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INTERACTION OF HIGH VELOCITY CLOUDS WITH MAGNETIZED DISKS: THREE-DIMENSIONAL NUMERICAL SIMULATIONS

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ABSTRACT

High-velocity clouds are flows of neutral hydrogen, located at high galactic latitudes, with large velocities ($| V_{LSR} | \geq 100$ km/s) that do not match a simple model of circular rotation for our Galaxy. Numerical simulations have been performed for the last 20 years to study the details of their evolution, and their possible interaction with the Galactic disk. Here we present a brief review of the models that have been already published, and describe newly performed three-dimensional magnetohydrodynamic simulations.

Key words : ISM: clouds—ISM: magnetic fields—ISM—MHD

I. INTRODUCTION

At present we know that a considerable quantity of atomic neutral hydrogen (HI) extends and occupies a fraction of the halo of our Galaxy. This gas is located at high latitudes and displays radial velocities that can be positive or negative (infall) with respect to the mid-plane of the Galactic disk, and that cannot be explained by a simple model for galactic rotation (Muller et al. 1963; Mirabel 1981; Bajaja et al. 1985; Wakker 1991; Wakker & van Woerden 1997). Several of these objects have been detected in the spectral lines of molecular hydrogen (Ritcher et al. 1999), some heavy elements (Wakker 2001), and highly ionized species (Fox et al. 2004). Clouds with radial velocities, relative to the Local Standard of Rest (LSR), larger than ~ 100 km/s are known as high velocity clouds (HVC), and those with velocities between 40 and 100 km/s are called intermediate velocity clouds (IVC). The use of only v_{LSR} as the criterion to classify HI flows is somewhat restrictive because the range of velocities allowed by the model of circular galactic rotation varies strongly with position. In fact, Wakker (1991) introduced the concept of "deviation velocity" $v_{\rm dev}$ (i.e., the difference between $v_{\rm LSR}$ and the maximum velocity allowed by the rotation model), and classified clouds with $v_{\rm dev} > 50$ km/s as HVCs (Wakker & van Woerden 1997), even though they do not match the original classification based on the LSR. Regarding their distances, the information is still scarce and recent observations derive values that range from some parsecs up to dozens of kiloparsecs and, therefore, lead to possible mass ranges of 10^5–10^6 solar masses (Wakker 2001; Espresate et al. 2002; Putman et al. 2003; Smoker et al. 2004). Consequently, clouds moving with spatial velocities of 100 km/s with respect to the galactic disk will inject kinetic energies of approximately of 10^{51}–10^{53} erg during their collisions. These ranges of values indicate that the bulk motion of the HVC system, and its interaction with the gaseous disk, represents a rich source of energy and momentum for the interstellar medium (ISM). Finally, their genesis are still unclear, some models indicate that they could be of galactic origin (Shapiro & Field 1976) and others point out to an extragalactic origin (Oort 1970; Giovanelli 1981; Braun & Burton 1999; Blitz 1999). Regardless of their actual origin, they may help to shape the general ISM. Here we present new three–dimensional (3D) simulations of HVCs colliding with a magnetized thick disk together with a short review on previous HVC collision experiments.

II. INTERACTION OF HVCs WITH THE ISM

The interaction of HVCs with the interstellar matter and the formation the large structures in the galactic disk has been studied for more than 20 years by different authors. In a pioneer work, Tenorio-Tagle (1981) made the first study for the formation of large cavities (super-rings) when a HVC collides with a gaseous thin disk. In subsequent years, detailed hydrodynamic (HD) numerical calculations were performed to study the evolution of structures, such as supershells, created by HVC collisions at different locations of the Milky Way (Tenorio–Tagle et al. 1986, 1987). Also, the formation of a number of other peculiar features like Orion and Monoceros, which are large molecular cloud complexes located far from the galactic plane (Franco et al. 1988), Gould's belt which is inclined some 20 degrees with respect to the midplane (Franco et al. 1988; Comerón & Torra 1992; Comerón 2001), supershells in

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external galaxies (Rand & Stone 1996), and Galactic worms with a mushroom-like shape (Kudoh & Basu 2004).

