This is a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law." in either case, put on a public domain creative commons license. Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

Please provide feedback

Please support the ScholarWorks@UMBC repository by emailing scholarworks-group@umbc.edu and telling us what having access to this work means to you and why it's important to you. Thank you.

JGR Space Physics

RESEARCH ARTICLE

10.1029/2018JA026301

Key Points:

- High-cadence magnetic field data from DSCOVR and Wind provide details of oblique heliospheric shock magnetic structure and oscillations
- Oblique, collisionless e-p-alpha plasma heliospheric shocks are modeled, reproducing main properties of the observed downstream oscillations
- Effects of alpha particles on the downstream magnetic oscillations and total density structure are revealed in low Mach number low-beta shocks

Supporting Information:

- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3
- Data Set S4

Correspondence to:

L. Ofman,
 ofman@cua.edu

Citation:

Ofman, L., Koval, A., Wilson, L. B. III, & Szabo, A. (2019). Understanding the role of α particles in oblique heliospheric shock oscillations. *Journal of Geophysical Research: Space Physics*, 124, 2393–2405. <https://doi.org/10.1029/2018JA026301>

Received 14 NOV 2018

Accepted 8 MAR 2019

Accepted article online 8 APR 2019

Published online 29 APR 2019

Understanding the Role of α Particles in Oblique Heliospheric Shock Oscillations

L. Ofman^{1,2} , A. Koval^{2,3}, L. B. Wilson III² , and A. Szabo²

¹Department of Physics, Catholic University of America, Washington, DC, USA, ²NASA GSFC, Heliospheric Physics Laboratory, Greenbelt, MD, USA, ³Goddard Planetary Heliophysics Institute, University of Maryland, Baltimore County, Baltimore, MD, USA

Abstract Recent observations by DSCOVR provide high temporal resolution (50 samples per second) magnetic vector field data that allows investigating the details of oblique heliospheric shock oscillations. It was found that some of these shocks exhibit magnetic oscillations, both downstream and upstream of the shock front. The DSCOVR/MAG magnetic field data are supplemented by an extensive database of low Mach number ($M < 3$) low- β (< 1) shock data observed by Wind albeit with lower temporal resolution. Motivated by the observations, we use the 2.5D hybrid model of the oblique shocks with α particles in addition to kinetic protons and electron fluid. We model the properties of the oblique shocks for a number of typical parameters found in observations and study the effects of the shock parameters and the relative α particle abundances on the properties of the shock magnetic field, density, and velocity oscillations. We find the α particles “surf” on the shock front and produce a wake of density oscillations. We examine the details of the phase space of the ions as well as the ion velocity distribution functions in various parts of the shock and study their nonthermal properties. We determine the effects of the α particle kinetic properties and abundances on the structure and dynamics of the shock downstream oscillations for a range of parameters relevant to low Mach number low- β heliospheric shocks.

1. Introduction and Motivation

Magnetized, collisionless shocks are ubiquitous phenomena in the heliosphere and in astrophysical plasma. They are often associated with coronal mass ejections, as well as with the interaction of the solar wind with solar system bodies (i.e., magnetospheric bow shocks). Of particular interest are super-Alfvénic Mach number oblique shocks where the shock normal exhibits an angle with the ambient magnetic field, since they are associated with the most energetic coronal mass ejections, affecting space weather conditions. Despite enormous efforts in theory, numerical simulations, and in situ observations of heliospheric shocks (see recent reviews, Bale et al., 2005; Krasnoselskikh et al., 2013; Marcowith et al., 2016), there is still no proper description of the mutual interaction between the electromagnetic fields and ions in the shock front. Such description is crucial for understanding processes of energy redistribution and dissipation in shocks, and associated oscillations of magnetic field magnitude and components, since incident ions carry the momentum and energy and shape the shock structure.

Oscillations of magnetic field and waves associated with heliospheric shocks, both upstream and downstream, have been reported extensively, for example, using STEREO (Blanco-Cano et al., 2016; Kajdič et al., 2012; Russell et al., 2009) and Wind (Wilson et al., 2007, 2009) spacecraft observations. Recently, it has been shown that the downstream oscillations could be associated with the gyration of the downstream ion distribution, and therefore, the oscillations are important in the processes of dissipation of the shock momentum and energy (Balikhin et al., 2008; Gedalin, 2016; Ofman et al., 2009; Ofman & Gedalin, 2013a). Electron-scale fluctuations, such as magnetosonic-whistler precursors (e.g., Wilson et al., 2017), can and do influence ion dynamics by perturbing the incident bulk flow by $\sim 13\%$, and the relative density fluctuations $\delta n/n$ could be high $\sim 75\%$ (e.g., Goncharov et al., 2014). Similar fluctuations have also been found to strongly heat thermal ions to suprathermal energies (e.g., Wilson et al., 2012). Thus, while electron kinetic interactions could be important in the upstream region oscillations, it is not clear if such fluctuations affect downstream oscillations, as previous studies have shown that low-frequency upstream waves are generally not transmitted across a collisionless shock (e.g., Wilson, 2016, and references therein). Hence, in the present study we focus on the effects of the ions on the downstream oscillations.

In order to model the non-Maxwellian distributions and gyration of ions, as well as pick-up ions self-consistently, kinetic modeling of the ions must be used, extending the modeling beyond the limitations of magnetohydrodynamic (MHD) approximation. The particle-in-cell (PIC) methods are often applied for modeling of the kinetic physics of shocks, while hybrid models use PIC for the ions and fluid description for the electrons from the early works of Leroy et al. (1982) and Winske and Quest (1988). In hybrid models, the electrons are treated as neutralizing massless fluid, and the electric field is obtained from a generalized Ohm's law with anomalous resistivity that models the collisionless energy exchange between ions and electrons empirically. More recently, for example, Ofman et al. (2009) used the 1-D hybrid model to study the collisionless relaxation of proton distributions in laminar quasi-perpendicular shocks in electron-proton solar wind plasma. Ofman and Gedalin (2013a) extended the study to two spatial dimensions (with three components of velocities and fields) using the 2.5-D hybrid model, and Ofman and Gedalin (2013b) studied moderate to high Mach number rippled quasi-perpendicular collisionless shocks and the deviation of the shock normal in the rippled shock from a laminar quasi-perpendicular shock.

