The collisions of high-velocity clouds with the galactic halo

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\begin{abstract}
Spiral galaxies are surrounded by a widely distributed hot coronal gas and seem to be fed by infalling clouds of neutral hydrogen gas with low metallicity and high velocities. We numerically study plasma waves produced by the collisions of these high-velocity clouds (HVCs) with the hot halo gas and with the gaseous disk. In particular, we tackle two problems numerically: 1) collisions of HVCs with the galactic halo gas and 2) the dispersion relations to obtain the phase and group velocities of plasma waves from the equations of plasma motion as well as further important physical characteristics such as magnetic tension force, gas pressure, etc. The obtained results allow us to understand the nature of MHD waves produced during the collisions in galactic media and lead to the suggestion that these waves can heat the ambient halo gas. These calculations are aiming at leading to a better understanding of dynamics and interaction of HVCs with the galactic halo and of the importance of MHD waves as a heating process of the halo gas.

\textit{Keywords:} Numerical simulations, high-velocity clouds, plasma waves, dispersion relations
\end{abstract}

\section{1. Introduction}
Spiral galaxies are surrounded by hot coronal gas for whose existence three main origins are under debate: 1) Most plausibly, star-formation activity in the galactic disk (stellar wind and supernova type II explosions) pushes hot gas into the halo, by this, producing the hot-gas halo \cite{1,2}. 2) Galaxy growth within the ΛCDM cosmology will inherently lead to gas accretion and by this produce a hot halo with virial temperatures if the cooling time is too long as for temperatures above $10^6$ K and thus for large galactic masses of $M > 10^{11} M_{\odot}$. 3) And at least, cosmological simulations suggest that $30 - 40\%$ of all baryons reside in a cosmic web of shock-heated warm-to-hot intergalactic medium accumulating as an extended hot halo around massive galaxies \cite{3}.

Another gas phase existing in the halo of spiral galaxies are high-velocity clouds (HVCs). In the Milky Way these gas complexes are detected in HI at high galactic latitudes \cite{4} and are falling with high speeds towards the galactic disk. Since galactic halo gas is preferentially assumed to be produced through the above-mentioned process 1), some of this hot gas is suggested to condense, cool \cite{5}, and to fall back to the galactic plane, or HVCs can stem directly from galactic HI gas that is swept-up by superbubbles, lifted into the halo, and returns on ballistic trajectories. While the first is, however, contradicted by Binney and collaborators \cite{6} because of heat conduction, the second process would require also positive HI cloud velocities which are, however, not observed.

This expected galactic fountain effect \cite{7} can, however, not explain HVC velocities close or even above the galactic escape value. Moreover, HVCs contain clearly less than solar metal abundances and have probably larger distances \cite{8,9} than achievable from
superbubble expansion, so that their origin from the galactic disk is very unlikely. In addition, there also exists a population of intermediate velocity HI clouds (IVCs). With their higher metallicity and far lower velocity of only $50 - 100 \, \text{km} \cdot \text{s}^{-1}$ these clouds as well as those even slower (and smaller), so-called low-velocity clouds (LVCs), are also likely to reflect at least partly back-falling bullets expected from a galactic fountain.

A not insignificant part of LVCs, however, can be assumed to have passed the galactic halo and is decelerated by the drag of the ram pressure exerted by the hot halo gas \(^{10}\). This also leads to gas stripping from the clouds which is discernible as head-tail structure of HVCs \(^{11}\). As observed in several HVCs before and expected theoretically \(^{12}\), the HVC 125+41-207 shows a two-phase structure with a low and high velocity dispersion for column densities larger than $2 \times 10^{19} \, \text{m}^{-2}$.

