# REMOTE NUMERICAL SIMULATIONS OF THE INTERACTION OF HIGH VELOCITY CLOUDS WITH RANDOM MAGNETIC FIELDS

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## ABSTRACT

The numerical simulations associated with the interaction of High Velocity Clouds (HVC) with the Magnetized Galactic Interstellar Medium (ISM) are a powerful tool to describe the evolution of the interaction of these objects in our Galaxy. In this work we present a new project referred to as Theoretical Virtual i Observatories. It is oriented toward to perform numerical simulations in real time through a Web page. This is a powerful astrophysical computational tool that consists of an intuitive graphical user interface (GUI) and a database produced by numerical calculations. In this Website the user can make use of the existing numerical simulations from the database or run a new simulation introducing initial conditions such as temperatures, densities, velocities, and magnetic field intensities for both the ISM and HVC. The prototype is programmed using Linux, Apache, MySQL, and PHP (LAMP), based on the open source philosophy. All simulations were performed with the MHD code ZEUS-3D, which solves the ideal MHD equations by finite differences on a fixed Eulerian mesh. Finally, we present typical results that can be obtained with this tool.

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

## I. INTRODUCTION

High velocity clouds (HVC) are (H I) clouds located at high latitudes, representing a fraction of the gaseous halo of our Galaxy. The radial velocities, relative to the Local Standard of Rest (LSR), at larger than $\sim$ 100 km/s and cannot be explained by a simple model of galactic rotation (Muller et al. 1963; Mirabel 1981; Bajaja et al. 1985; Wakker 1991; Wakker & van Woerden 1997). They are composed principally of neutral atomic hydrogen (H I), however, some show molecular hydrogen (Ritcher et al. 1999), heavy elements (Wakker 2001) and surrounding, highly ionized gas (Fox et al. 2004). The explanation for their origin is either galactic (Shapiro & Field 1976) or extragalactic (Oort 1970; Blitz 1999), and the evolution of their interaction with the halo is unclear because their distances and tangential motions are unknown. Limits to the locations of some particular HVCs are in the range of some parsecs up to dozens of kiloparsecs. The resulting possible mass range is $10^5$–$10^6$ M$_\odot$ (Wakker 2001; Putman et al. 2003; Smoker et al. 2004; Wakker et al. 2007). Therefore, a cloud moving with a speed of 100 km/s will have a kinetic energy of approximately of $10^{51}$–$10^{53}$ ergs. This range of values indicates that the bulk motion of the HVC system, and its interaction with the ISM, could represent a rich source of energy and momentum for the Galactic gas.

Numerical simulations of the evolution of HVC collisions with the Milky Way have been performed for more than two decades by different authors. Some of this works were used for modeling the origin of large–scale structures near the Galactic plane, such as supershells (Tenorio–Tagle et al. 1986, 1987), the peculiar location of the Orion and Monoceros molecular cloud complexes (Franco et al. 1988); the formation of structures similar to Gould's Belt (Comerón & Torra 1994; Comerón 2001), as well as the formation of Galactic worms with mushroom shapes (Kudoh & Basu 2004). The details of resulting supersonic flows depend of on the model assumptions, and the intensity and initial configuration of the magnetic field. Santillán et al. (1999) made models that illustrate the effects of magnetic pressure, and differentiate them from those due to magnetic tension. Finally, the interaction of the HVCs with the outerskirts of galactic disks can maintain transonic turbulent motions in the warm phase ($\sim$ 2500 K) of H I (Santillán et al. 2007; Sánchez–Salcedo et al. 2007).