The Deep Space Climate Observatory, or DSCOVR, was launched in 2015 to L1 orbit; the Lagrangian point (where the spacecraft's motion around the Sun matches that of the Earth at constant distance of about 0.01 AU from the Earth toward the Sun), by the National Aeronautics and Space Administration for the National Oceanic and Atmospheric Administration, and among other experiments, carries the PlasMag instrument suite (see <https://www.nesdis.noaa.gov/content/dscovr-deep-space-climate-observatory>) that measures the magnetic field and the velocity distribution functions (VDFs) of the electron, proton, and α particles of solar wind plasma with higher time resolution than existing instruments, providing real time monitoring of the solar wind data. While the high cadence plasma data are still being analyzed and evaluated, the flux-gate magnetometer (MAG) experiment on DSCOVR already provides high cadence (50 samples per second) three-component magnetic field measurements. Our study is motivated by recent observations of high-frequency magnetic oscillations associated with heliospheric shocks passing through L1 (and likely impacting the Earth's magnetosphere) that are resolved for the first time, thanks to the high-cadence of the MAG/DSCOVR data. We have used Wind spacecraft data (also at L1) where available for the same shock events (Wilson et al., 2017) to determine the α particle relative abundance at lower temporal cadence (92s), for cases where the magnetic and proton measurements are similar in both spacecraft. Our modeling approach allows investigating the relation between the well-resolved oblique shock magnetic structure and the lower-resolution plasma dynamics, providing the theoretical means of constraining the plasma parameter space consistent with observations.

Most previous theoretical and modeling studies have considered electron-proton plasma; however, α particles may have significant effects on the structure and downstream oscillations of magnetic field in oblique shocks due to their significant mass flux in the solar wind, in particular at times of increased solar activity, as evident from Wind data (e.g., Kasper et al., 2012). Test particle methods were used previously to model the acceleration of heavy ions by oblique shocks (e.g., Gedalin, 2017; Yang et al., 2011) and recently applied in combination with electron-proton hybrid models in low Mach number shocks (e.g., Gedalin et al., 2018). The effects of various degree of α relative abundance on reformation of perpendicular shocks were studied with 1-D PIC models (Rekaa et al., 2014). In particular, Gedalin (2017) studied the effects of α particles on a shock structure using particle-tracing methods and pressure balance conditions and found that the α particles decrease the amplitude of the downstream magnetic oscillations while increasing the magnetic compression. While the particle-tracing methods may provide a qualitative description of the minor ion dynamics in the shocks' magnetic field, due to the limitations of the particle-tracing approach, more advanced methods are needed to model the interaction between these ions, waves, magnetic field, and the shock plasma self-consistently.

The present 2.5-D (i.e., two spatial coordinates and three components of velocities and fields) model uses the PIC method to model the ions, while electrons are modeled as background neutralizing fluid, providing self-consistent ion-kinetic dynamics, nonlinear wave-particle interaction, and collective plasma effects. The hybrid model is appropriate for modeling collisionless shocks on ion-kinetic and larger scales, with the 1.5-D hybrid model first applied to study shocks (e.g., Quest, 1985; Winske & Quest, 1988), and were used extensively since then in one and two dimensions (see, e.g., recent studies by Burgess & Scholer, 2015; Burgess et al., 2016; Gingell et al., 2017; Ofman & Gedalin, 2013a, 2013b, and references therein). Motivated by new DSCOVR and past Wind data, we model for the first time oblique shocks using 2.5-D hybrid model with kinetic protons and α particles with typical solar wind relative abundance ($\sim 5\text{--}10\%$) treated

Figure 1. Four examples of oblique heliospheric shocks that exhibit downstream oscillations, detected with DSCOVR/MAG. The panels show the magnetic field intensity and the magnetic field components in geocentric solar ecliptic coordinates (red, B_x ; green, B_y ; blue, B_z). (a) 31 December 2016; (b) 9 November 2016; (c) 29 July 2016; (d) 8 July 2017. The parameters of the shocks are marked on the panels and given with error bars in Table 1.

fully self-consistently and investigate the role of α particle abundances on the downstream oscillations of oblique heliospheric shocks. While our modeling study is motivated by available observations, it is not our goal to reproduce the data in detail; rather, we are expecting a qualitative agreement, due to limitations of both observations and modeling approaches. We also study the effect of α particle abundance on the shock stationarity and coplanarity, in addition to the effects of other parameters such as Mach number and β of the oblique shocks, using the 2.5-D hybrid model. These modeled shock properties cannot be directly determined with single-point spacecraft observations.

The paper is organized as follows: In section 2 we present the observational motivation for our study, in section 3 we present our 2.5-D hybrid model of shocks, in section 4 we discuss the numerical results, and section 5 is devoted to summary and conclusions.