Since in external galaxies seen edge-on like e.g. NGC 891 and NGC 4361 the hot halo gas is permeated with vertical magnetic field lines, and because the galactic hot halo gas is assumed to be mostly replenished by superbubbles which open perpendicular to the gaseous disk and, by this, also open the galactic magnetic field perpendicularly as it is coupled to the ionized gas, HVCs must be assumed to interact with the halo magnetic field. Unfortunately, topology, strength, and signatures of the galactic magnetic field are not well known and not yet manifested by observations. Consequently, the magnetic coupling of HVCs with the halo magnetic field is still vague and not yet elaborated. This innocence is not only caused by uncertainty of the field topology but mainly due to the total absence of magnetic field measurements in HVCs.

Only Zimmer et al. \(^{13}\) interpreted observations of X-ray gas connected with HVCs \(^{14}\), and preferentially with the HVC complex C, as signatures of magnetic reconnection and explored the magnetic interaction of HVCs with the Reynolds layer \(^{15}\). Another and far more realistic interpretation of the multi-gas phase coincidence in HVCs is the sweep-up of hot halo gas by the large complexes on their passage through the halo. HVC models by Vieser & Hensler \(^{16}\) in which the clouds survive the disruption by Kelvin-Helmholtz instability due to self-gravitation, heat conduction, and cooling, the gas accumulation from such surrounding hot gas has been demonstrated.

Subsequently, Santillan et al. \(^{17}\) investigated the collision of HVCs with the magnetic galactic gas disk by means of 2D numerical models. In contrast to the model assumptions of both studies no HVCs, i.e. large cloud complexes with velocities of $-200 \, \text{km} \cdot \text{s}^{-1}$ and below, are found close to the galactic disk. Another limitation is that the magnetic field (in 2D) is only directed parallelly to the galactic plane.

2. Motivation of the numerical study

One of the unsolved problems in solar plasma physics is the heating of the solar corona. There exist mainly two possible explanations of this interesting problem – magnetic energy releasing and heating by the reconnection of magnetic field and heating the solar corona by plasma waves. In recent years, both of possible mechanisms were solved by many authors theoretically and also numerically (see e.g. \(^{18}\), \(^{19}\) or \(^{20}\)).

Since superbubbles expanding into the halo are supposed to cool adiabatically and the halo gas should continue at lower temperature to cool by radiation and by cloud evaporation, a continuous hot gas
supply is necessary. Because of the complexity of the multi-phase gas structure of the halo there is still a lack of sufficiently detailed quantitative explorations and results about its thermodynamics and magnetohydrodynamics [21]. An additional heating source would therefore elegantly provide a solution to prevent the halo cooling. During the collisions of HVCs on trajectories oblique or perpendicular to the magnetized galactic halo or galactic disk, the magnetic field lines along the galactic disc are distorted [13], gas is compressed, and MHD waves are generated.

Such MHD waves (including reconnection of magnetic field) may, on one hand, lead to heating of the ambient gas and can, furthermore, influence the evolution and the dynamics of HVCs. This process is analogous to the coronal heating in the sun [22]. This similarity of MHD processes encourage us to begin analogous MHD studies of HVCs passing through the halo and approaching the galactic disk while interacting with the magnetic field.

3. Numerical model

3.1. Simulations of collisions of HVCs with galactic halo

In plasma physics, there exist several methods, how the plasma dynamics can be described and calculated, see e.g. [23], [24].

For the calculations of HVCs’ dynamics we used the full set of MHD equations [25] with the addition of gravitational term:

\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}),
\]

\[
\frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B} + \rho \mathbf{g},
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}),
\]

\[
\frac{\partial \mathbf{U}}{\partial t} = -\nabla \mathbf{S},
\]

\[
\nabla \cdot \mathbf{B} = 0.
\]

Here \(\rho\) is a mass density, \(\mathbf{v}\) (relative) flow velocity, \(p\) gas pressure, \(\mathbf{B}\) is the magnetic field and \(\mathbf{g}\) is the gravitational acceleration calculated by means of Eq. [17].

