Revista Mexicana de Astronomía y Astrofísica
Universidad Nacional Autónoma de México
rmaa@astroscu.unam.mx
ISSN (Versión impresa): 0185-1101
MÉXICO

2004
Shu-ichiro Inutsuka / Hiroshi Koyama
THE FORMATION OF MOLECULAR CLOUDS
Revista Mexicana de Astronomía y Astrofísica, diciembre, volumen 022
Universidad Nacional Autónoma de México
Distrito Federal, México
pp. 26-29

RevMexAA (Serie de Conferencias), **22**, 26–29 (2004)

THE FORMATION OF MOLECULAR CLOUDS

Shu-ichiro Inutsuka[1] and Hiroshi Koyama[2]

RESUMEN

Analizamos la propagación de ondas de choque sobre un medio interestelar atómico, tomando en consideración el calentamiento y enfriamiento radiativo, la conductividad térmica y la viscosidad física, a partir de cálculos magnetohidrodinámicos en tres dimensiones. Los resultados muestran que inestabilidades térmicas en el gas chocado llevan a la formación de condensaciones de alta densidad inmersas en un medio neutro tibio. Las condensaciones presentan una dispersión de velocidades que es supersónica con respecto a la fase fría y subsónica con respecto a la fase tibia. Resaltamos que la evolución dinámica impulsada por inestabilidades térmicas en el gas chocado es un proceso importante en la transición de material tibio a material molecular frío, si consideramos que se generan frecuentemente ondas de choque por explosiones de supernova en la Galaxia. Una vez que la columna de densidad del gas chocado excede el valor crítico ($\sim 10^{21}\mathrm{cm}^{-3}$), se espera que el medio bi-fásico evolucione en un medio frío, dentro de un tiempo de enfriamiento. Tambié se discute la evolución subsecuente, impulsada por la fuerza de gravedad.

ABSTRACT

We analyse the propagation of a shock wave into an atomic interstellar medium, taking into account radiative heating/cooling, thermal conduction, and physical viscosity, by means of three-dimensional magnetohydrodynamical simulations. The results show that the thermal instability in the post-shocked gas produces high-density molecular cloudlets embedded into a warm neutral phase. The molecular cloudlets have a velocity dispersion which is supersonic with respect to the sound speed of the cold medium and is subsonic with respect to the warm phase. The dynamical evolution driven by thermal instabilities in the shocked layer is an important basic process in the transition from a warm phase into cold molecular gas, as shock waves are frequently generated by supernovae in the Galaxy. Once the total column density of the ensamble of clouds becomes larger than the critical value ($\sim 10^{21}\mathrm{cm}^{-3}$), the two-phase medium is expected to evolve into a single phase medium, within a cooling time-scale. The further evolution, driven by the gravitational force, is outlined.

Key Words: **INSTABILITIES — ISM: CLOUDS — MAGNETOHYDRODYNAMICS: MHD — SHOCK WAVES**

1. INTRODUCTION

Stars are formed in molecular clouds. Molecular clouds are characterized by the *supersonic* line-width of their molecular emission lines, which can be related to the supersonic internal motion of gas, or *turbulence* in molecular clouds. Obviously this "turbulence" should be very different from well-studied incompressible turbulence in laboratory physics. The maintenance and dissipation processes of the turbulence in molecular clouds are supposed to be important in the theory of star formation (Mac Low & Klessen 2004). The understanding of the origin of turbulence and the internal substructure of molecular clouds has fundamental importance for a consistent theory of star formation and the ISM. Recent numerical simulations show that supersonic turbulence in an isothermal or an adiabatic medium decays quickly, within a crossing time, unless the driving energy is continuously supplied. In contrast, Koyama & Inutsuka (1999, 2000, 2002a) proposed that the propagation of a strong shock wave into a warm neutral medium (WNM) and a cold neutral medium (CNM) inevitably produces a turbulent post-shocked cold layer as a result of the thermal instability. Their results predict that molecular clouds are born with a turbulent velocity dispersion, with the cold cloudlets embedded in warm medium with a sound speed larger than the velocity dispersion of the cloudlets. Their study includes now the effects of viscosity, thermal conduction, and magnetic field (Inutsuka & Koyama 1999, 2002b; Koyama & Inutsuka 2002b, 2004). In this short article we briefly describe our recent progress. The importance of thermal instabilities is suggested also by Hennebelle & Pérault (1999,2000) and Kritsuk & Norman (2002).