2. In Situ Observations

For observational motivation of our study we select four cases of oblique super-Alfvénic interplanetary shocks that show clear evidence of downstream oscillations, with various α particle relative abundances. Figure 1 shows these examples obtained with the DSCOVR magnetometer high-resolution (50 samples per second) measurements. For each of the shocks the figure shows the magnetic field magnitude and three components in the geocentric solar ecliptic (GSE) system of coordinates as well as the following shock parameters: θ_{Bn} the angle between the shock normal and the upstream magnetic field, M the shock Alfvén

Table 1*The Parameters (With Error Bars) of Four Cases of Shocks Observed by DSCOVR That Show Evidence of Downstream Oscillations*

Date (YYYYMMDD)	Shock type	M	β_i	n_α/n_e	θ_{Bn} (deg)
20161231	Fast Reverse	2.1 ± 0.5	1.2 ± 0.4	0.057 ± 0.005	82 ± 9
20160729	Fast Reverse	2.2 ± 0.6	1.5 ± 0.1	0.055 ± 0.003	66 ± 18
20161109	Fast Forward	2.4 ± 0.2	0.5 ± 0.5	0.02 ± 0.002	87 ± 9
20170708	Fast Forward	2.1 ± 0.1	0.3 ± 0.3	0.005 ± 0.001	56 ± 2

Mach number, β the ratio of upstream ion pressure to magnetic pressure, and the ratio of α to proton number density measured by the Wind spacecraft Solar Wind Experiment (SWE) Faraday Cups (FCs; Ogilvie et al., 1995).

The parameters and uncertainties of the 9 November 2016 and 8 July 2017 shocks are from the Harvard-Smithsonian Center for Astrophysics DSCOVR shock database (https://www.cfa.harvard.edu/shocks/dsc_data/), while the parameters and uncertainties of the 29 July 2016 and 31 December 2016 shocks, which are not listed in the shock database, were computed using the same Vinas and Scudder (1986) and Szabo (1994) technique, which fits the MHD Rankine-Hugoniot conservation equations to measurements across a shock that are provided in the supporting information. DSCOVR magnetometer 1-s data and FC 1-min data used for shock parameter determination are publicly available via <https://cdaweb.gsfc.nasa.gov>. The 29 July 2016 and 31 December 2016 shocks with significant α to proton number density ratios (about 6%) show more irregular downstream oscillations than the 9 November 2016 and 8 July 2017 with small α to proton ratios (about 1–2%). The shock parameters are listed in Table 1.

In Figure 2 we compare the Wind magnetic field data from the Magnetic Field Investigation instrument (Lepping et al., 1995) and plasma data from the SWE instruments for the same shock detected on 9 November 2016. Both spacecraft are orbiting at L1, and the separation between the spacecraft was $\sim 93R_E$, where R_E is the Earth's radius. Wind and DSCOVR temperatures are shown in electron volts (energy corresponding to most probable thermal speed). The magnetic field magnitude, the magnetic field components in geocentric solar ecliptic coordinates, the velocity components, the proton temperature T_p , and number density N_p are shown (obtained from nonlinear fitting of a single, isotropic Maxwellian VDF to sets of the FC measurements; see <https://cdaweb.sci.gsfc.nasa.gov>). The Wind data also include the α particle number density, N_α . It is evident that all the measured magnetic and kinetic properties of the solar wind plasma agree well between the two spacecraft (with similar agreement for the other events in Table 1), supporting our confidence in both data sets, and providing justification in the use of N_α from Wind in the analysis and modeling of the shocks detected with DSCOVR. The DSCOVR magnetometer data are shown with 1-s cadence, and the particle FC data are with 1-min cadence (same data sets as used for shock fitting, described in this section). Wind Magnetic Field Investigation data are with 3-s cadence, and SWE FC data are with 92-s cadence; both products are publicly available at <https://cdaweb.gsfc.nasa.gov>.

3. Hybrid Simulation Model

We use the 2.5-D hybrid model where the ions are described kinetically as particles using the PIC method, while electrons are treated as neutralizing massless background fluid. The fields and velocities include all three components in a two-dimensional spatial domain for all particle species. The model is an extension of the 1.5-D hybrid code initially developed by Winske and Omidi (1993), expanded by Ofman and Viñas (2007) to 2.5-D model, and parallelized by Ofman (2010). We use similar 2.5-D hybrid modeling method as in Ofman & Gedalin (2013a, 2013b), but with the addition of α particle population. The equations of motions of the particles are solved using Cartesian coordinates with the x -direction defined along the shock normal, y -direction defined as the perpendicular direction in the plane, and the noncoplanar direction is z . The equations of motions of the ions are advanced in time subject to the Lorentz force, and the fields are calculated on a two-dimensional background grid (i.e., the PIC method; Birdsall & Langdon, 1991). The electric field is obtained from the solution of the electron momentum equation, neglecting electron inertia, equivalent to the generalized Ohm's law with electron pressure gradient, Hall, and resistive terms. The boundary conditions are periodic in the y -directions and reflecting in the x -direction right boundary, where the particles are injected with the Alfvén Mach number M at the left (origin) of the x -direction. The

Figure 2. Comparison of DSCOVR (left panels) and Wind (right panels) data for the shock on 9 November 2016. The magnetic field magnitude, the magnetic field components in GSE coordinates (red: B_x , green: B_y , blue: B_z), the velocity components, the proton temperature T_p , and the ion number densities are shown (N_p for DSCOVR; N_p and N_α for Wind) from nonlinear analysis of Faraday Cup measurements.

distances in the simulation are in terms of the proton inertia length $\delta = c/\omega_{pp}$, where c is the speed of light; $\omega_{pp} = (4\pi n_p e^2/m_p)^{1/2}$ is the proton plasma frequency; the time is in units of the inverse proton cyclotron frequency, Ω_p^{-1} , where $\Omega_p = \frac{eB_0}{m_p c}$; and the velocities are in units of the Alfvén speed, V_A . The electron number density is determined from the quasi-neutrality condition, $n_e = \sum_i Z_i n_i$, where Z_i is the charge number in units of the electron charge e and n_i is the ion number density. Thus, for $n_\alpha = 0.05 n_e$ we have $n_p = 0.90 n_e$, and the normalized mass density is given as $\rho = (n_p + 4n_\alpha)/n_e$ (labeled as “den” in the figures below). Additional details of the normalization used in the hybrid code can be found in previous papers (e.g., see Ofman & Viñas, 2007; Ofman, 2010; Winske & Omidi, 1993).