The plasma energy density \(U\) is given by:

\[
U = \frac{p}{\gamma - 1} + \frac{\rho}{2} v^2 + \frac{B^2}{2\mu_0},
\]

with the adiabatic coefficient \(\gamma = 5/3\), and the flux vector \(\mathbf{S}\) is expressed as:

\[
\mathbf{S} = \left( U + p + \frac{B^2}{2\mu_0} \right) \cdot \mathbf{v} - (\mathbf{v} \cdot \mathbf{B}) \frac{\mathbf{B}}{\mu_0}.
\]

The magnetohydrodynamic equations [11-14] were transformed into a flux conserving form, i.e.:

\[
\frac{\partial \Psi}{\partial t} + \frac{\partial F(\Psi)}{\partial x} + \frac{\partial G(\Psi)}{\partial y} = 0,
\]

and were solved numerically. The vector \(\Psi\) in our two-dimensional case is expressed as:

\[
\Psi = \begin{pmatrix} \rho \\ \rho v_x \\ \rho v_y \\ B_x \\ B_y \\ U \end{pmatrix}.
\]

The vector functions \(F(\Psi)\) and \(G(\Psi)\) are too complex to be presented here, for more information see e.g. [25].

For the numerical solution of this type of equations the two-step Lax–Wendroff algorithm is used. The numerical region is oriented in the \(x, y\)-plane, implemented at \(0 \leq x \leq L\) and \(0 \leq y \leq L\) and covered by a uniform grid with \(200 \times 200\) cells. We choose the \(x\) coordinate to be oriented in the galactic plane, while \(y\) points vertically into the halo.

Open boundary conditions are applied and the time step satisfies Courant-Friedrichs-Levy condition in the form [23]:

\[
\Delta t \leq \frac{\text{CFL} \cdot \Delta x}{\max(\epsilon_s + |v|)},
\]

where the Courant number CFL is set to 0.8.
3.2. Calculations of phase and group speeds

For the calculations of phase and group velocities of plasma waves in the galactic gas, we numerically solve the wave equation for plasma motions, where the equilibrium parameters (density and pressure) depend on y (e.g. [26]):

\[
\frac{d}{dy} \left[ f(y) \frac{dv_y}{dy} \right] + \varrho(\omega^2 - k_x v_{Alf}^2)v_y = 0. \tag{11}
\]

Here \(v_y\) is the velocity component normal to the magnetic field, \(\omega\) is the frequency, \(k_x\) is the longitudinal wavenumber along the \(x\)-axis, and Alfvén speed \(v_{Alf}^2 = B^2/\mu_0\varrho\).

The boundary conditions at the point \(y = y_{\text{max}}\) such that:

\[
\xi_1 = c \cdot f(0), \quad \xi_2 = 0, \quad \text{whereas the constant } c \text{ is arbitrary.}
\]

To obtain a solution of Eq. (11) a fixed value of \(k_x\) is used, integrating between \(y = 0\) and \(y = y_{\text{max}}\) the two first-order differential equations (14) and (15) by means of the fourth-order Runge-Kutta method. Exact value of the frequency \(\omega\) is obtained by the bisection iteration method when the velocity \(v_y\) satisfies the boundary condition at the second point \(v_y(y = y_{\text{max}}) = 0\) for both wave modes (“kink” and “sausage” mode).

The total gas pressure \(p_{\text{tot}}\) (gas and magnetic) is expressed as:

\[
\frac{i\omega}{\varrho} p_{\text{tot}} = -c_s^2(\omega^2 - k_x^2 c_s^2) \frac{dv_y}{dy}. \tag{16}
\]

and for the calculation of the magnetic tension force \(T_1\) we use the equation in the form, see [26]:

\[
\frac{i\omega}{\varrho} T_1 = (\omega^2 - k_x^2 c_s^2) \frac{v_{Alf}^2}{c_s^2} \hat{e}_x - v_{Alf}^2 k_x^2 v_y \hat{e}_y. \tag{17}
\]

This force is a part of the Lorentz force \(j \times B\) and appears whenever the magnetic field lines are curved. Magnetic tension force is determined by how much the magnetic pressure changes with distance (for detailed information see [26]).

