# Mexican Virtual Solar Observatory: hydrodynamic simulations of the evolution of CMEs

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**Resumen**

El concepto de Observatorio Virtual Solar (VSO, por sus siglas en inglés) está asociado a una serie de herramientas computacionales que nos ayudan a investigar, manipular y analizar datos observacionales vinculados al Sol que se encuentran distribuidos alrededor del mundo (Hill 2000). Un VSO no solamente proporciona un eficiente y rápido acceso a los datos solares existentes, sino que representa una poderosa herramienta para realizar simulaciones numéricas para estudiar la evolución de una variedad de fenómenos asociados a la actividad solar. En este trabajo presentamos una descripción del modelo numérico que utiliza el Observatorio Virtual Solar Mexicano (MVSO, por sus siglas en inglés) para realizar simulaciones hidrodinámicas remotas para estudiar la evolución de CMEs en el medio interplanetario.

**Palabras clave:** Observatorio Virtual, eyecciones de masa coronal, simulaciones numéricas, bases de datos.

**Abstract**

The Virtual Solar Observatory (VSO) concept contains software tools for searching, manipulating, and analyzing data from archives of solar data at many different observatories around the world (Hill 2000). The VSO not only provides fast and reliable access to existing solar data, but also represents a powerful and unique machinery to perform numerical simulations of a variety of different phenomena associated with solar activity. In this work we present the Numerical Model that the Mexican Virtual Solar Observatory (MVSO) uses to develop Remote Hydrodynamic Simulations to study the Evolution of Coronal Mass Ejection in the Interplanetary Medium.

**Key words:** Virtual Solar Observatory, remote numerical simulations, database, coronal mass ejections.

## Introduction

In general Virtual Solar 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 MVSO will allow observational solar researchers to make numerical simulations in real time through a simple Web page (Hernández-Cervantes *et al*. 2008). In this paper we focus on the numerical method that the MVSO uses to simulate the evolution of coronal mass ejections (CMEs) in the interplanetary medium.

## Numerical method

All remote numerical simulations are performed with the magnetohydrodynamical (MHD) code ZEUS-3D, which solves the three-dimensional system of ideal (non-resistive, non-viscous, adiabatic) non-relativistic MHD equations by finite differences on a fixed Eulerian mesh. The code can perform simulations in three dimensions and include magnetic fields however, to simplify the calculations here we restrict our simulations to two-dimensions and neglect all magnetic effects. Nevertheless, in the HD regime the simulations have proved to be very useful in understanding the basic physical aspects of the injection and Heliospheric evolution of the CMEs (Gosling and Riley, 1996; Gonzalez-Esparza *et al*. 2003; Gonzalez-Esparza *et al*., 2004). On the other hand, ZEUS-3D numerically integrates the following coupled partial differential equations (hydrodynamic case) as a function of time and space (Stone & Norman 1992)

$$\frac{D\rho}{Dt} = \nabla \bullet (\rho v) = 0, \quad (1)$$

$$\rho \frac{Dv}{Dt} = -\nabla p - \rho \nabla \Phi, \quad (2)$$

$$\rho \frac{D}{Dt}\left[\frac{e}{\rho}\right] = -p \nabla \bullet v, \quad (3)$$

where

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + v \bullet \nabla$$

Here, the dependent variables are the mass density $\rho$, the velocity field $v$, gravitational potential $\Phi$ and the internal energy density $e$. The fluid equations are closed with an equation of state, in this case

$$p = 2nkT, \quad (4)$$

where $p$ is the gas pressure assumed to be isotropic, $n$ the numerical density, $k$ is Boltzmann's constant and $T$ the fluid temperature. Finally, the relation between gas pressure and internal energy density is

