Contribution of supernovae-driven galactic fountain on fuel rate

K. Sung and Kyujin Kwak
Physics Department, Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea
E-mail: sung@unist.ac.kr

Abstract. The interstellar medium in our galaxy is a complex system which involves multiphase gas in a wide range of temperatures and densities. Accompanied by physical processes such as cooling, gravity and magnetic fields it is known that the supernovae blast waves can resuffle the ISM by generating a galactic fountain. In our study, we mainly focus on estimating the fuel rate of the fountain which is defined as the supply rate of material from the gas falling back into the galactic disk. We take into account the effect of cooling by combining the use of non-equilibrium ionization (NEI) and collisional ionization equilibrium (CIE). Dealing with cooling in this manner, we aim to reduce computation time by using a prebuilt CIE cooling table at applicable physical conditions instead of constantly considering time dependent ion fractions for NEI cooling.

1. Introduction
First introduced by Shapiro & Field (1976), the idea that there can exist a gas flow in a galactic scale has been revisited and developed ever since. Such gas flow can be created from successive supernovae blasts in the galactic disk by heating up the disk gas. The ejected gas cools down and condenses into atomic hydrogen clouds which in turn falls down to the disk at velocities $\sim 100 \text{ km} \cdot \text{s}^{-1}$ to form a galactic fountain. Notable galactic fountain models include, analytic fountain models by Bregman (1980) and Kahn (1981), two-dimensional models by Houck & Bregman (1990) and Rosen et al. (1993), and three-dimensional models by de Avillez (2000), Joung & Mac Low (2006) and Kwak et al. (2009).

While the previous galactic fountain models mainly focus on the physical and dynamical structure of the ISM, in this study, we aim to estimate the fuel rate on the galactic disk by considering both collisional ionization equilibrium (CIE) and non-equilibrium ionization (NEI) cooling. By using a prebuilt CIE cooling table at applicable high temperatures, we avoid tracking time dependent ion fractions and therefore reduce computation time. The fuel rate describes the supply efficiency of materials from the infalling gas clouds. Such concept is carried along from our previous work regarding the infall of high velocity clouds (HVCs) on the galactic disk where we have shown that the fuel rate strongly depends on the physical configuration of the system even when the total infall rate of the materials is fixed.

In the following Section 2, we describe the basic setup for our simulations and introduce how we estimate the fuel rate. In Section 3, we only discuss the expected outcome and limitations of the simulation model in a qualitative manner as we are currently in the process of building a complete simulation model that includes physical processes such as gravity, magnetic field and...
cooling in a three-dimension Cartesian geometry. At the conclusion, we summarize our study in Section 4.

2. Simulation methods

2.1. Simulation setup

We use FLASH 4.4 which is a modular, adaptive-mesh, parallel multiphysics simulation code capable of handling general compressible flow problems. Message-Passing Interface (MPI) library is used for parallelization and the Adaptive Mesh Refinement (AMR) is managed by the PARAMASH library (Fryxell et al. 2000)

The computation domain is represented in a 3-D Cartesian geometry that is 10 kpc long from -5 to 5 kpc in the z-direction with a squared shape horizontal cross section of (1 kpc)$^2$ and the midplane of the galactic disk positioned at $z = 0$. The boundary condition is periodic for the horizontal directions and outflowing for the vertical direction where the total box contains $(256)^2 \times 2560$ cube cells at the maximum refine level of 6 determined by density. This converts to a grid resolution of 3.91 pc.

As the gravitational field is plane-parallel to the center plane of the galactic disk, the disk shows a density gradient due to gravity where the average HI volume number density of the galactic disk is $1.00 \times 10^{-1}$ cm$^{-3}$ (Launhardt et al. 2002). The temperature of the disk is determined by simply following the ideal gas law to maintain the pressure balance with the ISM at a temperature of $10^6$ K and HI volume number density of $1.00 \times 10^{-4}$ cm$^{-3}$.