4. Initial conditions

4.1. Collisions of HVCs with galactic halo

Numerical solutions of MHD equations are performed in 2D space. The absolute size of the simulation box amounts 3 kpc × 3 kpc. The initial position of modeled HVC is located 1250 pc above the galactic plane with an initial velocity of \(v_0 = -200 \text{ km} \cdot \text{s}^{-1}\).

The mass density distribution of the galactic gas is given by the equation:

\[
\varrho(y) = \varrho_0 |0.6 e^{-y^2/(280pc)^2} + 0.37 e^{-y^2/(540pc)^2} + 0.1 e^{-|y|/400pc} + 0.03 e^{-|y|/900pc}|. \tag{18}
\]
and for the expression of the gravitational acceleration we use the equation (17):

\[
g(y) = 8 \cdot 10^{-7} [1 - 0.52e^{-|y|/325\text{pc}} - 0.48e^{-|y|/900\text{pc}}] \text{ m} \cdot \text{s}^{-2}.
\] (19)

The galactic midplane gas density in Eq. (18) is \( \rho_0 = 2.24 \times 10^{-21} \text{ kg} \cdot \text{m}^{-3} \) and the initial magnetic field \( B_0 = 5.0 \mu\text{G} \). The total pressure is given by the relation \( p(y) = \int g \text{d}y \), with the boundary condition that \( p_{\text{out}} = p(y = 5.0 \text{ kpc}) = 0 \text{ Pa} \). The galactic midplane value of the total pressure \( p_0 = 2.7 \times 10^{-13} \text{ Pa} \) [17].

4.2. Phase and group speeds

For both studied cases (uniform magnetic field parallel to the galactic plane and galactic current sheet configuration), we assume, in the state of equilibrium, initial plasma velocity \( v = 0 \).

Equilibrium demands that the pressure (plasma plus magnetic) is uniform, i.e.:

\[
p + \frac{B^2}{2\mu_0} = \text{const.} \tag{20}
\]

4.2.1. Uniform magnetic field

In this case, the magnetic field is assumed \( B = B_0 = \text{const.} \) in the whole simulation region. The total pressure \( p \) according to the Eq. (20) is also assumed to be a constant, \( p = p_0 \).

4.2.2. Current sheet

In the case of current sheet configuration the magnetic field is given by the equation (18):

\[
B = B_0 \tanh \left( \frac{(y - L/2)}{a} \right) \hat{e_x},
\] (21)

and the equilibrium in Eq. (18) yields a plasma pressure given by:

\[
p(y) = p_0 \text{sech}^2 \left( \frac{(y - L/2)}{a} \right),
\] (22)

given that \( p \to 0 \) (cold plasma) as \((|y|/a) \to \infty \) [26], and where \( a = 0.5 \text{ kpc} \) is the semi-width of the current sheet.

Numerical solutions of Eq. (11) are performed only for the so-called “kink” mode [26], which well corresponds to the situation of the HVC collision with galactic disk.

5. Results and discussions

In this section we present some selected numerical results obtained by means of our simulations.

5.1. Collisions of HVCs with galactic halo

In Figs. 2 and 3 we present the “time evolution” of a HVC collision with galactic media. Fig. 2 shows the perpendicular collision, whereas in Fig. 3 an oblique passage of the HVC with \( \alpha = 45^\circ \) through the galactic halo is depicted.

The situations (a) show the gas density distribution at the “beginning”, i.e. \( T_a = 0.6 \text{ Myr} \) after the onset of the calculation, while the locations (b) present the density distributions for the time \( T_b = 7.9 \text{ Myr} \) in the case of perpendicular collision (Fig. 2) and \( T_b = 12.8 \text{ Myr} \) for oblique cloud infall (Fig. 3).

Figure 2: The “time evolution” of the collision of HVCs with galactic halo in the case of perpendicular cloud infall. a: cloud at 0.6 Myr after the start of the models, b: position and structure at time \( T_b \) (see text).

In both cases at time \( T_b \) a dense regime in front of the HVC is clearly visible, where the galactic gas is
compressed as the HVC moves towards denser galactic disk and is decelerated.