When a B-field is included, the evolution of the interaction depends on the model assumptions, and intensity and initial configuration of magnetic field (Santillán et al. 1999). For instance, MHD models in two-dimensions (2Ds) are in reality in 2.5D, because the Lorentz force is perpendicular to the plane defined by the directions of the field and HVC motion, and one has to make specific assumptions on the field properties at the boundaries of the simulations. Thus, the results when the field is forced to be anchored at fixed points of the boundaries are different from cases in which the foot points of the field are able to move freely with the flow. Similarly, the results also vary when ones uses periodic boundaries. With these restrictions in mind, Santillán et al. (1999) made models that could illustrate the effects of magnetic pressure and tension. For the cases with tension, the initial magnetic lines were set parallel to the horizontal axis of the 2D numerical simulations, and the field at the boundaries were fixed to specific grid points (like strings in a guitar). The HVC distorts and compresses the B–field lines during the evolution, increasing both the field pressure and tension, forming a magnetic barrier for the moving gas. This prevents the cloud material from penetrating into the disk and leads to the formation of head–tail structures in HVCs (Santillán et al 1999; Santillán, Franco & Kim 2001; Knoz, Brüns & Birk 2002). The case without tension is created by setting the B perpendicular to the plane of the simulation (and HVC motion), and letting them move freely with the flow. The magnetic lines then are not distorted and there are no tension effects. The gas from the HVC can travel longer paths and penetrate deeper into the disk in this case. The magnetic pressure provides a very effective drag that slows down the flow faster than in the purely hydrodynamic case, and distorts the morphology of the shocked layer. Also, the creation of MHD waves produce strong perturbations in regions that are far away from the location of the impact, even at the other side of the galactic plane.

III. 3D–MHD NUMERICAL SIMULATIONS

In order to study the three-dimensional evolution for the interaction of a HVC with a magnetized interstellar medium, we set the magnetic field parallel to the galactic plane and use the MHD code ZEUS–3D (Stone & Norman 1992a, 1992b). The reference system in our simulation is one in which the disk gas is at rest and the origin of our Cartesian computational mesh (x, y, z) is at the Solar neighborhood. The resolution of the computational domain is the 23.44 pc/zone, i.e., we have a computational mesh of $128 \times 128 \times 128$ cells in a cube of 3 kpc of side. The boundary conditions are *periodic* in the x and y axes, and *outflow* in the z–axis. The evolution was computed in the isothermal regime (γ=1.01), since explicit cooling or heating functions are

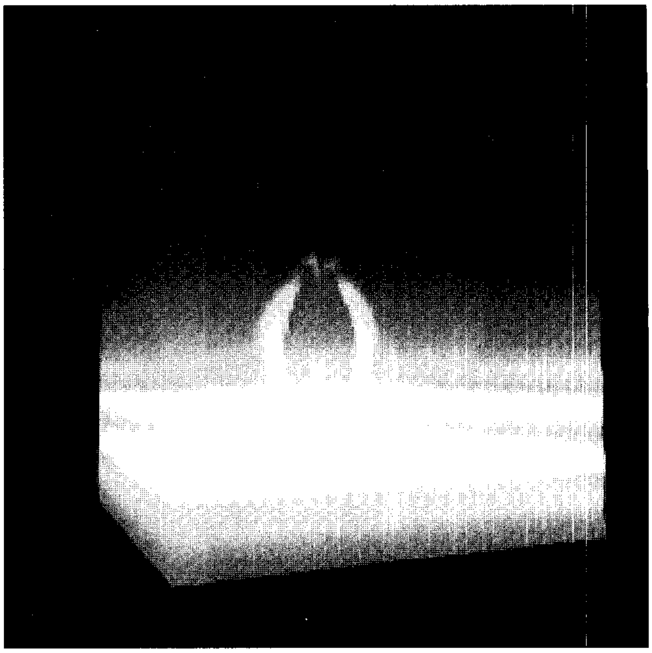

Fig. 1.— Structure produced by the interaction of HVC with a magnetized gaseous disk. The snapshot shows the volume rendering of logarithmic density.

not included in our numerical scheme. In most published papers the HVCs are simulated as a single and unique event. Following the usual recipe, we simulate the clouds in the following way: at the starting time of our simulations we introduce a sphere, at a height of $\sim$ 2.5 kpc, with $n_{\rm HVC}$=0.1 cm^{-3} and $v_{\rm HVC}$=100 km/s. The total injected energy and mass in the ISM is $E_{\rm HVC} = 10^{53}$ ergs and $\sim M_{\rm HVC} = 4 \times 10^6$ M$_\odot$.

The magnetic disk model is plane parallel, and we follow the scheme described by Martos (1993) and Santillán et al. (1999). Two forms of pressure, thermal and magnetic, provide the support of gas against the gravitational field of the disk (we do not include cosmic–ray pressure). For completeness, we perform only the hydrodynamic (HD) but also the MHD simulations.

