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The phase transition dynamics and the formation of magnetized molecular clouds in the interstellar medium

Kazunari Iwasaki
Department of Earth and Space Science, Osaka University
e-mail: iwasaki@astro-osaka.jp

The interstellar medium (ISM) consists of phases which have a wide range of densities and temperatures. One component is atomic gas which has a thermally bistable structure in the optically thin regime as a result of the balance between radiative cooling and external heating. The bistable gas consists of two thermal equilibrium phases, i.e., a clumpy phase (cold neutral medium, CNM, HI clouds) and a diffuse warm phase (warm neutral medium, WNM). In the temperature range between them, the gas is thermally unstable. The phase transition between the CNM/WNM drives a self-sustained turbulence in the atomic gas (Iwasaki & Inutsuka 2014).

The phase transition from atomic gases to molecular clouds, which is the site of the star formation, is triggered by some energetic phenomena, such as supernova explosions, expansions of super-bubbles, and galactic spiral waves. The shock compression of the atomic gas causes the thermal instability that triggers the phase transition from the WNM to cold clouds. Magneto-hydrodynamical instabilities combining with the thermal instability drive turbulence where the cold clouds move with a supersonic velocity dispersion in the WNM. The cold clouds evolve into molecular clouds if they acquire a sufficient amount of the gas.

Inoue & Inutsuka (2008, 2009) found that magnetic fields make the molecular cloud formation inefficient. They showed that interstellar clouds, which are the precursor of molecular clouds, are formed only if the WNM is compressed almost along the magnetic field. Otherwise, the formation of dense cold clouds is prohibited by the shock-amplified magnetic field, and only HI clouds form. Inoue & Inutsuka (2012) considered super-Alfvénic head-on colliding flows of HI clouds surrounded by the WNM which are piled-up by previous episodes of compression. They found that the molecular cloud formation is possible in the shock compression parallel to the magnetic field.

Iwasaki et al. (2018) examined the molecular cloud in more general situations by changing the mean density of the upstream atomic gas $\langle n_0 \rangle$, collision speed V_0, and magnetic field strength B_0, and the angle θ between the upstream flow and magnetic field. Figure 1 shows the results with different angles but the same parameters $(\langle n_0 \rangle = 5\ \mathrm{cm}^{-3}, V_0 = 20\ \mathrm{km\ s}^{-1}, B_0 = 5\ \mathrm{cm}^{-3})$. The left panel of Figure 1 shows the result with $\theta = 3°$. A super-Alfvénic anisotropic turbulence is maintained by accretion of the highly inhomogeneous upstream atomic gas. The post-shock layer is largely extended by the turbulence. Even a small obliqueness of the magnetic field drastically changes the post-shock structure (the middle panel of Figure 1). The shock compression amplifies the tangential component of the magnetic field which weakens the post-shock turbulence. As a result, the post-shock layer becomes denser than that formed by a colliding flow almost aligned to the magnetic field. If the magnetic field is further inclined to the upstream flow, the shock-amplified magnetic pressure suppresses gas compression, leading to an extended post-shock layer (the right panel of Figure 1).

Iwasaki et al. (2018) found that magnetic fields provide a diversity of the structure of molecular clouds in the early phase. This may cause a diversity of the physical properties of dense clumps and dense cores, some of which is the birth sites of stars.

References

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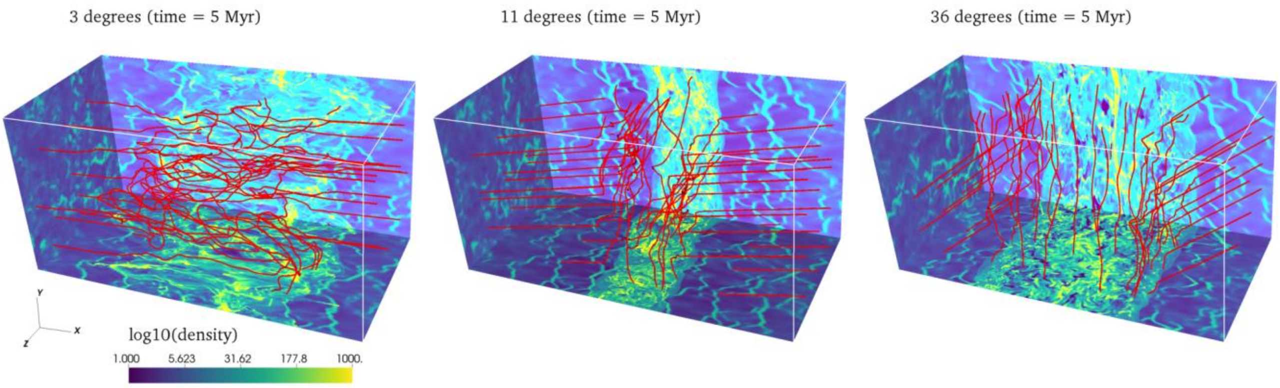

Figure 1. The results of colliding flow simulations with different angles ($\theta = 3°, 11°, 36°$) but the same parameters ($\langle n_0 \rangle = 5\ \mathrm{cm}^{-3}, V_0 = 20\ \mathrm{km\ s}^{-1}, B_0 = 5\ \mathrm{cm}^{-3}$). The collision velocity is parallel to the x axis. The color maps indicate density slices at the three orthogonal planes. The magnetic field lines are plotted by the red lines.