

Origin of the Cometary Structure of the HVCs: 3D-MHD Numerical Simulations

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(Received Sep. 10, 2001; Accepted Nov. 15, 2001)

ABSTRACT

Here we continue the MHD study started by Santillán et al (1999) for the interaction of high-velocity clouds (HVCs) with the magnetized thick gaseous disk of our Galaxy. We use the MHD code ZEUS-3D and perform 3D-numerical simulations of this interaction, and study the formation of head-tail structures in HVCs. Our results show that clouds located above 2 kpc from midplane present velocity and column density gradients with a cometary structure that is similar to those observed in 21 cm emission

Key Words : ISM: clouds – ISM: magnetic fields – MHD – turbulence – waves

I. INTRODUCTION

High velocity clouds (HVC) are atomic HI complexes located at high galactic latitudes, and moving with large velocities ($|V_{LSR}| \geq 90$ km/s) that do not match a simple galactic rotation model. They were discovered by Muller et al. (1963). Brüns et al. (2000), based on the Leiden/Dwingeloo HI survey found from a sample of 252 clouds with $N_{HI} \geq 10^{19}$ cm⁻² that only 20% display simultaneously a velocity and column density gradients, with a cometary structure called head-tail HVCs (HT-HVCs). The best-known examples are HVC192-24-130 and HVC189-30-205 belong to the anti-center complex, and HVC128-36-425. This cloud, in particular, present a beautiful cometary structure with the highest observed radial velocity (-425 km s⁻¹) in the sample.

Their origin may be associated with a Galactic fountain (Shapiro & Field 1976) or gas stripping from the Magellanic clouds and other dwarf galaxies in the Local Group. Because of the poor distance information on HVCs, observational results cannot decisively uncover their particular origin. Recently, Quilis & Moore (2001) did three-dimensional hydrodynamical simulations in order to test this ideas. They preferred the Galactic fountain model, since the required density for the medium in which they move should be at least 10^{-4} cm⁻³ to form the HT-HVCs. This is larger than the expected density in the outer halo at a distance around 100 kpc.

Santillán et al. (1999) studied the evolution of HVCs in a magnetized gaseous Galactic disk by means of two-dimensional MHD numerical simulations. The initial magnetic field is oriented parallel to the disk and they consider two different field topologies: parallel and perpendicular to the plane of motion of the clouds. The effect of the interaction cloud-Galactic disk produces HVCs with cometary appearance after a long time evolution.

In this paper we continue this study, extending

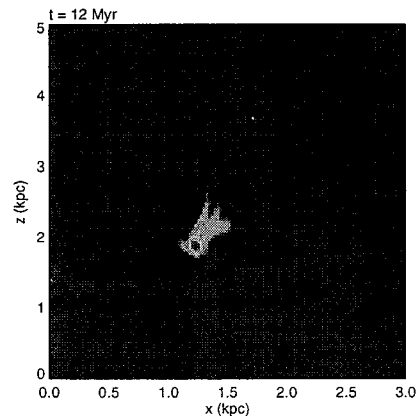


Fig. 1.— Column density, represented in logarithmic color-scale, in the x - z plane. In this case we only consider the material that moves at velocities above than 60 km s⁻¹

our numerical simulation to three-dimensions to analyze the role of the magnetic field, which was ignored by Quilis & Moore (2001), in the formation of the HT-HVCs. Again, the evolution of these objects is followed with the MHD code ZEUS-3D.

II. NUMERICAL METHOD

The numerical calculations were performed with the MHD code ZEUS-3D (Stone & Norman 1992a,b; Norman 2001), using the UNAM's ORIGIN-2000 supercomputer. Our simulations have the following characteristics: the reference system is one in which the disk gas is at rest and the origin of our Cartesian compu-

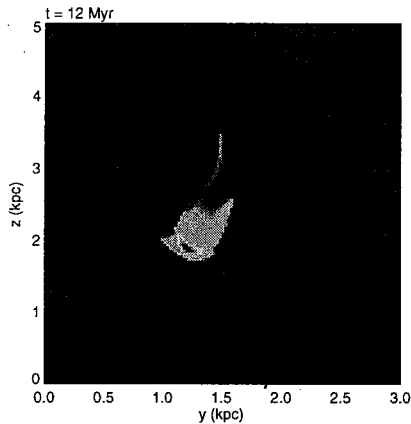


Fig. 2.— Same as figure 1 but in the y - z plane

tational mesh (x, y, z) is the local neighborhood. The resolution of the computational mesh is $128 \times 128 \times 128$ cells, and the boundary conditions are *periodic* in the axes x and y , and *reflecting-outflow* in the z -axis. The spatial dimensions presented here are $3 \text{ kpc} \times 3 \text{ kpc} \times 5 \text{ kpc}$.

