21aD2-3

Simulations of the formation of molecular clouds by the interstellar gas compressed by an astrophysical jet

宇宙ジェットに圧縮された星間ガスによる分子雲形成シミュレーション

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In order to study the formation mechanism of molecular clouds by the interaction of an astrophysical jet with the interstellar gas, we have carried out magnetohydrodynamic (MHD) simulations of jet propagation taking into account the interstellar cooling. At the initial state, interstellar neutral hydrogen (HI) clouds is thermally stable, but enhancement of the density by the shock compression increases the cooling rate. As a result, temperature decreases and cold, dense gas is formed by cooling instability. We report application of these simulations to molecular clouds observed toward the stellar cluster Westerlund 2.

1. Introduction

Astrophysical jets transport the energy released near the compact object (e.g. black hole) to the distant region. An important role of the jet propagation is the interaction with the interstellar medium. For example, it is possible that interaction of the jet with the interstellar HI gas can form molecular clouds.

In order to study the formation mechanism of molecular clouds by the interaction of the jet ejected from the galactic jet source SS433 with HI clouds, we have carried out MHD simulations taking into account the interstellar cooling [1]. Numerical results indicate that thermally stable HI cloud is compressed by the jet and the density enhancement makes the HI cloud thermally unstable since the density enhancement increases cooling rate. As a result, temperature decreases and cold, dense cloud is formed. In these region, molecular clouds can be formed.

Molecular clouds are observed toward the stellar cluster Westerlund 2 and the TeV γ -ray source HESS J1023-575 by NANTEN2 and Mopra telescope [2]. The TeV γ -ray source locates between these molecular clouds. The shape of these molecular clouds is arc-like in right direction and jet-like in left side of the TeV γ -ray source. If these molecular clouds are formed by the interaction of the jet with interstellar HI clouds, the different shape of molecular clouds comes from the difference in distribution of interstellar HI clouds. Figure 1 schematically shows the interaction of the jet with a big HI cloud and clumpy HI clouds. We study the effect of the distribution of HI clouds on structures of the jet and the shape of molecular clouds.

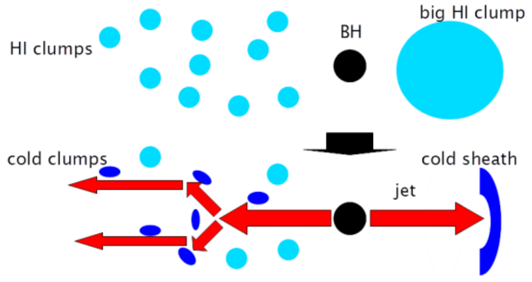

Fig.1. Schematic picture of the interaction of the jet with a big HI cloud and clumpy HI clouds

2. Numerical Method

We solve following basic equations.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \tag{1}$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v} \otimes \boldsymbol{v} + p + \frac{B^2}{8\pi} - \frac{\boldsymbol{B} \otimes \boldsymbol{B}}{4\pi} \right) = 0 \tag{2}$$

$$\frac{\partial}{\partial t} \left(e + \frac{B^2}{8\pi} \right) + \nabla \cdot \left[(e+p)\boldsymbol{v} - \frac{(\boldsymbol{v} \times \boldsymbol{B}) \times \boldsymbol{B}}{4\pi} \right] = -\rho L \tag{3}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) \tag{4}$$

$$e = \frac{p}{\gamma - 1} + \frac{\rho v^2}{2} \tag{5}$$

ρ, **v**, p, ***B*** and e are density, velocity, pressure, magnetic field and the energy density of the gas, respectively. We adopted the cooling function,

$$\rho L = n(-\Gamma + n\Lambda) \exp\left\{ -\left[\max\left(\frac{T}{7000} - 1, 0 \right) \right]^4 \right\} \tag{6}$$

$$\Gamma = 2 \times 10^{-26} \mathrm{ergs\ s^{-1}} \tag{7}$$

$$\begin{aligned} \Lambda \ &= \ 7.3 \times 10^{-21} \exp\left(\frac{-118400}{T+1500} \right) \\ &\quad + 7.9 \times 10^{-27} \exp\left(\frac{-200}{T} \right) \mathrm{ergs\ cm^3\ s^{-1}} \end{aligned} \tag{8}$$

where Γ and Λ are heating rate and cooling rate, respectively. They have the same form as those used by Inoue et al. [3].

