Estimating the Fuel Supply Rate on the Galactic Disk from High-velocity Cloud (HVC) Infall

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Abstract

Previous studies suggest that the estimated maximum accretion rate from approaching high-velocity clouds (HVCs) on the Galactic disk can be up to \( \sim 0.4 \, M_\odot \, yr^{-1} \). In this study, we point out that the hydrodynamic interaction between the HVCs and the Galactic disk is not considered in the traditional method of estimating the infall rate, and therefore the true supply rate of fuel from HVCs can be different from the suggested value depending on the physical configurations of HVCs including density, velocity, and distance. We choose 11 HVC complexes and construct four different infall models in our simulations to give an idea of how the fuel supply rate could be different from the traditional infall rate. Our simulation results show that the fuel supply rate from HVC infall is overestimated in the traditional method and can be lowered by a factor of \( \sim 0.072 \) when the hydrodynamic interaction of the HVC complexes and the disk is considered.

Key words: Galaxy: disk – hydrodynamics – ISM: clouds – methods: numerical – stars: formation

1. Introduction

First discovered by Muller et al. (1963), high-velocity clouds (HVCs) are known as neutral atomic hydrogen clouds moving with a velocity that deviates from the Galactic rotation by up to \( \sim 300 \, km \, s^{-1} \). The typical size of an HVC complex can be a few to 15 kpc across with the \( H I \) mass in the range of \( 10^7 \sim 5 \times 10^7 M_\odot \). While the exact distances to the HVC complexes are still questionable and should be further constrained, it is widely accepted at the current stage that a majority of the complexes exist at a distance \( \leq 10 \, kpc \) (Wakker et al. 2007, 2008; Thom et al. 2008; Putman et al. 2012).

Recent studies suggest that HVCs have multiple origins, including stripped gas material of nearby (dwarf) galaxies like the Magellanic Stream, Galactic fountains, and infowing intergalactic gas (Wakker & van Woerden 1997, 2013; Blitz et al. 1999). Assuming that the HVCs are infowing intergalactic gas is often favored in theoretical galactic chemical evolution (GCE) models, especially when it is metal-poor material that is supplied into the galaxy from HVCs. For example, in the GCE model with two main infall episodes, the present infall rate of primordial material is predicted as \( \sim 0.4 \, M_\odot \, yr^{-1} \) (Chiappini et al. 2001; Chiappini 2008).\(^1\) Note that the continual, and at the same time, occasional infall of HVCs can be a source of metal-poor gas with the mass accretion rate being up to \( \sim 0.4 \, M_\odot \, yr^{-1} \), although only about one-half of the currently infalling material has low metallicity (Putman et al. 2012).

The infall rate is derived from the physical properties such as mass, velocity, and distance of the HVCs, and is traditionally given in the form of an equation given as

\[
M = \sum \frac{M_v}{D},
\]

where \( M_v \) is the mass of an HVC, \( v \) is the observed radial velocity, and \( D \) is the distance (Wakker et al. 2007; Thom et al. 2008; Putman et al. 2012). The advantage of estimating the gas infall rate from the equation above is that the simplicity allows us to directly utilize the observed physical properties of HVC complexes. However, there are some obvious limitations of this approach, due to the fact that \( D \) will not be the same distance as the distance from the HVC to the point where it will collide with the galactic disk. Furthermore, \( v \) will also be different from the true radial velocity with the possibility of acceleration/deceleration. But more significantly, we believe there is a different part in this method that can be reconditioned to better estimate the supply rate of material into the Galactic disk from such gas inflow.

The essence of the traditional method of infall rate estimation is the assumption of steady and full accretion of HVC mass until “time to impact (=v/D).” Kinematic consequences that occur from the hydrodynamic interaction between the disk and HVCs are neglected in the traditional approach, and therefore in this study, we make an attempt to qualitatively show that the true fuel supply rate can change depending on the physical properties of the HVC regardless of the total infall rate itself. Further, we select 11 different HVC complexes and set up four different infall cases in our numerical simulations to give an idea how the fuel supply rate could be different from the traditional infall rate depending on the physical configuration of each HVC complex.

2. Simulation Methods

2.1. Simulation Setup

We use FLASH 2.5 (Fryxell et al. 2000) for our simulations, which is a modular, adaptive-mesh, parallel simulation code capable of handling general compressible flow problems. Message-Passing Interface library is used for parallelization and the PARAMESH library manages Adaptive Mesh Refinement. The computation domain is configured in a 2D cylindrical geometry that can extend up to 10 kpc in the horizontal (i.e., \( r \)-) direction and 40 kpc in the vertical (i.e., \( z \)-) direction depending on the distance and radius of the infalling HVC. As the HVC complex approaches and interacts with the...
galactic disk, the refinement level gradually increases to its maximum which corresponds to 9.7 pc × 9.7 pc spatial resolution for each cell. For the boundary conditions, it is reflecting at the left vertical axis \((r = 0)\) and outflowing at the rest of the three remaining boundaries. The thickness of the gaseous disk is 250 pc \((\text{Rougoor 1964})\) with the HI volume number density of \(0.1 \text{ cm}^{-3}\) \((\text{Kalberla & Dedes 2008})\). The HI volume number density of the ISM is \(1.0 \times 10^{-4} \text{ cm}^{-3}\).

