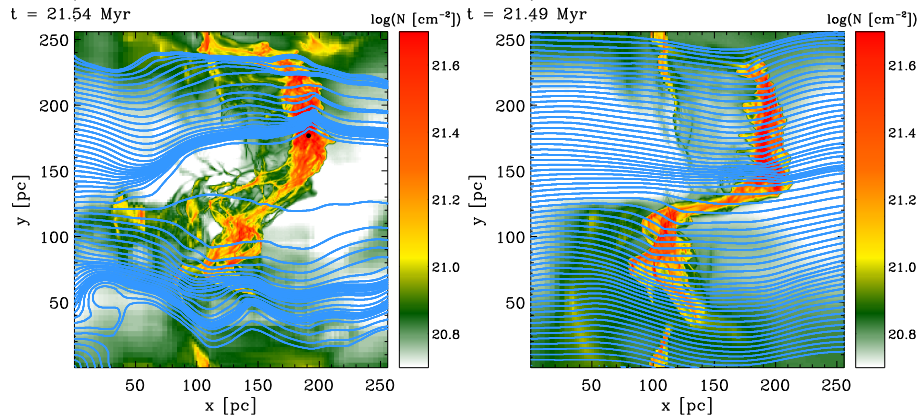


Figure 3. Results from colliding flow simulations investigating the formation of molecular clouds. Here, the flows collide with an oblique angle of 60° . *Left panel*: The weak field case ($3 \mu\text{G}$). The *Right panel* shows the same situations in the case of a stronger background magnetic field of $5 \mu\text{G}$. In the case of a weak magnetic field supercritical cloud cores can form that allow the formation of stars (marked with black dots). Stronger initial magnetic fields prohibit the formation of stars even in the case of large oblique angles of the flows. The blue stream-lines indicate the magnetic field morphology in the projected 2D plane. [From Körtgen & Banerjee (2015)²⁷].

our colliding flow studies for various initial conditions. Only in the *initially* marginally subcritical case ($B = 3 \mu\text{G}$) we observe signs of star formation within supercritical cores^a. For slightly stronger initial magnetic fields ($B \gtrsim 4 \mu\text{G}$) no supercritical cloud cores are generated, hence there is no star formation activity, regardless whether ambipolar diffusion is active or the flows collide with an oblique angle. Nevertheless the results of those simulations show the observed behaviour in the low column regime ($N \lesssim 1 \times 10^{21} \text{ cm}^{-2}$), where gas assembles along field lines without changing the field strength by much (see also the latest analysis from PLANCK observations of individual molecular clouds)³⁰. Only within supercritical, self-gravitating cores the magnetic field gets enhanced by compression due to flux freezing. Furthermore, we observe that star formation is immediately initiated, when the gas becomes supercritical promoting a picture of “rapid” star formation²⁹.

4 Conclusions

Here, we summarise our recent results from MHD simulations of colliding flows with varying initial conditions on the possible formation of supercritical cloud cores from subcritical initial conditions. Although dense clouds are easily formed within colliding flow scenarios due to thermal instability, the generation of supercritical clumps are largely determined by the initial conditions. Furthermore, increasing initial turbulence lead to lower masses of the cores and clumps because the HI streams become less coherent. Otherwise, increasing magnetic field strengths lead to more massive molecular clouds, which nevertheless do not become supercritical. Oblique flows still lead to cloud cores with masses comparable to

^aIf we assume $\mu_{crit} \approx 0.13/\sqrt{G}$ for spherical cores⁴³ we get $\mu/\mu_{crit} = 0.97 (3 \mu\text{G}/B)$ for our head-on colliding flow configurations.

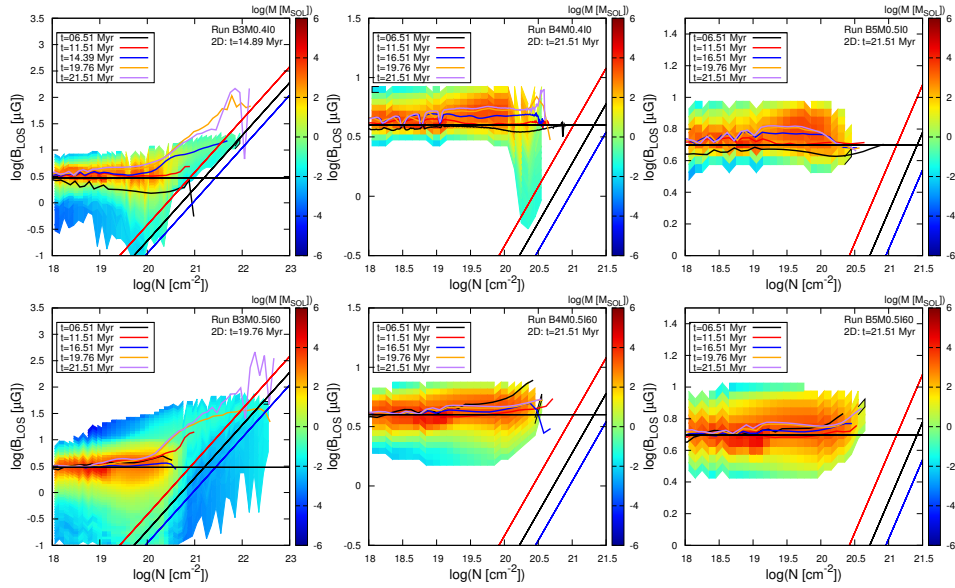


Figure 4. Results from colliding flow simulations with various different initial conditions. Shown are histograms of the line-of-sight field strength B_{LOS} as function of the column density N . From left to right: $B = 3 \mu\text{G}$, $B = 4 \mu\text{G}$ and $B = 5 \mu\text{G}$, respectively. Top: $\Phi = 0^\circ$, Bottom: $\Phi = 60^\circ$. Different line colours denote different times. Also shown are the criticality condition (red line¹⁸), corrected for projection effects (black line⁴⁸), and assuming equipartition of turbulent and magnetic fields (blue line⁴⁹). Colour coded is the mass distribution within this two parameter space. [from Körtgen & Banerjee (2015)²⁷].

what has been observed recently. But starting with subcritical HI flows, in no case the magnetic flux loss is sufficient to allow the build-up of supercritical cloud cores. Generally, increasing inclination of the flows lead to increasing diffusivity of the magnetic field. Again, regardless of the variation of the inclination, no tendency for faster accumulation of gas or faster transition to thermally dominated regions was seen in our simulations.

We therefore stress the role of magnetic fields in the context of molecular cloud and star formation. We point out the complete lack of supercritical regions for realistic initial field strengths. From the observational side, HI clouds may be supercritical as a whole, but their observed, dense subregions be subcritical.

Hence, the question remains, how magnetically *supercritical* cloud cores are formed?

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