3.1. Model Parameters

In the PIC method each numerical particle (a super-particle) represents a large number of physical particles with the conversion determined by the choice of normalization for the number density. Typically, we use $1,024 \times 128$ computational cells with 800 to 1,600 numerical particles per cell (ppc) where half of the numerical particles assigned to model protons and half to model α particles. The required resolution and the number of ppc of each ion species for various model parameters are determined by convergence tests, where the numerical parameters, such as the number of ppc’s or number of cells, are increased until convergence of the results is achieved (i.e., the output quantities, such as magnetic field magnitude, density, and velocity become nearly independent of the numerical parameters of the model). In order to further reduce statistical noise and increase accuracy, the numerical particles are approximated with a Gaussian shape function, and the temporal integration is performed with the second-order rational Runge-Kutta method (Wambecq, 1978). In the present study we use the cell size with the dimensions $\Delta x = \Delta y = 0.4\delta$ or 0.2δ , both producing very similar results for the same physical shock parameters. The spatial resolution of the ion motions is typically sub- δ , as the typical time step $\Delta t \sim 0.01\Omega_p^{-1}$, and the ions move a small fraction of δ between

Table 2*Summary of the Parameters Used in the 2.5-D Hybrid Models of Oblique Shocks in the Present Study*

Case #	$M (V_A)$	β	n_α/n_e	θ_{Bn}
1	2.5	0.4	0.05	60
2	2.5	0.4	0.10	60
3	2.5	0.4	0	60
4	1.25	0.4	0.05	60
5	2.1	1.2	0.06	80

subsequent time steps. The field solver is advanced with two sub-time steps per one particle motion time step for improved numerical accuracy, and a fourth-order filter is applied to the magnetic field to remove high-frequency numerical noise. In the present study the electron thermal pressure to magnetic pressure ratio β_e is equal to the normalized electron temperature. In our definition of ion β_i 's we use n_e to calculate thermal pressures with the corresponding ion temperatures, T_i . With this normalization $\beta_e = \beta_p = \beta_\alpha$ indicates equal temperatures for all plasma components. The angle between the shock normal and the direction of the magnetic field θ_{Bn} is specified in the initial state with the two components of the magnetic field in the x - y plane. The physical parameters of the oblique shocks modeled in the present study are given in Table 2.

4. Numerical Results

In Figures 3-8 we present the results of the 2.5-D hybrid modeling of the cases with parameters summarized in Table 2. The magnetic field magnitude $|B|$, the total mass density, and the component density structure in the x - y plane of an oblique shock with 5% (relative to n_e) α particles are shown in Figure 3 at time $t = 50\Omega_p^{-1}$. For this model run (case 1) the parameters are $\beta_e = \beta_p = \beta_\alpha = 0.4$, $\theta_{Bn} = 60^\circ$, and $M = 2.5$ (in terms of V_A). The shock front is evident in the magnetic and density structure, where the downstream region shows clear evidence of oscillations. A notable feature is the peaked and quasi-periodic density structure of the α particles. While the relative number density of the α particles is small, they show clear evidence of “surfing” on the shock front with strong localized density peaks, qualitatively similar to pickup ions

Figure 3. The normalized magnetic field and the mass density structure in the x - y plane for an oblique shock with 5% α particles at $t = 50\Omega_p^{-1}$. The parameters are $\beta_e = \beta_p = \beta_\alpha = 0.4$, $\theta_{Bn} = 60^\circ$, and $M = 2.5$ (case 1). (a) The magnetic field magnitude $|B|$, (b) the total mass density, (c) the proton density, and (d) the α density.

Figure 4. (a) The normalized density structure of the shock in the x -direction averaged over the y -direction for the cases with 5% α particles (red, case 1), 10% α particles (green, case 2), and protons only (blue, case 3) at $t = 50\Omega_p^{-1}$. (b) Same as (a) but for proton densities. (c) The α particle densities for cases 1 and 2. (d) The corresponding magnetic field magnitude structure in the x -direction of the oblique shocks (red, case 1; green, case 2; blue, case 3) in the cut of the 2-D computational domain at the middle of the “box” in the y -direction. The vertical dashed lines demonstrate the nearly in-phase oscillations of the magnetic field and density in case 1, and the close phase relation is evident for other cases as well. The other shock parameters are $\beta_e = \beta_p = \beta_\alpha = 0.4$, $\theta_{Bn} = 60^\circ$, and $M = 2.5$.

(e.g., Lee et al., 1996). The term “surfing” in the context of electron acceleration by laser-driven waves in plasma was first coined by Katsouleas and Dawson (1983) and adapted by Lee et al. (1996) to describe pickup-ion acceleration in perpendicular and quasi-perpendicular shocks, based on original Sagdeev (1966) idea. In this scenario the ions are trapped between the shock potential and the Lorentz force due to their motion in the shocks’ magnetic field and are accelerated after experiencing multiple reflections at the shock front before escaping downstream (see Figure 2 in Lee et al., 1996). Because of the small abundance of the α particles in the solar wind and, correspondingly in our model, their collective dynamics resembles single-particle orbits in the background magnetic field of the shock. While the surfing acceleration signature (i.e., the local α particle density increases or bunching) is most evident just behind the shock front, the wave-like structure is also evident with decreasing magnitude further in the downstream region. Thus, the total mass density structure oscillations in the downstream region consist from contributions of both ions, with notable α particle contribution due to their large mass number ($A = 4$). The oscillations in the density are related to the corresponding oscillations of the total pressure in nearly coplanar oblique shock, $p_e + p_{i,xx} + B^2/8\pi = \text{const.}$ (where p_e is the electron thermal pressure and $p_{i,xx}$ is the diagonal component of the ions pressure), and are also evident in the oscillations of the magnetic field magnitude in the downstream region (see the discussion in Balikhin et al., 2008; Gedalin et al., 2018; Ofman et al., 2009; Ofman & Gedalin, 2013a). Ofman et al. (2009) has generalized Balikhin et al. (2008) results for low Mach number, low- β shocks using 1.5-D hybrid modeling and theoretical study of $e - p$ quasi-perpendicular shocks and shown that the gyration of the downstream ion distribution could produce the oscillations of ion pressure and magnetic field as well in higher Mach number, higher β shocks. Here we consider the effects of α particles on the oscillations in the 2.5-D hybrid modeling study. Since the shock has a moderate super-Alfvénic Mach number, we see some evidence of corrugate structure of the shock front (e.g., Ofman & Gedalin, 2013b). However, the corrugation effects are small for the present shock parameters, with small apparent effect on the local normal direction.