In the first HD case, the impact of the HVC creates a strong galactic shock directed downwards, and a reverse shock that penetrates into the cloud. The galactic shock moves radially away from the location of impact, but energy is not conserved and its strength decreases rapidly with time. Nonetheless, momentum conservation keeps it strongest in the direction of motion of the impinging cloud. As in previous HD models, when the cloud approaches the plane, the shocked layer collects gas from the disk and generates a symmetrical structure, similar to a *bowl*. When the magnetic field is included, the evolution changes significantly. At early times the evolution is similar to the purely hydrodynamic case. However, as the B–field lines begin to be compressed (or the magnetic pressure gets increased), a precursor in the form fast magnetosonic wave begins to move ahead of the nose of the shocked cloud material. The material behind the shocked HVC also begin to expand along the field lines, accumulating material and forming a shell-like structure (see Figure 1).

IV. CONCLUSION

In this work we have presented a chronology of the numerical simulations, HD and MHD, associated with the interaction of the HVC with the galactic disks. With the HD simulations they could have studied the formation and evolution of structures such as super–rings, supershells, large molecular cloud complex outside the galactic plane and small columns of gas perpendicular to the gaseous disk (worms) with mushroom–like shape. On the other hand, in the case MHD the numerical calculations have allowed us to investigate the formation of HVC with cometary structure (Head–Tail HVC). When the HVC interacts with the magnetized interstellar medium, it distorts and compresses the B–field lines that form a magnetic valley, or a magnetic barrier, where great amount of the material of the cloud is accumulated. Finally, in this paper, we presented recent results of 3D–MHD numerical simulations that show the formation of a thin supershell in the galactic plane after a cloud collides with the magnetized gaseous disk. The thickness of the supershell is associated with the magnitude and topology of the initial B-field.

The numerical calculations were performed with the code ZEUS–3D using supercomputer ALPHA SERVER SC-45 at the Computer Center of the UNAM.

REFERENCES

Bajaja, et al. 1985, ApJS, 58, 143.

Blitz, L, Spergel,D.N., Teuben, P.J., Hartmann, D. & Burton, W.B. 1999, ApJ, 514, 818.

Braun, R. & Burton, W. B. 1999, A&A, 341, 437

Comerón, F. & Torra, J. 1992, A&A, 261, 94.

Comerón, F. 2001, A&A, 365, 417.

Espresate, J., Cantó, J. & Franco, J. 2002, ApJ, 575, 194

Fox, A.J., Savage, B.D., Wakker, B.P., Richter, P., Sembach, K.R. & Tripp, T.M. 2004, ApJ, 602, 738

Franco, J., Tenorio–Tagle, G., Bodenheimer, P., Rozyczka, M. & Mirabel, I.F. 1988, ApJ, 333, 826

Giovanelli, R. 1981, AJ, 86, 1468

Konz, C., Brüns, C. & Birk, G. 2002, A&A, 391, 713.

Kudoh, T. & Basu, S. 2004, A&A, 423, 183

Martos, M.A. 1993, Ph.D. thesis, Univ. Wisconsin–Madison.

Mirabel, I.F. 1981, ApJ, 247, 97.

Muller, C.A, Oort, J.H. & Raimond, E. 1963, *C.R. Acad.Sci. Paris* 257, 1661.

Oort, J.H. 1970, A&A, 7, 381.

Putman, M.E., Bland-Hawthorn, J., Veilleux, S., Gibson, B.K., Freeman, K.C. & Maloney, P.R. 2003, ApJ, 597, 948.

Rand, R. & Stone, J. M. 1996, AJ, 111. 190

Richter, P., de Boer, K.S., Widmann, H., Kappelmann, N., Gringel, W., Grewing, M. & Barnstedt, J. 1999, Nature, 400, 382.

Santillán, A., Franco, J., Martos, M. & Kim, J. 1999, ApJ, 515, 657.

Santillán, A., Franco, J. & Kim, J. 2001, JKAS, 34, S341.

Shapiro, P.R. & Field, G.B. 1976, ApJ, 205, 762

Smoker, J. V., et al. 2004, MNRAS, 352, 1279.

Stone, J.M., & Norman, M.L. 1992a, ApJS, 80, 753.

Stone, J.M., & Norman, M.L. 1992b, ApJS, 80, 79.

Tenorio–Tagle, G. 1981, A&A, 94, 338.

Tenorio–Tagle, G., Bodenheimer, P., Rozyczka, M. & Franco 1986, A&A, 170, 107.

Tenorio–Tagle, G., Franco, J., Bodenheimer, P. & Rozyczka, M. 1987, ApJ, 179, 219.

Wakker, B.P. 1991, A&A, 250, 499.

Wakker, B.P. 2001, ApJ, 136, 499.

Wakker, B.P. & van Woerden, H. 1997, ARA&A, 35, 217.