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2. MAGNETOHYDRODYNAMICAL SIMULATIONS

We solve the magnetohydrodynamical equations, which include radiative heating, cooling, thermal conduction, and physical viscosity. The descriptions are found in Koyama & Inutsuka (2000, 2002a). Thermal conduction could stabilize and even erase a density perturbation whose length scale is smaller than the Field length, $\lambda_{\rm F} = \sqrt{KT/\rho^2\Lambda}$, where K denotes the coefficient of thermal conduction, Λ cooling function (Field 1965). The Field length also determines the width of the intermediate region between the cold clumpy medium and the surrounding warm medium where heating and cooling, due to the thermal conduction, balance the radiative heating and cooling. A calculation with a large grid spacing cannot resolve the conduction fronts, and the mesh points on the surface of a cold clump become numerically unstable. Thus high spatial resolution is required for accurate calculations of thermal instabilities (Koyama & Inutsuka 2004).

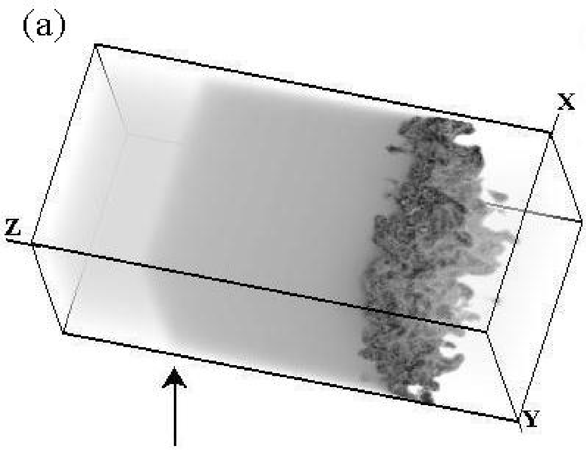

Fig. 1. The volume rendering of high-density region of the shock-compressed layer. The arrow denotes the location of the shock front.

To investigate the shock propagation into a WNM we consider a plane-parallel (x- and y-axis) shocked layer, produced by a shock wave that moves along the z-axis, perpendicular to the layer,

Figure 1 shows the snapshots ($t = 3.88$ Myr) of our three-dimensional calculations without a magnetic field. A uniform flow approaches the layer from the left-hand side with a velocity $V_{\rm z} = -13.6$ km/s and density $n = 0.3\ {\rm cm}^{-3}$ and temperature $T = 6000$ K. and pressure $P/k_{\rm B} = 2 \times 10^3 {\rm Kcm}^{-3}$. We assume that the shocked layer is occupied by a hot, tenuous gas (density $n = 1.2\ {\rm cm}^{-3}$) with a high pressure $P/k_{\rm B} = 8 \times 10^3 {\rm Kcm}^{-3}$. We set up initial density

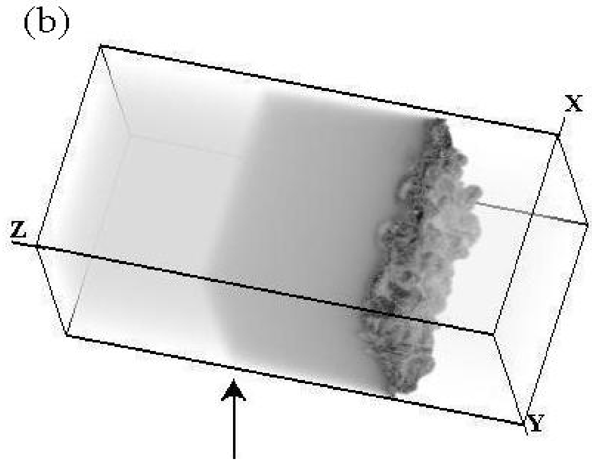

Fig. 2. Same as Fig.1, but for the magnetized case. The initial weak magnetic field is aligned along the x-direction and uniform. The magnetic pressure becomes comparable to the gas pressure in the post-shocked region.