Figure 5. Same as Figure 3, but with $M = 1.25$ (case 4). (a) The magnetic field magnitude $|B|$, (b) the total mass density, (c) the proton density, (d) the α density.

In Figure 4 we compare the structure of the oblique shocks and the downstream oscillations for three cases (cases 1–3 in Table 2). In case 1 there are 5% α particles in addition to protons, in case 2 there are 10% α particles, and in case 3 there are protons only, all in addition to electron fluid in our model. The densities are averaged over the y direction, eliminating the effects of the small-scale corrugation in the shock structure facilitating comparison to 1-D models and to single point in situ measurement. The comparison of the shock structure demonstrates the effect of α particles on the ramp and on the downstream oscillations. When protons only are present, the magnitude of the ramp is the lowest among the three cases, with increased ramp magnitude together with increased relative abundance of the α particles (Figures 4a). In Figures 4b the proton density structure is shown with strong downstream oscillations with a period of $\sim 3\delta$ in cases 1–3. It is evident that the proton density oscillation period is weakly affected by the presence of α particles in the first few periods near the shock front. The amplitudes of the oscillations are similar, taking into account the decreased proton density with increased α particle abundance with a fixed n_e arising from the quasi-neutrality condition. The density structure of the α particles in cases 1 and 2 is compared in Figures 4c. It is evident that the period of the oscillations is similar in both cases, with stronger increase in case 1 downstream density compared to the upstream value. There is also a shift of about 2.5δ between cases 1 and 2 in the location of the first peak of α particle density, likely due to the increased inertia of the α particles in case 2 compared to case 1. The density cuts through the center in the y -coordinate of the computational region show the details of the shock density structure and the downstream oscillations of the ions in the x -direction. The location of the shock front ramp in the proton density is evident with a downstream jump by a factor of 3.5, followed by downstream oscillation with an average period of $\sim 3\delta$. The α particle density ramp lags about $\sim 3\delta$ behind the protons ramp peak, with a jump by a factor of 7.5, followed by decrease to about the upstream density in about 6δ .

Figure 4d shows the magnetic field magnitude dependence on x -direction of the oblique shocks for the cases, with 5% α particles in addition to protons (red, case 1), with 10% α in addition to protons (green, case 2), and with protons only (blue, case 3). The results are shown for a cut at the middle of the y -coordinate of the computational box of the oblique shocks at $t = 50\Omega_p^{-1}$. For the nearly plane-parallel (laminar) structure of the shock, the magnetic field oscillations are nearly in phase and with similar relative amplitude as the thermal pressure oscillations shown in Figures 4a, as demonstrated by the overplotted dashed vertical lines. The effects of the α particles are also evident in the magnetic oscillations for cases 1 and 2. The α particles cause an increasing (with α relative abundance) shift (delay) in the location of the ramp. Also, the α particle

Figure 6. The perpendicular velocity distribution function of α particles (left panels) and protons (right panel) in the downstream region at $x = 355$ (top panels), $x = 361$ (middle panels), and $x = 367$ (lower panels) for the shock in case 1 at $t = 60$.

Figure 7. The parallel ($u_{x,i}$) proton (solid) and α (dashes) “fluid” velocity of the shock in the middle of the computational domain along the x -direction of the shock. (a) Case 1 and (b) case 5.

component in the total pressure affects the frequency and increases the amplitude of the oscillations (most evident for case 2).

The structure of lower Mach number ($M = 1.25$) oblique shock modeled with the 2.5-D hybrid code is shown in Figure 5 (case 4) for comparison with the results in case 1 (other parameters being the same). It is evident that in this case the shock structure is coplanar, or laminar, in contrast with $M = 2.5$ shock in case 1. Also, the amplitude of the ramp in this case is lower than in case 1, as expected: For $|B|$ the ramp maximum is 2.09 in case 4, compared to 3.40 in case 1, and the density ratio is about a factor of 2 between the two cases, as expected. The oscillation of proton density and the surfing oscillations of the α particles in the downstream region are present here as well, with corresponding lower amplitude, nearly in phase and with similar relative amplitude as the magnetic downstream oscillations of the oblique shock.

The VDFs of the ions are constructed directly by binning the calculated velocity components of the protons and ions in the 2.5-D hybrid code. In order to calculate the VDFs at a given $x = x_0$ spatial location summed over y , all particles in $x_0 \pm \Delta x$ region for all y are binned according to the velocities, with the color scale in Figure 6 corresponding to the number of particles in each species in the corresponding bin. We use 300×300 uniformly distributed bins in perpendicular velocity space (V_y, V_z). In Figure 6 left column shows the α particle perpendicular VDFs, and the right column shows the proton perpendicular VDFs at $x = 355, 361$, and 367 (the spacing chosen to sample locations of various oscillation and gyration phases) in the downstream regions of the oblique shock of case 1 at $t = 60\Omega_p^{-1}$. The non-Maxwellian structure of the VDFs is evident for both species, with strong non-Maxwellian nongyrotropic tails in the α perpendicular VDFs. While both species are gyrating perpendicular to the background magnetic field, the effect in α is stronger due to their larger gyroradius and the nonthermal tails exhibiting strong variation and rotation in velocity space at the various locations, in the fluid-like α particle population gyration.

