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Development of a formalism for computing transits of Earth-directed CMEs, plasma sheaths, and shocks. Towards a forecasting tool

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Abstract

Interplanetary Coronal mass ejections (ICMEs) (super-magnetosonically) faster than the ambient solar wind are preceded by shock waves. Earth-directed shock waves, plasma sheaths and ICMEs are precursors of the major geomagnetic storms. The plasma sheath between the shock and the ICME leading edge plays a very important role to determine the geoeffectiveness of the events. There are multiple efforts (empirical, analytical and numerical) to forecast ICME–shock transit times and arrival speeds to 1 AU. We present a formalism (combining analytical and empirical solutions) to compute trajectories of fast halo Earth directed ICMEs, plasma sheaths, and shocks. This formalism combines the 'piston-shock' semi-empirical model (Corona-Romero et al., 2013), and the MHD polytropic jump relations (Petrinec and Russell, 1997) to approximate the 1 AU plasma sheath and ICME properties. Nine Earth directed ICME–shock cases, including the "Bastille" and "Halloween" events were analyzed. The model obtained compares well with in situ data. Finally, we found a possible empiric relation for the free parameter of our formalism. If this empiric relationship is confirmed, it could turn this formalism into a space weather forecasting tool.

Keywords: Coronal mass ejections; Solar wind; Interplanetary shocks; Space weather

1. Introduction

Coronal mass ejections (CMEs) involve the release of large amounts of material, energy, and magnetic field from the Sun into the interplanetary medium (IP) (Gosling et al., 1974; Hundhausen and Gosling, 1976; Hundhausen, 1987; Hundhausen et al., 1999). They are also associated with solar flares, solar energetic particles and IP shock waves (Forsyth et al., 2006; Webb and Gopalswamy, 2006). CMEs propagate with initial speeds between 200 and 2000 km s^{-1} (Vourlidas et al., 2000). Interplanetary counterparts of CMEs (ICMEs) drive shock waves when their relative speed with the solar wind is larger than the local magnetosonic speed. These interplanetary shocks, driven initially by supermagnetosonically 'fast' ICMEs, accelerate, warm up and compress the ambient solar wind transforming it into plasma sheath (Burlaga et al., 1981;

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Leblanc et al., 2001; Vourlidas et al., 2003). Fast ICMEs, their associated shock waves, and plasma sheaths are the main triggering of intense geomagnetic storms (e.g. Echer et al. (2005, 2008) and Ontiveros and Gonzalez-Esparza (2010), and references therein). Thus, the arrival forecasting of such phenomena to the Earth's environment is a critical topic for space weather purposes.

Numerical simulations of interplanetary disturbances offer good approximations of the evolution of ICME boundaries, their shock waves and plasma sheaths (e.g. Riley et al., 2003; Odstrcil et al., 2004; González-Esparza, 2005; Chané et al., 2006). The improvement in numerical codes also increase their capability to mimic in situ data (e.g. Manchester et al., 2008; Rollett et al., 2013). At present, it is possible to systematically forecast space weather conditions through combination of empirical and numerical models, like WSA + ENLIL (Pizzo et al., 2011). Even more, those tools, enable to forecast arrivals of ICMEs and shocks, as well as to estimate their synthetic transits (e.g. WSA + ENLIL Solar Wind Prediction by NOAA). The WSA + ENLIL is a combination of the WSA empirical model (Wang and Sheeley, 1990; Arge and Pizzo, 2000) and a 3D-MHD numerical code (Odstrcil, 2003). The first approximates the background solar wind speed and interplanetary magnetic field, and its results are used as boundary conditions by the ENLIL code to simulate the solar wind.

However, it is convenient to have analytic and empirical models to approximate ICME–shock trajectories and arrivals, as a complement of the numerical approach. These simplified models illuminate the main physical aspects of the phenomena. On one hand, empirical models subtract tendencies from data sets and extrapolate them to make predictions. Gopalswamy et al. (2001, 2005) presented empiric models to forecast transit times and arrival speeds of ICMEs and shocks to the Earth's environment, respectively. On the other hand, analytic models employ a simplified expression to approximate the physical mechanism that governs the ICME–solar wind coupling. Such a coupling is commonly expressed through hydrodynamic drags (e.g. Vršnak, 2001; Vršnak and Gopalswamy, 2002; Cargill, 2004). The concepts of these works were followed by many others, Aschwanden (2006), Forbes et al. (2006), Mikić and Lee (2006), Schrijver and Siscoe (2009), and Zhao and Dryer (2014) made an extensive review of such studies and their application on space weather forecasting.

Analytic and empirical models demand low computing power to calculate trajectories and 1 AU arrivals of ICMEs and shocks, and point out the physical mechanisms involve in the evolution of these events in the solar wind. Besides the common limitations of analytic and empirical models (Kleimann, 2012), in general, they concentrate on solving the propagation of only one phenomena, say ICME or shock, and neglect the other. Furthermore, to the best understanding of the authors, unless otherwise argued, there are no analytic or empirical models that describe in situ transits of plasma sheaths associated to fast ICMEs.

This work aims at presenting a semi-empiric formalism to calculate 'synthetic transits' of shocks and plasma sheaths. We use the 'piston-shock' model by Corona-Romero et al. (2013) to estimate the ICME/shock trajectories. Unlike other analytic approaches, this piston-shock formalism simultaneously calculates the trajectories of both ICME and its associated shock. Based on the piston-shock results, we explore the calculations of the plasma sheath properties at 1 AU. The solutions of this formalism present a fast and easy-to-achieve first estimations for arrivals and properties of shocks and plasma sheaths, in the case of Earth directed fast halo CMEs. The order of the paper is as follows: Section 2 presents the extended 'piston-shock' formalism to calculate the kinematics of a fast ICME, plasma sheath and shock wave; in Section 3 we use the 'piston-shock' formalism to analyze nine fast halo-CMEs, including the "Bastille" and "Halloween" events; finally, Sections 4 and 5 presents the discussion and conclusions respectively.

2. Analytic model for ICME–shock kinematics

Cantó et al. (2005) presented a fully 1-D hydrodynamic analytic model to study the kinematics of fast ICMEs during their propagation up to 1 AU. The solution of the model shows that fast ICMEs present two propagation stages within 1 AU: (1) an initial short lived quasi-constant speed, followed by (2) a gradual deceleration where the ICME speed tends to equalize the ambient solar wind speed. The model is based on the transferring of momentum between the ICME and the ambient wind. Corona-Romero and Gonzalez-Esparza (2011) extended this 1-D model to include the shock propagation associated with the fast ICME, where the ICME plays the role of a piston driving a shock wave, by transferring energy and momentum through the plasma sheath.

The 'piston-shock' model simultaneously describes the trajectories of both: ICME and shock (see Fig. 1). The shock follows a similar two stage propagation, but the shock decaying begins after the ICME starts to decelerate. The ICME deceleration implies the uncoupling between the ICME and its shock wave; in this stage, the ICME does not transfers momentum to the shock and the shock decays as a blast wave due to the absence of its driving source. Afterwards, Corona-Romero and Gonzalez-Esparza (2012) extended this 1-D formalism to include geometrical and physical effects affecting the propagation of interplanetary shocks. This extended formalism assumes a bow shock shape, using empirical models to approximate the ICME radius and bow shock standoff-distance, the solution also includes the shear flows within plasma sheath. Corona-Romero et al. (2013), included IP magnetic field to the piston-shock model, and validated it with a study of case events reproducing type II emissions (associated with the propagation of interplanetary shocks) and approximating the in situ time and speed arrivals of the ICMEs and shocks. The piston-shock model calculates ICME and

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