fluctuations $\delta\rho/\rho \sim 0.05$, in a grid with an open boundary condition in the z-direction, and a periodic boundary condition for the x- and y-direction. In the figure the arrow denotes the location of the shock front. The shock front itself remains stable throughout the calculations. Behind the shock front, cooling dominates heating and the temperature decreases monotonically. The ISM in the range of 300–6000 K is thermally unstable and thus, the layer becomes subjected to a thermal instability. Figure 2 shows the result of the same calculation with a magnetic fields. The snapshot was taken at time 6.48 Myr. The initial uniform magnetic field corresponds to high plasma β: $P/B_x^2 = 2 \times 10^4$ in the WNM, $= 8 \times 10^4$ in the hot medium. In the post-shock layer, however, the magnetic pressure becomes comparable to the gas pressure. This is because the density becomes larger by a factor of 10^2 so that the magnetic pressure becomes about 10^4 times its initial value, although the thermal pressure does not increase as much, due to the efficient cooling. The cold clumps have a considerable translational velocity dispersion. A substantial fraction of the high-density gas is supersonic. The typical velocity dispersion is about a few km/s. The velocity of the nonlinearly developed perturbation has an upper limit that is essentially determined by the sound speed of the warmer medium ($\approx$ 10km/s), because the driving force of the instability is the pressure of the less dense warmer medium. This velocity smaller than the sound speed of the WNM is highly supersonic with respect to the sound speed of the cold medium. Thus we can understand why the supersonic velocity dispersion of the cold medium is comparable to (but less than) the sound speed of the WNM.

In the radiative shocked layers, the gas looses thermal energy through radiative cooling. Thus, the initial kinetic energy of the pre-shocked gas (in the comoving frame of the post-shocked gas) is converted into radiation energy, which escapes from the system. If, however, the post-shock gas becomes dynamically unstable due to thermal instabilities, as shown in this paper, a considerable fraction of the thermal energy is transformed into the kinetic energy of the translational motions of the cold cloudlets, which does not easily escape from the system. Therefore we can attribute the origin of interstellar turbulence to the conversion of thermal into kinetic energy via thermal instabilities. The size of the cold clumps is a few orders of magnitude smaller than the Jeans length, $\lambda_{\rm J} = 1.2\ {\rm pc}\sqrt{(T/20{\rm K})(2000{\rm cm}^{-3}/n)}$. Thus, each cloud is gravitationally stable.

3. IMPLICATIONS

The ISM is frequently compressed by supernova remnants (McKee & Ostriker 1977), and thus the real ISM is frequently exposed to the effects considered in our calculations. The intersection regions of SNe might produce larger cold clouds embedded in a warm medium. The average column density of the two-phase cloud has an upper limit ($N_H \sim 10^{21}{\rm cm}^{-2}$) determined by the attenuation of the external radiation, due to the large ensemble of cold cloudlets that shield themselves from the external heating radiation (Inutsuka & Koyama 1999). Thus, once the column density of the two-phase cloudlets becomes large enough, it evolves into a single phase medium of about $10K$, within a cooling time-scale. Obviously, this *genuine* molecular cloud would be the site of star formation. Our next work will be focused on the analysis of this transition from a two-phase medium into a single phase.

4. GRAVITATIONAL FRAGMENTATION

Observed molecular clouds have masses much larger than the (apparent) Jeans mass in each cloud, and often show remarkable filamentary structures. One of the most extensively studied star-forming regions is the Taurus dark cloud, where the infrared polarization measurements show the direction of well organized magnetic field lines perpendicular to the remarkable filaments. This kind of information on the morphology has some suggestion on the mode of SF. On larger scale, the Taurus dark cloud is located in a circular hole found in the map ($0 < V_{\rm LSR} < 2{\rm km/s}$) of HI 21cm line emission (Hartmann & Burton 1977). In general, HI holes may be formed by the expansion of supernova remnants or the effect of strong stellar winds. The observational study on the relation of the HI hole and the origin of Taurus dark cloud will be interesting future work.