The fluid velocity of the shock ions $u_{x,i}$ is computed by taking the first moment of the VDF of the protons and α particles. The x -dependence of $u_{x,i}$ in the middle of the computational domain is shown in Figure 7 for the shock in cases 1 and 5. Note that in case 5 the model parameters were chosen to match the shock parameters from spacecraft observations on 31 December 2016 in Table 1, shown in Figure 1a. It is evident that magnitude of the jump and the downstream oscillations show qualitative agreement with observations. The uniform upstream velocity is evident, and the downstream oscillations of the protons and α particles parallel fluid velocities are seen. The oscillations of the $u_{x,i}$ for the α particles are nonlinear with an amplitude larger than the upstream velocity, while the proton parallel fluid velocity oscillations are small in qualitative agreement with the observed proton velocity shown in Figure 2. The differences in the ramp of the shock between the two ion species are also evident in the model results.

The nonstationarity of the shocks in cases 1–3 is demonstrated in Figures 8a–8c by comparing the x -dependence of $|B|$ in the middle of the computational domain at three sequential modeled times of the shock propagation. The magnetic field magnitude of the shock is plotted at the three times shifted to the

Figure 8. The magnetic field magnitude $|B|$ of the shocks dependence on x cut in the middle of the y -dimension at three times shifted to the same frame for cases 1–4. (a) No α particles (case 3). The three times are $t = 40$ (solid), 50 (dots), and 60 (dashes) in units of Ω_p^{-1} . (b) Same as (a) but for case 1 with 5% α particles. (c) Same as (a) but for case 2 with 10% α particles. (d) The results for case 4 with $M = 1.25$ and 5% α particles. The three times are $t = 40$ (solid), 45 (dots), and 50 (dashes) in units of Ω_p^{-1} .

same spatial reference frame. The three times are $t = 40, 50$, and $60 \Omega_p^{-1}$ overplotted in panels a–c. The case without α particles (case 3) shows that the peaks of the oscillations are closely aligned in the downstream region (i.e., most stationarity), and the phase shift is small for the first four peaks for the for the present parameters ($M = 2.5$). For the case with 5% α particles relative abundance the nonstationarity is more evident than in the shock without α and becomes stronger in the shock with 10% α particles, other parameters being the same in the three cases. This is evident in the variation in the phase and magnitude of the oscillation peaks as a function of time. For comparison we show the results for case 4 with lower Mach number ($M = 1.25$) and 5% α particles in Figure 8d at three times $t = 40, 45, 50 \Omega_p^{-1}$. It is evident that in the latter case the magnetic field structure of the shock does not vary significantly with time, confirming the near stationarity of the shock for these parameters.

5. Summary and Conclusions

Motivated by recent observations with DSCOVR/MAG of collisionless heliospheric oblique shocks that show the magnetic structure and oscillations, we investigate the role of plasma parameters, including the effects of α particles on the properties of these oscillations. We use Wind spacecraft to estimate and constrain the α particle parameters in the shocks. For the first time we use the 2.5-D hybrid model with α particles included self-consistently to model collisionless oblique shocks with typical parameters found in observations. By comparing shocks with various α relative abundances (0, 5%, 10%) we find that even low relative abundance (5–10%) α particles show strong density oscillations affecting the total pressure significantly, and consequently the amplitude and frequency of the total magnetic field oscillations. The 2.5-D hybrid model shows that the α particles density structure is consistent with surfing acceleration mechanism (in the sense described by Lee et al. (1996)), producing a downstream wake with strong relative density oscillation amplitude. The shocks show evidence of nonstationarity, corrugations, and reformation for a $M = 2.5$, with a coplanar structure and stationarity at lower Mach number ($M = 1.25$). The nonstationarity is increased with increased α particle relative abundance. We examine the detail of the phase space of the ions as well as the ion VDFs in various parts of the shock and demonstrate their nonthermal properties as evident in the non-Maxwellian VDFs with nongyrotropic tails and phase-space gyro-motion. It is interesting to note that our study agrees with previous studies by Gedalin (2017), finding that α particles have strong effect on the downstream oscillations and on the gyro-phase mixing increasing the irregularity of the oscillations. In qualitative agreement with single-particle-tracing previous result (see Figure 2 in Gedalin (2017) for close to case 1 parameters), we find that the magnetic oscillation amplitude is increased significantly when α particles are present. In our 2.5-D hybrid modeling study the magnetic oscillations amplitude increase due to α particles is stronger than in previous particle-tracing studies especially near the shock front, due to the nonlinear wave-particle interactions, and in part due to the higher β of the ions in the present model. We also conclude that nonstationarity and noncoplanarity of the shocks is enhanced by the presence of 5–10% α particles and may impact the interpretation of single-point spacecraft observations and the determination of the shock normal.

In summary, we show the effects of the α particle kinetic properties and relative abundances on the magnetic and density structure as well as the dynamics of the downstream shock oscillations for a range of parameters relevant to low Mach number low- β oblique, collisionless heliospheric shocks. We compare the magnetic and density structure of the shocks and demonstrate the effects of α on the nonstationarity of the shocks. Our results help quantify the relation between the α particle physical parameters and the magnetic properties of oblique shocks in the heliosphere, providing an additional theoretical constraint for the determination of less well measured plasma properties using the magnetic field and density data of DSCOVR and Wind spacecraft.

