A&A 656, A152 (2021)
https://doi.org/10.1051/0004-6361/202141029

Astronomy & Astrophysics

Comment on "Non-interacting coronal mass ejections and solar energetic particles near the quadrature configuration of solar terrestrial relations observatory": CME shocks are fast magnetosonic shocks and not intermediate Alfvén shocks

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Received 9 April 2021 / Accepted 24 September 2021

ABSTRACT

Aims. The expression for the shock Mach number used by Ravishankar and Michalek (2020, A&A, 638, A42) is incorrect. We wish to provide a correct expression so they can redo their analyses.
Methods. Coronal mass ejection (CME) shocks are fast magnetosonic shocks and not intermediate Alfvén shocks. We give the steps for calculating the shock normal, shock velocity, and, thus, the shock Mach number. We also mention that the shock properties, such as being quasi-perpendicular or quasi-parallel, are another important parameter for the shock acceleration of energetic particles.
Results. We have corrected the errors existing in the Astronomy and Astrophysics literature concerning the mathematical expression for the Mach number for a CME shock. Hopefully, future authors will use the now-correct expression for the Mach number.
Conclusions. The correct shock Mach number expression has been given to Ravishankar and Michalek. It is hoped that they will redo their calculations (including using other shock properties) to see if their 2020 conclusions still hold true or not.

Key words. shock waves

1. Introduction

Ravishankar & Michalek (2020), hereafter referred to as RM20, have written a paper on the relationship between solar energetic particles (SEPs) and coronal mass ejections (CMEs). They have shown that the CME speed and Mach number of the associated shock are correlated with the SEP peak flux. The expression that they used to identify the shock Mach number, "the ratio of the CME speed to the sum of the Alfvén speed and the solar wind speed", stated mathematically is $M_S = V_{\rm CME}/(V_A + V_{\rm SW})$. This expression is incorrect. In Gopalswamy et al. (2010), an article that RM20 refer to, the definition is $M_S = (V_{\rm CME} - V_{\rm SW1})/V_A$, where $V_{\rm SW1}$ is the upstream solar wind speed. This expression is also incorrect.

Identification of the Mach number of a shock must be done in several steps. First, the shock normal direction must be identified. This can be done either using the magnetic coplanarity method (Colburn & Sonett 1966) or the mixed-mode method (Abraham-Shrauner 1972). The coplanarity method can be expressed as:

$$N_C = \pm\frac{\triangle B \times (B_1 \times B_2)}{|\triangle B \times (B_1 \times B_2)|}, \tag{1}$$

where N_C is the calculated coplanarity shock normal direction, B_1 and B_2 are the upstream (slow solar wind) and downstream (sheath) magnetic field directions, and $\triangle B = B_2 - B_1$ is the jump in the magnetic field direction across the shock. The subscripts "1" and "2" are standard notations for the upstream and downstream regions, respectively.

The Abraham-Schrauner mixed-mode method can be expressed as:

$$N_{\rm AS} = \pm\frac{\triangle B \times (\triangle V \times B_1)}{|\triangle B \times (\triangle V \times B_1)|}, \tag{2}$$

where $\triangle V = V_2 - V_1$, and V_1 and V_2 are the upstream (slow solar wind) velocity and the downstream sheath velocity vectors, respectively.

Once the shock normal, N, has been determined by either method, the shock velocity in the solar wind frame can be obtained by assuming the conservation of mass flux (ρV_S) in the shock rest frame. In the above, ρ is the plasma density and V_S is the shock velocity in the normal direction. Thus, the expression for the shock velocity in the upstream solar wind frame (Tsurutani & Lin 1985; Viñas & Scudder 1986; Schwartz et al. 1998) is:

$$V_S = \frac{\rho_2}{\rho_2 - \rho_1}(V_2 - V_1)\cdot N, \tag{3}$$

where ρ_1 and ρ_2 are the upstream and downstream plasma densities, respectively. To obtain the shock magnetosonic Mach number, M_{ms}, the shock speed, V_s, should be divided by the upstream magnetosonic wave speed, V_{ms1}:

$$M_{ms} = V_S/V_{ms1}. \tag{4}$$

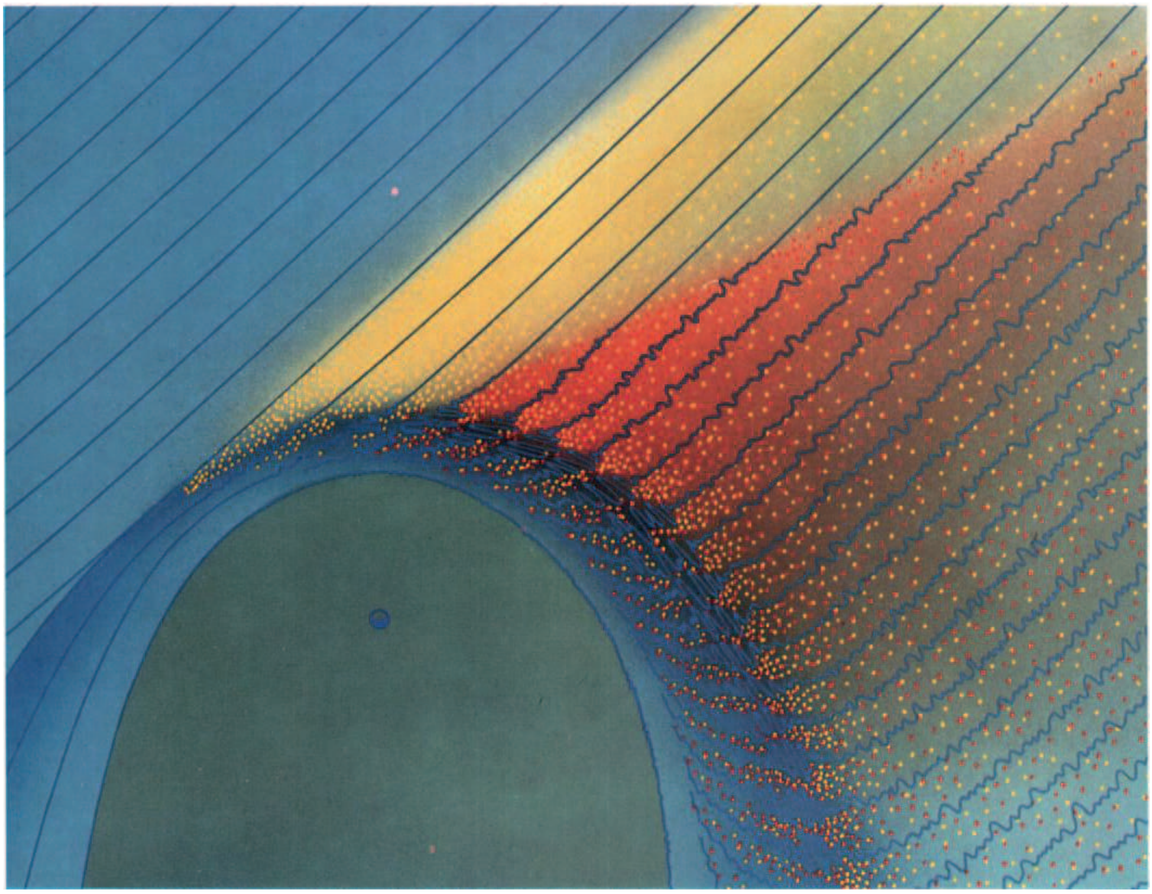

Fig. 1. Schematic of the Earth's bow shock (deep blue). The Sun is at the top of the figure, out of view. The schematic view is looking down on the bow shock and magnetosphere (shaded gray area). At the Earth's distance from the Sun, the interplanetary magnetic field lines have an angle of ~45° relative to the Earth-Sun line. These magnetic field lines are indicated by the light blue lines. The bow shock is quasi-parallel on the morning side, quasi-perpendicular on the afternoon side, and oblique at the shock nose at noon. Foreshock electrons are indicated by the yellow dots and foreshock ions by the orange dots. The figure is taken from Tsurutani & Rodriguez (1981).

One should note that the combination of Eqs. (3) and (4) has no resemblance to the expression used by Ravishankar & Michalek (2020).

For further discussions of fast collisionless shocks, we refer the reader to Kennel et al. (1985) and Papadopoulos (1985) and the many articles in the American Geophysical Union (AGU) press monographs edited by Stone & Tsurutani (1985) and Tsurutani & Stone (1985). For a fast mode shock to be driven by a "piston" (the CME), the piston must be traveling in the upstream solar wind frame faster than the upstream magnetosonic wave speed. So, the critical parameter is the upstream magnetosonic wave speed, V_{ms1}, and not the Alfvén speed, V_{A1}, as used in the expression by RM20. For a brief review of fast, intermediate, and slow mode shocks (and their geomagnetic effects), we refer the reader to Tsurutani et al. (2011).