Thermal energy of $10^{51}$ ergs is added for each supernova explosion, in a sphere that represents the initial supernova with a radius depending on the density of the local galactic disk. Such events will be randomly distributed inside the galactic disk at a constant rate which will further be tested as an input parameter. Collisional ionization equilibrium (CIE) cooling table is extensively used for temperatures $T > 10^6$ K. Otherwise, non-equilibrium ionization (NEI) cooling is considered.

In order to track the disk and ISM materials during the dynamical evolution of the system, scalar fields are added to the simulation by indexing the disk and ISM particles based on the initial position of a particle. Cloud materials will also be tracked using a similar method, however being indexed in a different manner based on a criteria that includes velocity, density and other surrounding physical conditions.

2.2. Fuel rate

In galactic chemical evolution models, the infall rate of material is traditionally given in the units of $M_\odot \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$ or sometimes $M_\odot \cdot \text{yr}^{-1}$ in case we fix the area of gas inflow. The simplest mathematical expression for the infall rate $\dot{M}_{\text{cloud}}$ of an inflowing gas cloud is

$$\dot{M}_{\text{cloud}} = M_{\text{cloud}} \cdot \frac{v}{D} \quad (1)$$

where $M_{\text{cloud}}$ is the mass of the infalling gas cloud in solar mass, $v$ is the radial velocity and $D$ is the distance from the galactic disk (Wakker et al. 2007; Thom et al. 2008). In our series of simulations, we take $D$ as the vertical distance between the midplane of the galactic disk and the center of the gas cloud. For a typical high velocity cloud infall scenario ($v = 70 \text{ km} \cdot \text{s}^{-1}$, $D = 5 \text{ kpc}$, and $M = 1.16 \times 10^6 M_\odot$), the infall rate is $1.66 \times 10^{-2} M_\odot \cdot \text{yr}^{-1}$.

We define two quantities $e_1$ and $e_2$ in order to address the fuel rate which can differ from the infall rate due to the interaction of the cloud with the disk. $e_1$ is defined as the time variation of the disk mass fraction,

$$e_1(t) = \frac{M_{\text{disk}}(t) - M_{\text{disk}}(0)}{M_{\text{disk}}(0)} = \frac{dM_{\text{disk}}(t)}{M_{\text{disk}}(0)} \quad (2)$$
where $M_{\text{disk}}(t)$ is the mass of the disk at time $t$ and $M_{\text{disk}}(0)$ is the initial mass of the disk. $e_2$ is the gas cloud infusion fraction onto the disk,

$$e_2(t) = \frac{M_{\text{cloud,disk}}(t)}{M_{\text{cloud}}}$$

where $M_{\text{cloud}}$ is the total mass of the gas cloud and $M_{\text{cloud,disk}}(t)$ is the mass of gas cloud materials accreted onto the disk at time $t$. Defined in such way, $e_1(t)$ shows the mass variation of a patch of the galactic disk during and after the interaction with a gas cloud. In the other hand, $e_2(t)$ shows how much the materials from an infalling gas cloud is accreted onto the disk.

3. Discussion

3.1. Cooling curve

Non-equilibrium ionization (NEI) cooling is considered when the cooling rate and the recombination rate are not together in sync. More specifically, when the recombination time scale is longer than the cooling time scale, cooling rate is not simply a function of temperature but we must consider the fraction of each ions at each time step of the simulation. Otherwise, when the recombination time scale is shorter than the cooling time scale it is safe to use collisional ionization equilibrium (CIE) cooling. The temperature limit for such case is $T > 10^{6.2}$ K (de Avillez 2012).

Cooling effects not only allow a galactic fountain of gas clouds after successive supernova explosions, but also play a significant role during the interaction between the gas material and the galactic disk. As the galactic disk collides with the infalling gas cloud, a reverse shock is generated due to density contrast, proceeds backwards into the gas and drives an expansion of the gas cloud into the ISM after collision. Cooling processes will suppress such rear expansion process and increase the infusion rate of materials onto the galactic disk.