Acknowledgments

L. O. acknowledges support by NASA Cooperative agreement NNG11PLA10A to CUA and discussions with M. Gedalin. Resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center. DSCOVR and Wind data are publicly available at <https://cdaweb.gsfc.nasa.gov>. The data of the 9 November 2016 and 8 July 2017 shocks are from the Harvard-Smithsonian Center for Astrophysics DSCOVR shock database (https://www.cfa.harvard.edu/shocks/dsc_data/), while the data of the 29 July 2016 and 31 December 2016 shocks are provided as a supporting information to this paper.

References

- Bale, S. D., Balikhin, M. A., Horbury, T. S., Krasnoselskikh, V. V., Kucharek, H., Möbius, E., et al. (2005). Quasi-perpendicular shock structure and processes. *Space Science Reviews*, 118, 161–203. <https://doi.org/10.1007/s11214-005-3827-0>
- Balikhin, M. A., Zhang, T. L., Gedalin, M., Ganushkina, N. Y., & Pope, S. A. (2008). Venus Express observes a new type of shock with pure kinematic relaxation. *Geophysical Research Letters*, 35, L01103. <https://doi.org/10.1029/2007GL032495>
- Birdsall, C. K., & Langdon, A. B. (1991). *Plasma physics via computer simulation*. Bristol, England: Adam Hilger.
- Blanco-Cano, X., Kajdič, P., Aguilar-Rodríguez, E., Russell, C. T., Jian, L. K., & Luhmann, J. G. (2016). Interplanetary shocks and foreshocks observed by STEREO during 2007–2010. *Journal of Geophysical Research: Space Physics*, 121, 992–1008. <https://doi.org/10.1002/2015JA021645>
- Burgess, D., Hellinger, P., Gingell, I., & Trávníček, P. M. (2016). Microstructure in two- and three-dimensional hybrid simulations of perpendicular collisionless shocks. *Journal of Plasma Physics*, 82(4), 905820401. <https://doi.org/10.1017/S0022377816000660>
- Burgess, D., & Scholer, M. (2015). *Collisionless shocks in space plasmas*. Cambridge, UK: Cambridge University Press.
- Gedalin, M. (2016). Transmitted, reflected, quasi-reflected, and multiply reflected ions in low-Mach number shocks. *Journal of Geophysical Research: Space Physics*, 121, 10,754–10,767. <https://doi.org/10.1002/2016JA023395>
- Gedalin, M. (2017). Effect of alpha particles on the shock structure. *Journal of Geophysical Research: Space Physics*, 122, 71–76. <https://doi.org/10.1002/2016JA023460>
- Gedalin, M., Zhou, X., Russell, C. T., Drozdov, A., & Liu, T. Z. (2018). Ion dynamics and the shock profile of a low-Mach number shock. *Journal of Geophysical Research: Space Physics*, 123, 8913–8923. <https://doi.org/10.1029/2018JA025945>
- Gingell, I., Schwartz, S. J., Burgess, D., Johlander, A., Russell, C. T., Burch, J. L., et al. (2017). MMS observations and hybrid simulations of surface ripples at a marginally quasi-parallel shock. *Journal of Geophysical Research: Space Physics*, 122, 11. <https://doi.org/10.1002/2017JA024538>