The initial spatial dimensions of HVCs are $117 \text{ pc} \times 117 \text{ pc} \times 215 \text{ pc}$, they have a mass and density of $10^4 M_\odot$ and 0.1 cm^{-3} , respectively. The cloud is launched with a velocity of 200 km s^{-1} , which corresponds to a kinetic energy of 4×10^{51} ergs. We positioned the cloud center at a height of 4 kpc from midplane, with an impact angle of 30° with respect to the z -axis.

III. RESULTS

The ambient medium that is interacting with the HVC is represented by a magnetized gaseous atmosphere, that is the high-latitude extension of the Galactic thick disk (Martos 1993; Santillán et al. 1999). The initial magnetic field has only a component along the x -axis and is stratified in the z -direction, $B_x(z)$. The gas is assumed isothermal with a sound speed of 8 km/s , and the effective disk scale height is $H = 166 \text{ pc}$.

Figures 1 and 2 present the evolution of a fast HVC in the Galactic halo. These snapshots show the column density, represented in logarithmic color-scale, in the x - z and y - z planes, respectively. We consider only the material that moves at velocities above 60 km/s .

The cloud has moved from its original position and now is located at 2 kpc above the midplane. It has developed a cometary structure with velocity and column density gradients, that are similar to those observed in

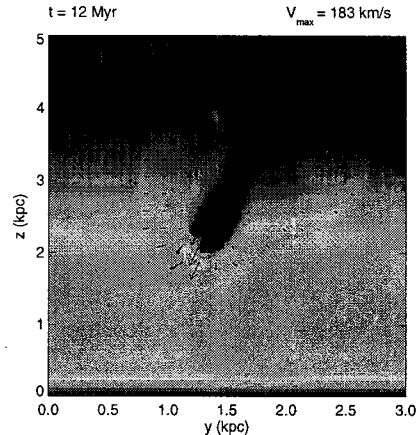


Fig. 3.— Density cut (logarithmic color-scale) in the y - z and velocity field (arrows)

21 cm emission. (Brüns et al. 2000)

Figure 3 shows a density cut (logarithmic color-scale) in the y - z plane, with the velocity fields (arrows). The impact creates a strong galactic shock directed downwards, this tends to move radially away from the location of impact. The initial cloud is completely shocked in a relatively short timescale, and the vacuum left by the cloud motion is filled up by infalling material and by re-expansion of the shocked layer. The shapes of the interstellar structures are modified by the lateral velocity component. The motion of the shocked layer creates the rear wake (with vorticity and swirling motions), and a tail that extends downstream to locations close to the point of impact.

The slower downward speeds, and the inclination of the structure, allows for the gas of the tail to catch up with the main body of the shocked layer. The velocity vectors within the structure are now larger, and clearly show the re-expansion into the rarefied regions. The shear between this faster flow and its surrounding medium is subject to Kelvin-Helmholtz instabilities, but we cannot resolve the instability here. The oscillatory motion of the finger-like tail, is due to the combined effects of the vorticity of the rear flow and the unresolved instability.

Finally, Figure 4 shows a density cut in the x - z plane (logarithmic color-scale), with the velocity (arrows) and magnetic field lines (lines). The initial shock fronts move faster than MHD waves, and are responsible for the strong deformation of the initial field configuration. A substantial fraction of the energy goes into the compression and tension of the distorted field lines. The disk material that is inside (and above) the

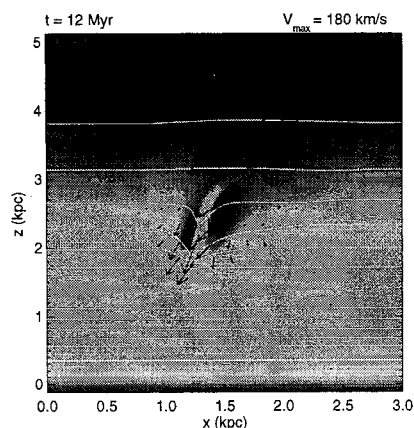


Fig. 4.— Density cut (logarithmic color-scale) in the x - z , velocity field (arrows), and magnetic field (lines)

distorted sections slides down along the field lines, like in an incline plane, the distortions disrupt the local hydrostatic equilibrium, and there is a clear infall of material in the perturbed region. This creates a dense “head” of the perturbation moving towards the disk. The asymmetries in the distorted lines produce two important effects in the tail. First, the downstream (right) field distortion has a larger extent, with a softer slope, than the one created upstream (left). Thus, there is more mass sliding down towards the tail from the downstream side. This provides additional momentum to the tail, and creates a large rarefied region behind it, that is maintained for a long timescale (up to the end of the run). Second, the gas that slides down from the upstream side provides an effective (ram pressure) force that opposes to the motion of the tail.

ACKNOWLEDGEMENTS

We are grateful to M. Norman for helpful comments that improved this work. A.S. wish to acknowledge the financial support given by the Organizers to participate in this excellent workshop. J.F. acknowledges partial support from a DGAPA-UNAM grant, and a bilateral agreement between CONACyT-México and KOSEF-Korea. This work has been partially support by an R&D grant from Cray Research, INC.

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