2.2. HVC Infall Parameters

We select 11 HVC complexes from the HVC catalog of Wakker (2005), and mostly adopt the provided information for the mass, distance, latitude \((b)\), and deviation velocity \((v_{\text{dev}})\), but also supplement the data set with observation results from recent studies (Thom et al. 2006, 2008; Lockman et al. 2008; Jin 2010; Peek et al. 2016). The input parameters for each complex are provided in Table 1. For each HVC complex, we consider two different cases for the vertical velocity, \(v_z\); (1) assuming that the observed velocity is purely radial, (2) by considering the intermediate case and extreme case \((v_z = 73 \text{ km s}^{-1}\) for the intermediate case and \(99 \text{ km s}^{-1}\) for the extreme case \((\text{Lockman et al. 2008})\).

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Name & \(b(a)\) \((^\circ)\) & \(v_{\text{dev}}(b)\) \((\text{km s}^{-1})\) & \(\Omega(c)\) \((\text{deg}^2)\) & \(D(d)\) \((\text{kpc})\) & \(M(e)\) \((10^6 M_\odot)\) \\
\hline
A & +40 & 141 & 288 & 8.0 & 1.0 \\
ACHV & −30 & 100 & 397 & 10.0 & 1.0 \\
ACVHV & −30 & 221 & 338 & 10.0 & 1.0 \\
C & +58 & 122 & 1546 & 10.0 & 5.0 \\
GCN & −31 & 243 & 130 & 20.0 & 0.22 \\
M & +62 & 95 & 174 & 4.0 & 1.0 \\
Smith & +13.4 & 73* & 58 & 12.4 & 1.0 \\
WA & +32 & 126 & 102 & 8.0 & 0.13 \\
WB & +32 & 52 & 289 & 8.0 & 0.70 \\
WD & +32 & 106 & 253 & 4.4 & 1.1 \\
WE & −20 & 106 & 51 & 9.4 & 0.12 \\
\hline
\end{tabular}
\caption{HVC Infall Parameters}
\end{table}

Note. (a) Galactic latitude, (b) deviation velocity, (c) solid angle, (d) distance, and (e) mass. The \(^*\) vertical velocity \(v_z\) of the Smith cloud is \(73 \text{ km s}^{-1}\) for the intermediate case and \(99 \text{ km s}^{-1}\) for the extreme case \((\text{Lockman et al. 2008})\).
When \( v_i = v_{\text{dev}} \sin(b) \) which we call intermediate case or (2) assuming that the space velocity is vertical, \( v_i = v_{\text{dev}} / \sin(b) \), which we call extreme case. The radius, \( R \) is estimated by assuming that the HVC complex is a perfect sphere and has a uniform density. Then, \( R \) follows the relation, \( \Omega D^2 \sim A \sim R^2 \), where \( \Omega \) is the observed solid angle, \( D \) is the distance, and \( A \) is the area of detection. We also add an extreme case that could represent a smaller and denser HVC complex by simply cutting down the radius in the previous intermediate case to half so that the relation instead becomes \( \Omega D^2 \sim A \sim 2R^2 \). Note that the mass of the HVC complex is the same in both intermediate and extreme density case and that the H I volume number density of the HVC complex ranges from \( 1.14 \times 10^{-3} \text{ cm}^{-3} \) (intermediate GCN) to \( 2.03 \times 10^{-2} \text{ cm}^{-3} \) (extreme WD). By considering two different velocities and two different sizes (one as the intermediate case and the other being extreme) for the approaching HVC complexes, we set up four different infall cases. A representative simulation run of the collision scenario between the disk and Complex C is shown in Figure 1. The figure illustrates the most extreme case (higher velocity and density) among the four possible setups for Complex C, where the vertical velocity and the H I volume number density are \( 143.9 \text{ km s}^{-1} \) and \( 5.20 \times 10^{-4} \text{ cm}^{-3} \), respectively.