These equations are solved numerically by applying the HLLD shceme [4]. Fifth order accuracy in space is preserved by MP5 method [5] and third order accuracy in time is preserved. To satisfy the solenoidal condition $\nabla \cdot \boldsymbol{B}=0$, we applied the generalized Lagrange multiplier scheme [6]. We incorporated the cooling term with time-implicit method.

3. Simulation Model

At the initial state, we assumed that HI clouds are in thermal equilibrium and pressure equilibrium with the warm interstellar medium. Temperature and number density of HI clouds are 200 K and about 6.9 cm^{-3}. For a big HI model, we put a HI cloud with radius 10 pc. For HI clumps model, we put HI clumps whose radius is 2 pc, randomly. We injected a Mach 3 jet with radius 1 pc whose temperature is about 2 million K. In the injection region, the jet has purely toroidal magnetic field. We imposed symmetrical boundary at z=0 and outer boundaries are assumed to be free boundaries.

4. Numerical Results

Figure 2 shows a result for big HI cloud model. Shock compressed HI cloud is cooled down by cooling instability and cold, dense sheath colored by blue is formed. Since the jet sweeps HI cloud, the shape of cold, dense cloud becomes arc-shape.

Figure 3 shows a result for clumpy HI clouds model. Since the jet propagates along channels between HI clumps, the jet breaks up into branches and cold, dense clumps are formed.

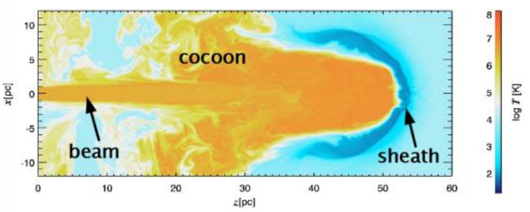

Fig.2. Result for a big HI cloud model. Color shows temperature distribution. Cold, dense sheath is formed.

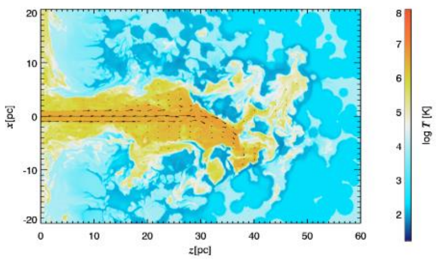

Fig.3. Result for clumpy HI clouds model. The jet breaks up into branches.

Figure 4 (a) and (b) show column density for a big HI cloud model and clumpy HI clouds model. For a big HI cloud model, the shape of peaks of column density becomes arc-shaped. On the other hand, for clumpy HI clouds model, shock compression takes place in various place where the jet sweeps the clouds. Therefore, cold, dense clouds distribute more widely than the big HI cloud model.

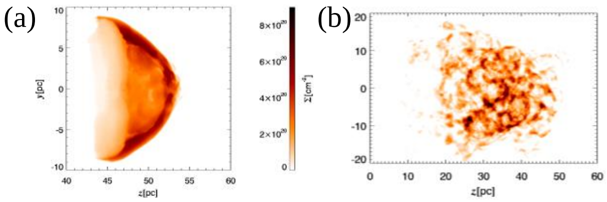

Fig.4. Column density distribution. Result for (a) a big HI cloud model and (b) a clumpy HI clouds model.

5. Summary

We carried out 3D MHD simulations of the interaction of the jet with interstellar HI clouds for two models; a big HI cloud model and clumpy HI cloud model. The density distribution of HI clouds affects jet propagation and the shape of cold, dense clouds. When the jet collides with a big HI cloud, the jet sweeps the HI gas and arc-shaped cold, dense cloud is formed. When the jet interacts with clumpy HI clouds, the jet breaks up into branches and distribution of cold, dense clouds becomes wider than a big HI model. The density distribution of interstellar HI clouds is an important factor for jet propagation and the shape of molecular clouds formed by the jet compression.

Acknowledgments

Numerical computations were carried out by XC30 at Center for Computational Astrophysics, NAOJ. This work is supported by Grant-in-Aid for JSPS Fellow (24.4786).

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