$$e = \frac{p}{\gamma\text{-}1} \quad (5)$$

At present, the MVSO only simulates the evolution of CMEs in the interplanetary medium, however, is possible include other astrophysical problems. The CMEs are huge regions of hot plasma from the outer solar atmosphere that are violently ejected over the course of several hours. The plasma is initially contained within closed coronal magnetic field lines, and is ejected at large speeds into interplanetary space. These events involve significant masses, typically $10^{15}$ to $10^{16}$ g and energies on the order of $10^{31}$ to $10^{32}$ ergs. CMEs play a major role in non-recurring storms in the magnetosphere and ionosphere of the Earth, which in turn are responsible for enhanced auroral activity, satellite damage, and some power station failures (Hundhausen, 1996). To simulate these disturbances we use a simplified model of the evolution of a CME in interplanetary space. Initially, we model the ambient solar wind by specifying the fluid velocity, density, and temperature at an inner boundary of the grid, which is located beyond the critical point where the solar wind becomes supersonic (r = 18 Ro ~ 0.083 AU), and then allowing the wind to evolve and reach stationary equilibrium. Then we add an ejecta-like perturbation at the inner boundary to simulate the appearance of the CME into the interplanetary medium; this simulation technique has been used by other authors (Gosling and Riley, 1996; Santillán *et al*., 2001; González-Esparza *et al*., 2004). For efficient use of computer resources, we mostly worked with moderate resolutions of $514^2$ zones in spherical coordinates $(R,\theta)$; the physical intervals of the simulations presented here are 0 to 1.5 AU and 0 to 180 degrees, respectively. The boundary conditions are in-out flow in the R direction and periodic in the $\theta$ coordinate and the evolution is computed in the adiabatic regime ($\gamma$=5/3). This computational tool will allow observational solar physicists, needing a theoretical model in order to interpret their data, to access high-performance remote numerical simulations through a simple website. For example, some years ago Gonzalez-Esparza *et al*. (2003) made 1-D numerical simulations to study the evolution of CMESs in the solar wind, detected by SOHO-LASCO and associated with interplanetary coronal mass ejection (ICME) and interplanetary (IP) shocks, which was later detected by WIND at 1 AU. Using the MVSO, the original 1-D study can easily be extended to encompass two dimensions. Finally, other example of the numerical simulation of the evolution of the CME in the interplanetary medium is shown in the two snapshots displayed in the fig. 1, where the density is shown in logarithmic gray-scale. The physics quantities (numerical density, temperature and velocity) of the medium at 1 AU change drastically, when the disturbance crosses by this point. This is clearly seen in the fig. 1 (more details of this simulations see http://mvso.astroscu.unam.mx).

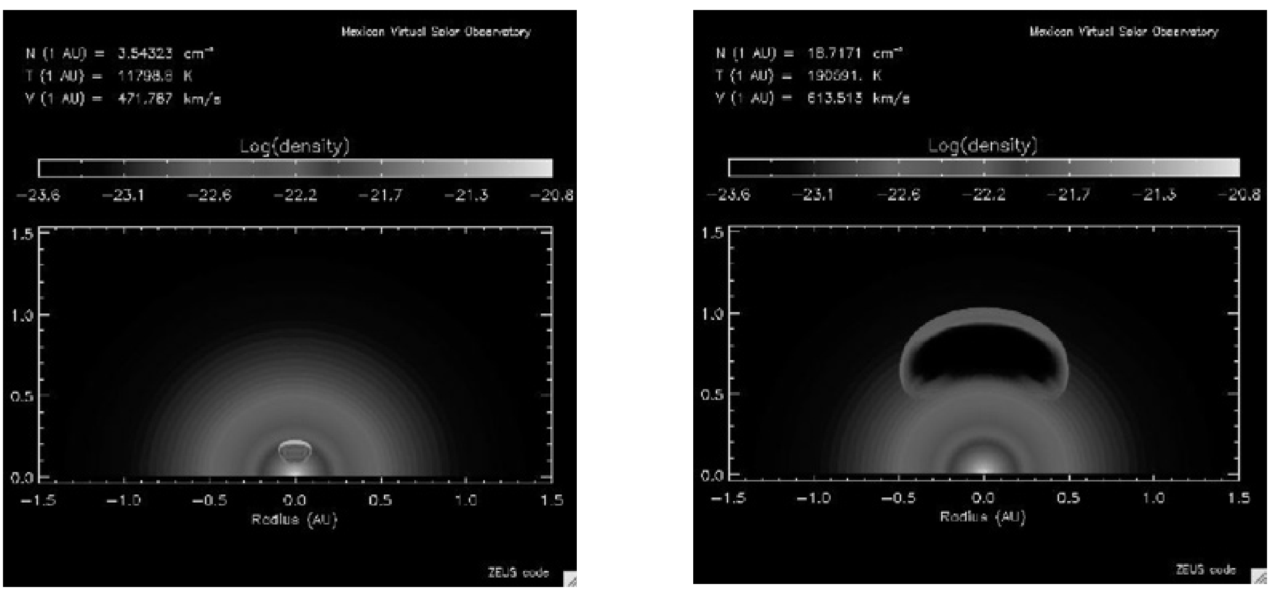


Fig. 1 Typical result produced by the MVSO; density (gray logarithmic scale) of the structure of CME at two selected times: 15 and 75 h (Courtesy of MVSO 2007).

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