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Propagation and interaction of interplanetary transient disturbances. Numerical simulations ☆

J. Américo González-Esparza *, S. Jeyakumar

Inst. de Geofisica, Universidad Nacional Autonoma de Mexico, Mexico DF 04510, Mexico

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Abstract

We study the heliocentric evolution of ICME-like disturbances and their associated transient forward shocks (TFSs) propagating in the interplanetary (IP) medium comparing the solutions of a hydrodynamic (HD) and magnetohydrodynamic (MHD) models using the ZEUS-3D code [Stone, J.M., Norman, M.L., 1992. Zeus-2d: a radiation magnetohydrodynamics code for astrophysical flows in two space dimensions. i – the hydrodynamic algorithms and tests. Astrophysical Journal Supplement Series 80, 753–790]. The simulations show that when a fast ICME and its associated IP shock propagate in the inner heliosphere they have an initial phase of about quasi-constant propagation speed (small deceleration) followed, after a critical distance (deflection point), by an exponential deceleration. By combining white light coronograph and interplanetary scintillation (IPS) measurements of ICMEs propagating within 1 AU [Manoharan, P.K., 2005. Evolution of coronal mass ejections in the inner heliosphere: a study using white-light and scintillation images. Solar Physics 235 (1–2), 345–368], such a critical distance and deceleration has already been inferred observationally. In addition, we also address the interaction between two ICME-like disturbances: a fast ICME 2 overtaking a previously launched slower ICME 1. After interaction, the leading ICME 1 accelerates and the tracking ICME 2 decelerates and both ICMEs tend to arrive at 1 AU having similar speeds. The 2-D HD and MHD models show similar qualitative results for the evolution and interaction of these disturbances in the IP medium.

Keywords: Solar wind dynamics; Coronal mass ejections; Interplanetary shock waves; Ejecta; Space weather; Numerical simulations

1. Introduction

Interplanetary counterparts of Coronal Mass Ejections (ICMEs) and Transient Forward Shocks (TFS) are dominant transient features in the solar wind dynamics at 1 AU. The study of their heliocentric evolution is important, not just to better understand this dynamics perse, but it is relevant to space weather applications. The association between TFS and CMEs was established from measurements by the Solwind coronograph and in-situ observations by Helios 1 (Sheeley et al., 1985). In general, fast ICMEs (i.e., having initial speeds $\geqslant 500$ km/s) are associated with TFS at 1 AU, whereas slow ICMEs (having initial speeds $\leqslant$ as the ambient wind velocity), do not drive shocks in the ecliptic plane. Based on observations, about half of the ICMEs detected in-situ in the ecliptic plane are associated with TFS, whereas 40% of the TFS are followed by ICME signatures (see e.g., González-Esparza et al., 1998). From these results we know that slow ICMEs do not drive shocks and TFSs have wider fronts in longitude than those of the ICMEs.

The numerical studies of interplanetary disturbances are very useful to illuminate physical characteristics and evolution of these events. Beginning with the self-similar analytical models of Parker (1963) and Simon and Axford (1966), the first numerical computer code – one dimensional

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* Corresponding author.
E-mail address: americo@geofisica.unam.mx (J.A. González-Esparza).

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hydrodynamic (1-D HD) – was developed by Hundhausen and Gentry (1969), and a variety of other models ranging from simple 1-D HD through 3-D HD and magnetohydrodynamic (MHD) codes have developed in subsequent years (Dryer, 1994; Vandas et al., 1997; Riley, 1999; Odstrcil and Pizzo, 1999; Cargill and Schmidt, 2002; Manchester et al., 2004; Wu et al., 2005). Although these new codes address more realistic situations, still the one dimensional models can be useful to illuminate some aspects of the propagation of interplanetary disturbances, focusing in particular problems. This approximation applies only where the evolution is driven by the dynamic pressure of the large-scale disturbances and the ambient wind.

When the frequency of solar activity is high, the CMEs can collide in the IP medium (Gopalswamy et al., 2002). These interactions can dominate the transfer of energy in the inner heliosphere during the periods of high activity. Wang et al. (2003) reported three events of multiple 'magnetic clouds', consisting of two interacting magnetic clouds separated by plasma sheet regions. This scenario of several interacting disturbances causes a very complex dynamics that it is almost impossible to understand from the analysis of in-situ spacecraft observations.