The published papers display only some details of the numerical calculations but observational astronomers sometimes need additional details of the theoretical models in order to interpret their data. In this work we present a new Astrophysical Computational Tool that will allow astronomers to access high-performance remote numerical simulations through a website called

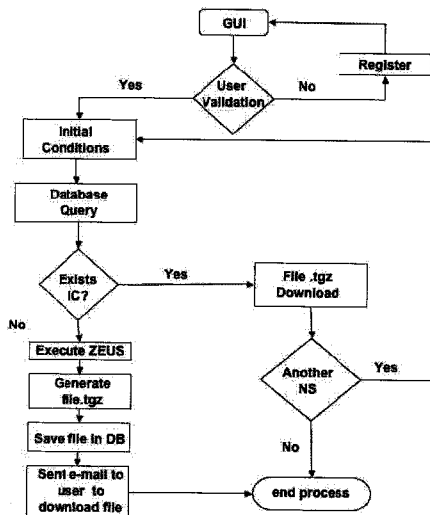---

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**Fig. 1.**— Flowchart of the computational implementation of the MTVO

the Mexican–Theoretical Virtual Observatory (MTVO).

## II.  COMPUTATIONAL BACKBONE OF THE MTVO

In general, Virtual Observatories provide easy and transparent access to diverse observational databases. However, the concept of a Theoretical Virtual Observatory has recently been developed providing access to numerical simulation databases produced by theoretical research (Wozniak 2004, Lemson 2006, Santillán et al. 2006).

The MTVO rests on a set of software tools that offer global solutions for web development. The operating system is Linux, the web server is Apache, the interface is SQL (Structure Query Language) and the relational database management system is MySQL; everything was programmed with PHP (Hypertext Pre-Processor). The computational backbone of the MTVO is structured into three stages: The Graphic User Interface (GUI); the Remote Numerical Calculations (RNC); and the Database (DB) creation and the search tools. The implementation is explained in the flowchart of Figure 1. The initial step is user validation and authentication by the system, then the user must introduce initial conditions (IC) of the physics problem to be simulated. The program searches if these values have been used previously by other user and gives a link to the archive of the previous numerical simulation. If no previous simulation is found, the system starts a new numerical calculation. It is important to mention that the user has the possibility of using only the archives of the DB without running a new simulation.

### (a)  Graphic User Interfaces

The application implemented in the MTVO is the study of the evolution of a HVC in the ISM, this medium include a random magnetic field. Actually there are two principal GUIs; one executes the numerical simulation in real time and the other performs a search in the database. In the first case, the GUI is designed to introduce the physical variables related to the ISM (numerical density, temperature and magnetic field intensity) and the HVC (radius, numerical density and velocity). The GUI includes various filters to validate the data integrity and verify that all variables are introduced. On the other hand, the GUI that performs the search in the DB is similar to the GUI of the RNC, because it includes the possibility of obtaining a simulation by the physical variables, date and username.

### (b)  Remote Numerical Calculation

This software comprises a group of programs with specific tasks. The initial conditions are added in an input file and those are included in the DB together with the username and the date. When the run is done, the program creates one tar file archive, compressed with Gnu Zip compression, with all output files; the name and location of this file are inserted into the DB. The simulation file includes the hydrodynamic variables (density, internal energy, velocity field and magnetic field) associated with the evolution of the HVC in HDF4 format. Finally, the system sends an email to the user informing the web address where this file can be downloaded.

### (c)  Database

Our website uses a relational database and the queries are in the standard language SQL. Presently we only service storage of the results for the application of the evolution of HVC, but future applications will include a variety of the other astrophysical problems. In the HVC case the DB contains the values for the initial conditions; also included is user information such as name, institution, email and password, output files and date. With these data the user has the option to make several searches of DB; for example, if the user wants to know the results already obtained for a given set of ISM properties, he or she only needs to introduce the values in the GUI and the system will get all the files that contain such values. The same can be applied if the user wants to search by two or more variables. When the user makes a search without any value, the system get all the simulations stored in the DB.