Because this infall motion towards denser gas causes a bow shock to form, consequently, also plasma waves are created.

In Figs. 4 and 5 are shown the total pressure of the galactic gas and magnetic field lines for both studied cases, i.e. perpendicular and oblique infall under angle $\alpha = 45^\circ$. The pressure on the head of the cloud is higher because the cloud moves through gas with increasing density near galactic disk, and the magnetic field lines are distorted because the magnetic field is "frozen" to the HVC.

5.2. Phase and group speeds

In Figs. 6 and 7 we present the phase and group speeds of wave signal, plasma velocity, total gas pressure and magnetic tension force for magnetic field oriented parallelly to the galactic plane and for a current sheet configuration, respectively.

Notice, that in the graph of the phase and group speeds the scale on the left-hand side corresponds to the phase speed (solid line), whereas the scale on the right-hand side corresponds to the group speed (dash-dotted line) of the plasma waves. If we compare the phase and group speeds for both studied cases, we can see that the profiles of phase speeds are similar, whereas the group speeds have different shapes. In the case of the current sheet the group speed becomes constant for high wavenumbers.

From the figures of total pressure $p_{\text{tot}}$ we can discern that for $k_x a = 5$ (red line) the lines are also the same, whereas for $k_x a = 10$ (blue line) the total pressure is zero outside of current sheet, because of
constant (zero) plasma velocity \(v_y\), see Eq. (16).

For the plasma velocity component \(v_y\) in Fig. 7 it is clearly visible, where the edge of the current sheet is located. Outside of the current sheet the plasma velocity is zero for \(k_xa = 10\) and falls to zero in case of \(k_xa = 5\). This means that practically only the part of the galactic gas, where the magnetic field is not constant, is moving. In the case of a parallel magnetic field, galactic gas moves over the whole simulation region. It is probably caused by the fact, that inside the current sheet is present the Lorentz force \(\mathbf{j} \times \mathbf{B}\) which does not allow the plasma waves generated in the center of the current sheet leave freely this space.

As one can see, the \(y\)-component of the magnetic tension force \(\mathbf{T}_1\) is in “anti-phase” to the plasma \(y\)-velocity component in all cases.

6. Conclusions

Our main aim is to investigate the effects of the collisions of HVCs with both the galactic media, hot halo gas and magnetic field, on their descendence towards the galactic disk. For this purpose here we present a first insight with respect to two aspects by 2D numerical models: at first, we solve numerically the set of MHD equations and simulate the collisions of HVCs with the galactic media for two cases (oblique and perpendicular collision). In the second part of this paper, the equation of plasma motion is treated numerically in order to obtain the dispersion relations of waves in galactic media.

In the literature [13] it is envisaged that the reconnection of magnetic field lines in the galactic halo can lead to its gas heating. Unfortunately, but as a physically reasonable by-product, heating of the halo gas by plasma waves is not yet taken into account. There exists practically no paper dealing with this interesting problem.

Our first results demonstrate that plasma waves provide an important heating process of the galactic halo gas in analogy to the solar corona. From the above-mentioned reasons our results are new and their further exploration of crucial importance for our understanding of the heating processes in the interstellar medium in general. Nevertheless, 2D simulations can only deal as a first insight but 3D simulations are urgent for the MHD treatment to deliver more accurate and reliable results. Therefore, as the next step we will advance our models to 3D.
and to higher spatial resolution. For this purpose we intend to use as a powerful, well tested and widely applied tool for astrophysical simulations of many applications the FLASH code \cite{28}, parallelized and with adaptive mesh refinement. Recently, \cite{29} performed first 3D models using FLASH, but with the main emphasis on the structural evolution of fountain clouds starting at a height of 5 kpc above the galactic disk. From the extension of our numerical models we expect important results and information about the MHD waves in galactic media. As further steps, also small-scale plasma processes like heat conduction must be included, that leads to the stabilization of clouds \cite{16} by suppression of KH instability.

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