2.3. Estimating Fuel Efficiency

From the collision between the HVC complex and the disk, a shock is generated and the velocity of the forward shock which propagates through the galactic disk \( v_{\text{sd}} \) is estimated from

\[
v_{\text{sd}} = \frac{4}{31 + \sqrt{\rho_\odot / \rho_i}} v_i, \tag{2}
\]

where \( \rho_\odot \) is the volume density of the Galactic disk, \( \rho_i \) is the volume density of the HVC complex, and \( v_i \) is the velocity of the HVC complex (Tenorio-Tagle 1981; Lee et al. 1996; del Valle et al. 2018). Without gravity and cooling included in our simulations, the rear shock that is generated from the collision will be continuously expanding back into the interstellar medium (ISM). Also, some amount of the disk material would be permanently removed from its original position. Therefore, we define the characteristic time \( \tau_{\text{char}} = h_d / v_{\text{sd}} \), where \( h_d \) is the thickness of the disk to approximate the long-term evolution by assuming that the infusion process is completed at \( t = t_i + 2\tau_{\text{char}} \), where \( t_i \) is the time at impact. For such a time period, we investigate the time evolution of the HVC mass that is infused into the disk and apply Equation (1) to further estimate the rate of mass infusion for multiple HVC collisions. For an example, the time evolution of the mass infused into the disk from the Complex C inflow is illustrated in Figure 2. Note that this plot is made from the simulation run shown in Figure 1. As full accretion is the underlying assumption in the traditional scheme, the fuel efficiency is estimated as the ratio of infused HVC mass obtained from the simulation results to the traditional prediction, i.e., the total HVC mass fully accreted onto the disk. Figure 2 shows that the fuel efficiency can be quite low, because the HVC material cannot penetrate into the disk. This occurs mainly because the density of Complex C is lower than that of the disk. As illustrated in Figure 1, the spherical complex is deformed into a horizontally flat shape and bounces back into the ISM when the low-density cloud impacts the high-density disk. In contrast, we find that the high-density cloud penetrates into and passes through the low-density disk, although we do not show the results of our test simulations.

3. Results

3.1. Proof of Concept

We set up two different infall cases where five HVCs with the same mass of \( 1.0 \times 10^6 \text{M}_\odot \) and the H I volume number density of \( 1.0 \times 10^{-3} \text{ cm}^{-3} \) fall down on the Galactic disk. For the first case, the velocity is fixed at \( 100 \text{ km s}^{-1} \), but the distance of each HVC increases from \( 2 \text{kpc} \) to \( 10 \text{kpc} \) with an increment of \( 2 \text{kpc} \). In the second case, the distance is fixed at \( 4 \text{kpc} \), but the velocity of the HVCs decreases from \( 120 \text{ km s}^{-1} \) to \( 40 \text{ km s}^{-1} \) with a decrement of \( 20 \text{ km s}^{-1} \). As full and steady accretion of mass is assumed until the time to impact in the traditional scheme, the infusion of mass as a function of time will look similar to a staircase function (Putman et al. 2012) as in the left panels of Figures 3 and 4. On the other hand, the simulation results, which are represented with dotted lines on the same panels, show peaks where the maximum infusion of each HVC has occurred at sometime after impact and then smooth down as the infusion is further processed and finally completed. The right panels of Figures 3 and 4 show the HVC mass infusion rate (i.e., infall rate) estimated from Equation (1) at times where each HVC has completed the infusion process. The simulation result is represented with filled diamonds and the traditional estimation with empty diamonds. The fuel efficiency estimated as the ratio of infused HVC mass from our simulations to the total mass in the traditional estimation is 0.211 for the first case and 0.111 for the second. The average efficiency of the infall rate is 0.217 for the first case and 0.246 for the second. While detailed investigation on the interaction between an HVC complex and the Galactic disk, which depends on the density, size, velocity, and distance of the complex is further required, we see in both cases that the infusion (or supply) rate of mass from
HVCs into the Galactic disk is overestimated in the traditional estimation compared with that in the simulation where we consider the interaction between HVCs and the disk.

3.2. HVC Complexes

Using the HVC parameters in Table 1, we set up four different infall cases from the combinations between two different velocities and two different densities. The results for these cases are shown in Figure 5. While the HVC complexes in case 1 and case 2 share the same velocity, the ram pressure and drag force acting on the complexes are different, due to different densities when moving through the halo. As a result, the complexes in case 2 generally have later impact times compared with those of the complexes in case 1, and this also applies between case 3 and case 4, which have the same intermediate velocities but different densities. As in the left panels of Figures 3 and 4, the traditional estimation of the HVC mass infusion as a function of time is illustrated as a staircase function, although it looks different in each case. The results obtained with the hydrodynamic simulations are represented in dotted lines and the fuel efficiency is 0.186, 0.044, 0.174, and 0.042 for cases 1, 2, 3, and 4, respectively. Despite the difference in velocity, the final efficiency in case 1 is similar to that in case 3, where the two cases share the same density. Such feature is also found between case 2 and case 4. Since the complexes in cases 1 and 3 have a larger density than those in cases 2 and 4, we can conclude that the final efficiency depends strongly on the density than on the velocity of the cloud or it increases as the density of cloud increases when the hydrodynamical interaction between the cloud and disk is...
considered. This likely occurs because the densities of the HVC complexes in consideration are smaller than the density of the disk, but the denser complex still penetrates into the disk more efficiently. The right panel of Figure 5 shows the HVC mass infusion rate (i.e., infall rate) estimated from Equation (1) at time points where the infusion process has been completed for each HVC complex. The average efficiency of the infusion rate is 0.249, 0.092, 0.247, and 0.072 for cases 1, 2, 3, and 4, respectively. Again, the average efficiencies of the infall rate in cases 1 and 3 (2 and 4) are similar regardless of their velocity differences, but efficiencies in cases 1 and 3, where the density of the complexes are larger, are higher than those in cases 2 and 4. Overall, we see in all 4 cases that the supplied amount of mass from infalling HVC complexes into the Galactic disk are overestimated in the traditional estimation compared with our simulation results that include the hydrodynamic interaction between HVCs and the disk. This is mainly because all the complexes in consideration have a lower density compared with the gaseous disk. In other words, individual complexes, regardless of the selection of density and velocity, have a similar trend of fuel efficiency to that shown in Figure 2.