We present numerical simulations of ICMEs and TFSs to study their evolution and interaction. One of the aims of this study is to develop the tools to interpret the observations of interplanetary disturbances that we will obtain, employing the interplanetary scintillation (IPS) technique, from the Mexican Array Radio Telescope (MEXART) (González-Esparza et al., 2004b). In the first part of the paper we apply a simple 1-D HD model to address the evolution of the velocity of the ICME and its associated TFS with heliocentric distance. In the second part we simulate two interacting ICMEs in 2-D using a HD and MHD models.

2. Numerical simulations

We employ the numerical code ZEUS-3D (v3.4.2) for our simulations. This code solves the system of ideal MHD equations (non-resistive, non-viscous) by finite difference scheme on an Eulerian mesh (Stone and Norman, 1992). Our numerical set up is similar to that of Gosling and Riley (1996). The ambient solar wind is launched at the inner boundary located beyond the critical point ($R_o = 0.08$ AU), where the fluid speed, density and temperature are specified as the initial conditions. The outer boundary of our numerical grid is at 1.4 AU. Initially we allow the calculations of solar wind to reach an equilibrium state to observable values of ambient solar wind at 1 AU. After this, we introduce a perturbation (change in velocity, density and temperature) at the inner boundary to simulate the propagation of a CME into the interplanetary medium. These ICME-like perturbations were square pulses with a given initial speed, additionally characterized by small increments in density and temperature, over a finite extent of time. After this time the velocity of the ICME pulse on the trailing side falls to solar wind value in a cosine form and we set the initial conditions back to the ambient solar wind values. The boundary conditions of all our numerical runs are in-flowing at the inner boundary and out-flowing at the outer-boundary (more details on the simulations setup can be found in González-Esparza et al., 2003a). We use a resolution of 1024 zones for the 1-D simulations.

For the 2-D MHD model the initial setup is similar to the one described above with a finite angular width for the CME at the inner boundary. For the MHD model the solar wind magnetic field is assumed to be a monopole. At the inner boundary (R_o), the Parker's spiral like magnetic field is introduced. The components of the magnetic field in spherical polar coordinates are: $B_r = B_o(R_o^2/r^2)$, $B_\phi = -B_o(R_o^2/r^2)\Omega r \sin(\theta)/v_{sw}$, and $B_\theta = 0$, where θ is the heliospheric co-latitude, the heliocentric distance $r = R_o$ and $\Omega = 2.9 \times 10^{-6}\,\mathrm{s}^{-1}$. The strength of the magnetic field B_o at R_o is 1016 nT. We set the emf ($V \times B$) of the magnetic field for the given velocity to maintain $\nabla \cdot B = 0$ at the inner boundary (Clarke, 1996). In addition, simultaneously we also solve the continuity equation $\frac{\partial}{\partial t}(\rho_c) + \nabla \cdot (\rho_c V) = 0$, where ρ_c is the density of the CME, to track the location of the CME (cf. Odstrcil and Pizzo, 1999). The ambient wind and the ICME structure are the same between the HD and MHD cases, but for the solar wind magnetic field in our MHD model. The 2D simulations were carried out in the meridional plane, with outflowing boundary conditions except at the inner boundary where inflow boundary conditions were used. In our numerical grid, the range of r is from 0.083 to 1.4 AU with 256 zones and range of θ is from 22.5° to 157.5° with 256 zones.

Fig. 1 shows an example of a 1-D HD simulation of a ICME-like pulse and its driven shock propagating in the interplanetary medium. The plots show the bulk speed profiles of the ejecta and its TFS at three different times after the ICME initiation. The numerical model allow us to track the ICME boundaries (solid cases) and its TFS at all the times, so we can study their evolution (location and speed) with the radial distance.

3. ICME and shock deceleration in the interplanetary medium

Fast ICMEs decelerate as they propagate in the IP medium. This deceleration appears clearly while comparing estimates of CME initial speeds and their associated ICME transit velocities at 1 AU (e.g., Gopalswamy et al., 2001). Manoharan (2005) used the interplanetary scintillation (IPS) technique to measure the ICME speeds in the inner heliosphere for about 30 ICMEs and found that these disturbances decelerated in two phases within 1 AU. The dependence of speed with the heliocentric distance suggests that up to a distance of about 80 solar radii, the ICMEs propagate with a small deceleration and at larger distances the deceleration of ICMEs increase significantly.

In González-Esparza et al. (2003a) (here after paper 1), we performed numerical simulations (1-D HD) showing