## III.  NUMERICAL MODEL

In order to study the evolution of the interaction of a HVC with a magnetized interstellar medium, we set a random magnetic field (see Fig. 2) that satisfy the divergence–free constraint ($\nabla \bullet B = 0$) at all times, where the horizontal component dominates over the
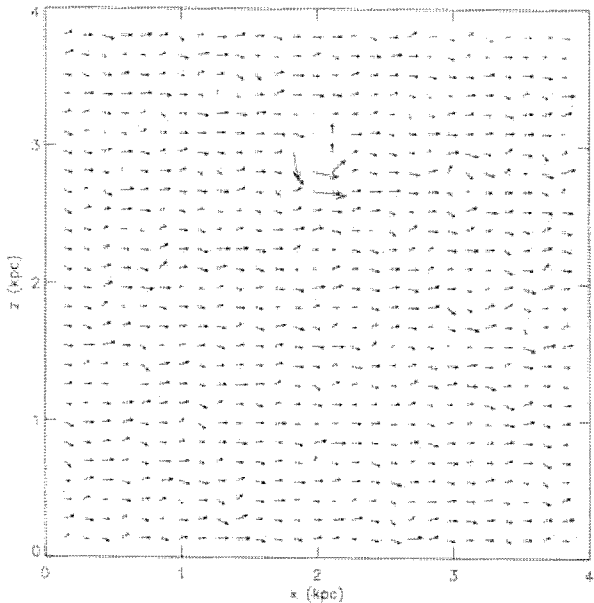
**Fig. 2.**— Initial topology of the random magnetic field, where the maximum intensity is 2 $\mu$G

TABLE 1.
INITIAL CONDITIONS

| | $n$ $(\mathrm{cm}^{-3})$ | $v$ $(\mathrm{km/s})$ | $T$ $(\mathrm{K})$ | $B$ $(\mu\mathrm{G})$ | $r$ $(\mathrm{pc})$ |
|---|---|---|---|---|---|
| ISM–1 | 1.0 | 0.0 | 1000 | 0 | – |
| ISM–2 | 1.0 | 0.0 | 1000 | 2 | – |
| HVC | 0.1 | 100.0 | 1000 | – | 150 |

els are plane parallel with constant density and temperature, and initially the gas is at rest. The initial conditions for the example presented in this paper are given in Table 1, where ISM–1 and ISM–2 represent the Galactic interstellar gas, without and with random magnetic fields, respectively.

Figure 3 shows the HD and MHD simulations of a cloud whose center position is located 3 kpc above from the origin, with an initial velocity of 100 km/s. In the following snapshots, the density is shown in logarithmic color–scale plots The first two snapshots show the shock evolution at 3 Myr, for the ISM–1 and ISM–2 models, respectively. In both models, the interaction between the HVC and the interstellar gas creates a strong galactic shock directed downwards and a reverse shock that penetrates into the cloud. The galactic shock tends to move radially away from the location of impact (Santillán et al. 1999). At this time, there are no differences between the models. Nevertheless, when 45 Myr of evolution have passed, the structure of the HVC has changed slightly; in both models a large fraction of the original cloud mass remains locked up in the shocked layer, and a small amount of it has re-expanded back into the rear wake and tail. However, in the HD–case, the cloud covers a distance greater than in the MHD–case, due to the magnetic tension produced by the horizontal–component of random magnetic field. The HVC distorts and compresses the $B$–field lines during the evolution, increasing both the field pressure and the tension, and forming a magnetic barrier for the moving gas (Santillán et al 1999; Knoz, Brüns & Birk 2002). Finally, we can see clearly in figure 3 that the structure of the evolution of HVC produced by hydrodynamic simulations is completely different from that produced by numerical calculations that include magnetic fields, when 90 Myr have passed. In the case where the galactic gas is described for ISM–1 (the magnetic field is null) the interaction of the HVC with this medium presents a thin structure and the size of perturbation region has grown to nearly 3 kpc. On the other hand, for the case where the Galactic gas is magnetized, the evolution of the cloud presents a thick structure of ~ 2 kpc and a great amount of gas collects in a magnetic valley formed by the interaction of the cloud with the horizontal–component of the random magnetic field.