4. Discussion

Though we have attempted to eliminate the long-term dynamical effects during the collision between the Galactic disk and an HVC complex by assuming that the infusion of mass from HVCs are completed at the time $2r_{\text{char}}$ after impact, we are well aware of the fact that the simulation in this study is a simplified model and has limitations as we did not include gravity, cooling, and magnetic fields that could also play important roles in the interaction between the disk and HVC. Below, we give a list of improvements that could be made on our current simulation setup and briefly discuss how each element could act on the fuel efficiency.

1. Adopting a nonuniform density profile for the HVC complexes, Galactic disk, and halo material. Section 3.2 shows that the fuel efficiency depends more strongly on the density of the HVC complexes than on the velocity. Furthermore, considering the case where the complexes have a nonuniform density profile, the lower-density gas at the edge of the complex will mix with the ISM in the halo instead of being infused into the disk due to shear instabilities (e.g., Kwak et al. 2011), which in turn will result in lower fuel efficiency.\(^2\)

2. Considering the galactic gravitational field. Gravity is a fundamental physical process in almost every astrophysical situation. However, at reasonably short timescales of the infusion process, the hydrodynamic interactions are dominant over the effects of gravity. Therefore, we expect the impact on fuel efficiency from gravitational fields would be more significant at later times long after the collision between the complex and the disk. We eliminated the gravitational effects by assuming that the infusion process is completed at the time $2r_{\text{char}}$ after impact. However, if gravity were considered instead of making such an assumption, there could be cases of steady accretion when the cloud does not survive after impact, or maybe the fuel efficiency will increase in general as the HVC materials would “tend” to stick better onto the Galactic disk. We should also consider that the velocity of the HVC complexes would increase at the time of impact due to gravitational acceleration.

3. Taking into account the magnetic fields in the Galaxy. How the magnetic field affects fuel efficiency can be complicated, as it depends on the orientation of the field. In general, the magnetic field will restrain the growth of shear instabilities (Mac Low et al. 1994; Jones et al. 1996), which could increase the fuel efficiency by making the HVCs survive longer in the halo. However, the field lines will be compressed during the collision when their orientation is perpendicular to the HVC velocity. In this case:

\(^2\)Interaction of the infalling HVCs with the gas pushed up into the halo by stellar and/or supernova feedback would also decrease the fuel supply rate (Fraternali & Binney 2008).
case, the complex would encounter resistance which would potentially prevent the infusion of mass and lower the fuel efficiency (Santillán et al. 1999; Kwak et al. 2009).

4. Considering cooling effects during the infusion process. As there is no cooling included in our simulation, the rear shock will be ever expanding back into the ISM. Assuming that radiative cooling is important, the HVC material bounced back from the disk will mix with the ISM close to the disk instead of propagating far away from the galactic disk. From then on, gravity could take over and allow additional accretion which will increase the fuel efficiency in the long term.

5. Considering the actual path of HVC inflow (i.e., nonvertical drop). The early hydrodynamic interaction timescale will increase when the path of HVC inflow is nonvertical. The magnetic field orientation along with other physical conditions of the inflowing HVCs must be considered; however, a longer mixing-time would generally allow more accretion of mass from inflow and increase the fuel efficiency.

5. Conclusion

This work is motivated from a simple idea that HVC complexes may not continuously nor fully accrete on the Galactic disk because the hydrodynamic interaction between the disk and HVCs is not considered in the traditional method of estimating the infall. We selected 11 HVC complexes and constructed four infall cases to point out that the infall rate from HVCs in the GCE is to figure out how stars form from HVC infall, which also requires a detailed investigation on the amount of H$_2$ that is converted from the H I which has survived from HVC infall.

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