3.2. Estimating fuel rate

For this particular study, the fuel rate is addressed by considering two quantities. One is to track the time evolution of disk mass fraction and the other is to track the time evolution of infalling gas cloud material infusion fraction on the disk. Both quantities give us an idea of how gas clouds would influence the structure and composition of the disk through the hydrodynamic and thermodynamic interactions. However, it is important to identify the physical properties of the gas clouds generated after disk material outburst in order to correctly estimate the infusion rate of clouds $e_2(t)$, as the simulations in this study begin with supernovae outblasts which are different from infall-only cases.

3.3. Excluded physics

Focusing on applying the NEI and CIE combined cooling curve and investigating the ionization profile during the dynamical evolution of the system, we exclude magnetic fields in the current simulation. However, magnetic fields are known to participate in the interaction between the cloud and disk. The magnetic field lines could be compressed during the collision between the gas cloud and the galactic disk which can possibly restrain the exchange of materials between the disk and cloud.

Conduction can play a role in transferring energy, but it turns out that the energy transportation is dominated by dynamical flow over thermal conduction in our simulations because the ISM is continuously disturbed by SN. Therefore, thermal conduction is not included.
4. Summary
From our previous study of HVC infall, we carry the idea that the traditional infall rate requires assistance from a new parameter called the fuel rate and apply it to the supernovae-driven galactic fountain model. The fuel rate needs to include the supply efficiency of materials from the infalling gas clouds on the galactic disk. In order to address the fuel rate more accurately, we considered two quantities which indicate the supply efficiency into the disk, one as the mass variation fraction of the galactic disk and the other as the cloud material infusion fraction onto the galactic disk. Since the fuel rate depends heavily on the physical configuration of the infalling gas, it is important to correctly indentify the physical configuration of the gas clouds generated from cooled down materials supplied by successive supernova outbursts. In the supernova-driven fountain simulations, we use both CIE and NEI cooling depending on the temperature of the gas. We apply CIE cooling at temperatures $T > 10^{6.2}$ K, while NEI cooling needs to be used at temperatures $T < 10^{6.2}$ K in order to trace the cooling process more accurately.

Acknowledgments
This work has been supported by NRF (National Research Foundation of Korea) Grant funded by the Korean Ministry of Education (NRF-2015H1A2A1031629-Global Ph.D. Fellowship Program and No. 2016R1A5A1013277, 2016R1D1A1B03936169 and 2014R1A1A1006050). The software which will be used in this work was in part developed by the DOE-supported ASC/Alliance Center for Astrophysical Thermonuclear Flashes at the University of Chicago.

References
[1] Avillez M A 2000 MNRAS. 315 479
[2] Avillez M A, Breitschwerdt D, Asgekar A and Spitoni E 2012 Proc. of IAU 10(H16) p 606
[3] Bregman J N 1980 ApJ 236 577
[4] Fryxell B, Olson K, Ricker P, Timmes F X, Zingale M, Lamb D Q, MacNeice P, Rosner R, Truran J W and Tufo H 2000 ApJS 131 1
[5] Houck J C and Bregman J N 1990 ApJ 352 506
[6] Joung M K R and Mac Low M-M 2006 ApJ 653 2
[7] Kahn F D 1981 in Investigating the Universe ed. F D Kahn and D Reidel (Dordrecht:Kluwer), 1
[8] Kwak K, Shelton R and Raley E A 2009 ApJ 699 2
[9] Launhardt R, Zylka R and Mezger P G 2002 A&A 384 112
[10] Rosen A, Bregman J N and Norman M L 1993 ApJ 413 137
[11] Shapiro P R and Moore R T 1976 ApJ. 207 460
[12] Thom C, Peek J E G, Putman M E, Heiles C, Peek K M G and Wilhelm R 2008 ApJ 684 364
[13] Wakker B P et al. 2007 ApJL 670 113