It should be mentioned that intermediate Alfvén shocks are believed to exist in the interplanetary medium (Tsurutani et al. 2005, 2018). The nature of these phase-steepened Alfvén waves is considerably different than that of CME magnetosonic shocks. Also, because of the strong dissipation effects of the Alfvén waves, clear diagnostics of the speed of the potential shocks and their Mach numbers are difficult to obtain.

Energetic particle acceleration at collisionless shocks depends on another property of shocks besides the Mach number. Figure 1 shows a schematic of the equatorial cut of the Earth's bow shock looking down on it from above. The Sun is at the top, out of view. At 1 AU, the distance of the Earth from the Sun, the Parker magnetic field spiral is nominally at an angle of ~45° relative to the Sun-Earth line. The angled magnetic field lines (light blue) are shown in the top portion of the schematic. On the right side of the bow shock (the dawn-morning side), the magnetic fields are nearly parallel to the shock normal, indicating that the shock is quasi-parallel in nature at these locations. On the left side of the bow shock, the shock normal is more perpendicular to the magnetic field, indicating the quasi-perpendicular nature of the shock in the afternoon sector.

The theoretical mechanisms for particle acceleration at shocks are different for different shock properties. At quasi-perpendicular shocks, where the shock normal direction is nearly perpendicular to the upstream magnetic field, energetic particles become further energized as they gradient-drift along the shock surface in the direction of the convection electric fields (Sonnerup 1969; Pesses et al. 1979; Decker et al. 1981; Bale et al. 2005). Particles can also be accelerated by a first-order Fermi mechanism as they interact with the shock or shock foot (Wu 1984; Leroy & Mangeney 1984; Meziane et al. 2019). For quasi-parallel shocks, where the shock normal direction is nearly parallel to the upstream magnetic field, the particle energization is via a second-order Fermi mechanism, the particles being scattered both in the upstream (Tsurutani et al. 1983) and downstream locations by plasma waves (Hudson 1965; Fisk & Lee 1980; Kennel et al. 1984a,b; Lee et al. 2012;

Zank et al. 2015; Desai & Giacalone 2016). For oblique shocks, all mechanisms are operative. Most computer codes now include these various acceleration mechanisms.

Thus, from the above description, particle acceleration occurs all along the shock, with different efficiencies providing different peak fluxes and spectra. The interplanetary magnetic field is also not absolutely constant in direction. The interplanetary medium is filled with waves and discontinuities, so the angle between the magnetic field and the Sun-Earth line is changing every minute. Thus, any measure of the particles at one point in space can be a mixture of these various processes occurring at the shock. The same general situation exists for CME shocks.

2. Conclusions

Coronal mass ejection shocks are fast mode magnetosonic shocks and not intermediate Alfvén shocks. The expression for the CME shock Mach number used by RM20 is incorrect. The correct expression for the Mach number is provided in this paper, reproduced from Tsurutani & Lin (1985). RM20 claims to have used an expression for the Mach number given by Gopalswamy et al. (2010) and Mäkelä et al. (2011). RM20 did not use the same shock Mach number expression (however, the expressions from Gopalswamy et al. (2010) and Mäkelä et al. (2011) are also incorrect). Every scientific paper should stand alone, and the authors of RM20 are responsible for making sure that the physics in their paper is correct, independent of previous publications. We have explained that particle acceleration at shocks is not simply a function of the shock Mach number. The nature of the shocks (quasi-parallel or quasi-perpendicular) and their upstream conditions are of paramount importance. We hope that the authors of RM20 will redo their analyses using correct expressions for the shock Mach number. It is possible that their conclusion, that the energetic particle peak flux is related to the shock Mach number, is incorrect. However, further analyses need to be done before a conclusion can be reached. It should also be noted that CME shocks first form some distance from the Sun's photosphere, ~3 to 4 R_s away (Tsurutani et al. 2003), depending on the speed of the CME and the properties of the upstream medium. This feature is present because, at closer distances, the CME speeds are typically sub-magnetosonic. It should also be noted that the shock Mach number is not constant with radial distance from the Sun. Therefore, care should be taken when making calculations similar to those of RM20.

Acknowledgements. Portions of this work were performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA. GSL thanks the Indian National Science Academy, New Delhi, for support under the INSA – Honorary Scientist Scheme.

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