- Goncharov, O., Šafránková, J., Němeček, Z., Přech, L., Pitňa, A., & Zastenker, G. N. (2014). Upstream and downstream wave packets associated with low-Mach number interplanetary shocks. *Geophysical Research Letters*, 41, 8100–8106. <https://doi.org/10.1002/2014GL062149>
- Kajdič, P., Blanco-Cano, X., Aguilar-Rodriguez, E., Russell, C. T., Jian, L. K., & Luhmann, J. G. (2012). Waves upstream and downstream of interplanetary shocks driven by coronal mass ejections. *Journal of Geophysical Research*, 117, A06103. <https://doi.org/10.1029/2011JA017381>
- Kasper, J. C., Stevens, M. L., Korreck, K. E., Maruca, B. A., Kiefer, K. K., Schwadron, N. A., & Lepri, S. T. (2012). Evolution of the relationships between helium abundance, minor ion charge state, and solar wind speed over the solar cycle. *Astrophysical Journal*, 745, 162. <https://doi.org/10.1088/0004-637X/745/2/162>
- Katsouleas, T., & Dawson, J. M. (1983). Unlimited electron acceleration in laser-driven plasma waves. *Physical Review Letters*, 51, 392–395. <https://doi.org/10.1103/PhysRevLett.51.392>
- Krasnoselskikh, V., Balikhin, M., Walker, S. N., Schwartz, S., Sundkvist, D., Lobzin, V., et al. (2013). The dynamic quasiperpendicular shock: Cluster discoveries. *Space Science Reviews*, 178, 535–598. <https://doi.org/10.1007/s11214-013-9972-y>
- Lee, M. A., Shapiro, V. D., & Sagdeev, R. Z. (1996). Pickup ion energization by shock surfing. *Journal of Geophysical Research*, 101, 4777–4790. <https://doi.org/10.1029/95JA03570>
- Lepping, R. P., Acuña, M. H., Burlaga, L. F., Farrell, W. M., Slavin, J. A., Schatten, K. H., et al. (1995). The wind magnetic field investigation. *Space Science Reviews*, 71, 207–229. <https://doi.org/10.1007/BF00751330>
- Leroy, M. M., Winske, D., Goodrich, C. C., Wu, C. S., & Papadopoulos, K. (1982). The structure of perpendicular bow shocks. *Journal of Geophysical Research*, 87, 5081–5094. <https://doi.org/10.1029/JA087iA07p05081>
- Marcowith, A., Bret, A., Bykov, A., Dieckman, M. E., O’C Drury, L., Lembège, B., et al. (2016). The microphysics of collisionless shock waves. *Reports on Progress in Physics*, 79(4), 46901. <https://doi.org/10.1088/0034-4885/79/4/046901>
- Ofman, L. (2010). Hybrid model of inhomogeneous solar wind plasma heating by Alfvén wave spectrum: Parametric studies. *Physical Review Letters*, 115(A14), 4108. <https://doi.org/10.1029/2009JA015094>
- Ofman, L., Balikhin, M., Russell, C. T., & Gedalin, M. (2009). Collisionless relaxation of ion distributions downstream of laminar quasi-perpendicular shocks. *Journal of Geophysical Research*, 114, A09106. <https://doi.org/10.1029/2009JA014365>
- Ofman, L., & Gedalin, M. (2013a). Two-dimensional hybrid simulations of quasi-perpendicular collisionless shock dynamics: Gyration downstream ion distributions. *Journal of Geophysical Research: Space Physics*, 118, 1828–1836. <https://doi.org/10.1029/2012JA018188>
- Ofman, L., & Gedalin, M. (2013b). Rippled quasi-perpendicular collisionless shocks: Local and global normals. *Journal of Geophysical Research: Space Physics*, 118, 5999–6006. <https://doi.org/10.1002/2013JA018780>
- Ofman, L., & Viñas, A. F. (2007). Two-dimensional hybrid model of wave and beam heating of multi-ion solar wind plasma. *Journal of Geophysical Research*, 112, A066104. <https://doi.org/10.1029/2006JA012187>
- Ogilvie, K. W., Chornay, D. J., Fritzenreiter, R. J., Hunsaker, F., Keller, J., Lobell, J., et al. (1995). SWE, A comprehensive plasma instrument for the wind spacecraft. *Space Science Reviews*, 71, 55–77. <https://doi.org/10.1007/BF00751326>
- Quest, K. B. (1985). Simulations of high-Mach-number collisionless perpendicular shocks in astrophysical plasmas. *Physical Review Letters*, 54, 1872–1874. <https://doi.org/10.1103/PhysRevLett.54.1872>
- Rekaa, V. L., Chapman, S. C., & Dendy, R. O. (2014). Ion pre-acceleration in fully self-consistent particle-in-cell simulations of supercritical perpendicular reforming shocks in multiple ion species plasmas. *Astrophysical Journal*, 791, 26. <https://doi.org/10.1088/0004-637X/791/1/26>
- Russell, C. T., Jian, L. K., Blanco-Cano, X., & Luhmann, J. G. (2009). STEREO observations of upstream and downstream waves at low Mach number shocks. *Geophysical Research Letters*, 36, L03106. <https://doi.org/10.1029/2008GL036991>
- Sagdeev, R. Z. (1966). Cooperative phenomena and shock waves in collisionless plasmas. *Reviews of Plasma Physics*, 4, 23.
- Szabo, A. (1994). An improved solution to the “Rankine-Hugoniot” problem. *Journal of Geophysical Research*, 99, 14,737–14,746. <https://doi.org/10.1029/94JA00782>
- Vinas, A. F., & Scudder, J. D. (1986). Fast and optimal solution to the “Rankine-Hugoniot problem”. *Journal of Geophysical Research*, 91, 39–58. <https://doi.org/10.1029/JA091iA01p00039>
- Wambeck, A. (1978). Rational Runge-Kutta methods for solving systems of ordinary differential equations. *Computing*, 20, 333–342.
- Wilson, L. B. (2016). Low frequency waves at and upstream of collisionless shocks. *Washington DC American Geophysical Union Geophysical Monograph Series*, 216, 269–291. <https://doi.org/10.1002/9781119055006.ch16>
- Wilson, L. B., Cattell, C., Kellogg, P. J., Goetz, K., Kersten, K., Hanson, L., et al. (2007). Waves in Interplanetary Shocks: A Wind/WAVES Study. *Physical Review Letters*, 99(4), 41101. <https://doi.org/10.1103/PhysRevLett.99.041101>
- Wilson, L. B. III, Cattell, C. A., Kellogg, P. J., Goetz, K., Kersten, K., Kasper, J. C., et al. (2009). Low-frequency whistler waves and shocklets observed at quasi-perpendicular interplanetary shocks. *Journal of Geophysical Research*, 114, A10106. <https://doi.org/10.1029/2009JA014376>
- Wilson, L. B. III, Koval, A., Szabo, A., Breneman, A., Cattell, C. A., Goetz, K., et al. (2012). Observations of electromagnetic whistler precursors at supercritical interplanetary shocks. *Geophysical Research Letters*, 39, L08109. <https://doi.org/10.1029/2012GL051581>
- Wilson, L. B. III, Koval, A., Szabo, A., Stevens, M. L., Kasper, J. C., Cattell, C. A., & Krasnoselskikh, V. V. (2017). Revisiting the structure of low-Mach number, low-beta, quasi-perpendicular shocks. *Journal of Geophysical Research: Space Physics*, 122, 9115–9133. <https://doi.org/10.1002/2017JA024352>
- Winske, D., & Omid, N. (1993). Computer space plasma physics: Simulation techniques and software (pp. 103–160).
- Winske, D., & Quest, K. B. (1988). Magnetic field and density fluctuations at perpendicular supercritical collisionless shocks. *Journal of Geophysical Research*, 93, 9681–9693. <https://doi.org/10.1029/JA093iA09p09681>
- Yang, Z. W., Lembège, B., & Lu, Q. M. (2011). Acceleration of heavy ions by perpendicular collisionless shocks: Impact of the shock front nonstationarity. *Journal of Geophysical Research*, 116, A10202. <https://doi.org/10.1029/2011JA016605>