vertical component, and we use the MHD code ZEUS–3D (Stone & Norman 1992a, 1992b). The code can perform simulations in three-dimensional, but due to obvious computational restrictions, we presently we restrict the remote numerical calculations only to two–dimensional simulations. The reference system in our simulation is one in which the ISM is at rest and the origin of our Cartesian computational mesh $(x, y)$ is at the Solar neighborhood. For an efficient use of computer resources we worked with moderate resolution of the computational domain, 512 × 512 cells in a plane 4 kpc on a side, i.e., 7.8125 pc/zone. The boundary conditions are *periodic* in the $x$–axis, and *outflow* in the $y$–axis. The evolution was computed in the isothermal regime ($\gamma$=1.01), since explicit cooling or heating functions are not included in our numerical scheme, and the effects of self–gravity and differential rotation of the Galaxy are not included in the present version. In most published papers the HVCs are simulated as a single and unique event. In our numerical experiments we simulate the clouds in the following way; at each time step we introduce a sphere, at a height of ~ 3.0 kpc, with radius $r_{HVC}$, numerical density $n_{HVC}$ (cm$^{-3}$) and initial velocity $v_{HVC}$ (km/s).

## IV. RESULTS

In this section we present typical results obtained with the MTVO; in particular, we study the evolution of the HVC in both the hydrodynamic (HD) and the magnetohydrodynamic (MHD) regimes. The mod-
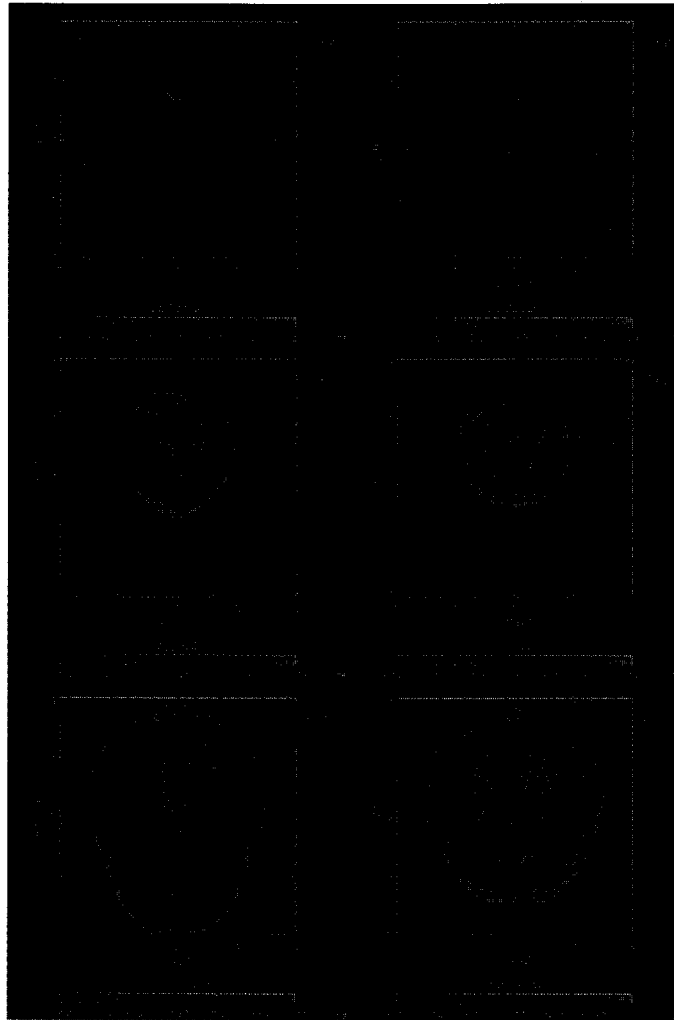
Fig. 3.— Evolution of HVC in two medium: without and with magnetic field. The sequence shows the density (color logarithmic scale) for three selected times (3, 45 and 90 Myr) The snapshots in the left–column show the HD regime and the snapshots in the right–column the MHD simulation.

## V. CONCLUSIONS

In this paper we present a new astrophysical computational tool that will enable to performance remote numerical simulations through to the Mexican Theoretical Virtual Observatory. This powerful tool can be accessed over the Internet by astronomers regardless of their location. The numerical calculations will allow to study the evolution of interaction of high velocity clouds with a interstellar medium with a random magnetic field.

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