4.1. *Formation of Filamentary Structure*

In the following, we briefly describe how filamentary structures form and evolve in the context of Triggered SF, in which a molecular cloud is, at first, compressed one-dimensionally or swept up into a sheet-like configuration (for a review, see Inutsuka & Tsuribe 2001). We assume that the magnetic field lines are also passively compressed and the resultant direction of the magnetic field lines is in the plane of the sheet, because the typical magnetic pressure in the ISM is much smaller than, e.g., the ram pressure of a supernova remnant. The modes of gravitational fragmentation of the magnetized sheet-like cloud can be summarized in Figure 3 where we plot the dispersion relation for the linear perturbation, and schematically show the resultant structures. The character of the fragmentation depends on the surface density of the sheet-like cloud (Nagai, Inutsuka, & Miyama1998).

For the layer with a thickness larger than the pressure scale height H $(= C_{\rm s}[2\pi G\rho_c]^{-1/2}$ where $C_{\rm s}$ is the isothermal sound speed and ρ_c is the midplane density), perturbations whose wavevector is *parallel* to the magnetic field grow faster than those perpendicular to the field. Therefore the layer fragments into filaments, and the direction of longitudinal axis of each filament is perpendicular to the magnetic field lines. The further evolution is explained in the next subsections.

On the other hand, the layer with a thickness much smaller than H becomes more unstable for perturbations *perpendicular* to the magnetic fields. In this case it fragments into filaments, and the direction of longitudinal axis of each filament is *parallel* to the magnetic field lines. The compressional motion is negligible and the resulting filaments are stable against radial collapse. Such quasi-equilibrium filaments may possibly break up into pieces again mainly through the motion along the axis direction of filaments, depending on the strength of the magnetic field. The resulting nearly spherical clumps, however, will not collapse into stars because the mass of each clump tends to be less than that of Bonner-Ebert sphere. Thus, this case is not directly related to active star formation.

In this way, the fragmentation direction is de-

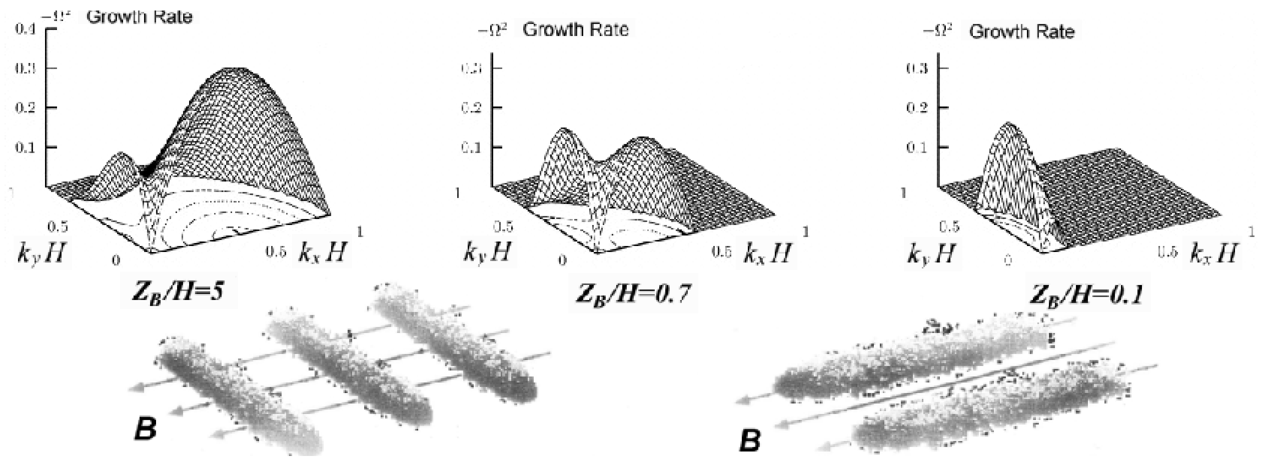

Fig. 3. Fragmentation of magnetized sheet-like clouds. The normal vector of the sheet is in the z-direction and H denotes the semi-thickness. The unperturbed magnetic field lines are in the x-direction.

termined only by the thickness (and hence, the surface density) of the sheet-like cloud, and not by the strength of the magnetic field. Simple analytical explanation for the reason for the difference of the fragmentation processes can be found in Inutsuka & Tsuribe (2001).

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