Development of Hybrid Plasma Simulations to Study Shock Waves Beyond the Solar System

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Abstract

In 2012, the Voyager 1 space probe left the solar system and began gathering the first ever *in situ* observations of plasma in the very local interstellar medium (VLISM). Since leaving the solar system, Voyager 1 has twice observed noticeable increases in the background magnetic field, observed on the scale of multiple days. Some have hypothesized that these observations could be the result of a shock, although the increase in the magnetic field occurs on a much broader scale than is typical for a shock within the solar system. Since plasmas within the solar system are nearly always considered collisionless, we use hybrid plasma simulations to investigate whether weak Coulomb collisionality between ions could result in such a broad shock structure. We first discuss an explicit simulation method that we ultimately show to be unsuitable for our purposes, but which carries valuable lessons nonetheless. Then we propose a more promising semi-implicit simulation scheme and present preliminary results in its development.

Introduction

After entering the VLISM, Voyager 1 made two observations of jumps in the magnetic field on unusually broad scales. Burlaga and Ness (2016) suggest that the disturbances in the magnetic field, shown in Figure 1, can be interpreted as shocks because of the electron plasma oscillations preceding the change in the magnetic field. We will refer to them as such for simplicity. Mostafavi & Zank (2018) study the VLISM using a one-dimensional, steady-state model for a perpendicular shock. They find that under these assumptions, the observed shocks can be explained by treating the VLISM as collisional with respect to thermal plasma. We develop hybrid plasma simulations that incorporate Coulomb collisions to work toward verifying these findings using a more sophisticated physical model. Our simulation methods can account for changes in the system that develop over time, and their flexible parameters make them suitable for studying other phenomena in the VLISM and beyond.

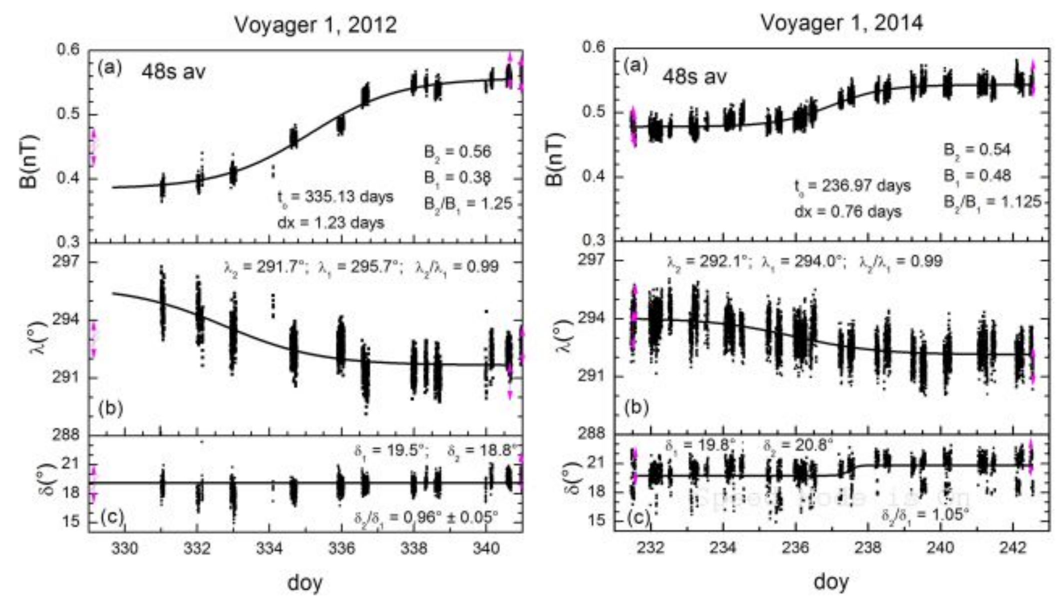

Figure 1: Voyager 1 observations of the magnetic field magnitude, inclination, and azimuthal angle in the VLISM near each of the observed disturbances, with best-fit curves added. Figure taken from Burlaga & Ness (2016).

General Methods

During the investigation, we model the VLISM plasma using a typical hybrid, 1D3V approach, with electrons modeled as a fluid and ions as particles. Maxwell's equations for the electromagnetic fields close the system. Fields and moments are calculated in cells with resolution of ½ of an ion inertial length using a variety of numerical methods. We modeled a VLISM plasma with the following parameters:

- $B = 5\ \mu G$ (Burlaga & Ness 2016)
- $\theta_{Bn} = 80°$ (Burlaga & Ness 2016)
- $n_i = 0.1\ cm^{-3}$ (Gurnett & Kurth 2019)
- $T = 30{,}000$ K (Richardson *et al.* 2019)
- $\ln \Lambda = 20$

We model Coulomb collisions between ions using the "collision field" approach as described in Jones *et al.* (1996). Collision frequency is an input to the simulation for ease of computation, but we predominantly used the expression

$$\nu_p = \frac{64\sqrt{\pi} n e^4 \ln \Lambda}{3\sqrt{2} m_p^2 v_t^3} \qquad (1)$$

derived from equation #7 from Jones *et al.* (1996), which for our parameters is approximately $10^{-7}\ s^{-1}$. A "collision mesh" is introduced which operates on the same grid as the fields and moments, calculating the effective force of short-range collisions on the particles within each grid cell based on the collision frequency parameter.

The Explicit Model

We began by using a simulation model created by Dr. Kaijun Liu in our preliminary work. The model uses an explicit formula to solve the fields. It starts at a quiet state, with ions flowing in from the left boundary. They are reflected backward by a "wall" at the right boundary, which in turn creates a shock traveling leftward. This results in a sharp shock, which we theorize would become wider over time if the model was run for a sufficiently long period.

This model produced highly unusual results when run for a long time. Figure 2 shows growth in the density in the upstream region, which does not make physical sense for this application. A thorough investigation of the code found this to be a result of artificial cooling from the numerical resistivity (η), which helps damp noise caused by the code's numerical solution methods. This artificial cooling is visualized in Figure 3. Both a contraction of particle velocity and an increase in the number density can be seen as the particles move away from the injection boundary.

We experimented with reducing the value of η to eliminate the unphysical cooling, but found that its damping effect was too important to sacrifice. With low enough values of η to eliminate the cooling, we found that the electric field exploded to extreme and unphysical values, as shown in Figure 4. This extraordinary electric field in turn accelerated particles far too quickly, leading to untrustworthy results and often crashing the simulation itself. These results suggest that this explicit simulation model is not stable enough to effectively study the weakly collisional interactions we are interested in.

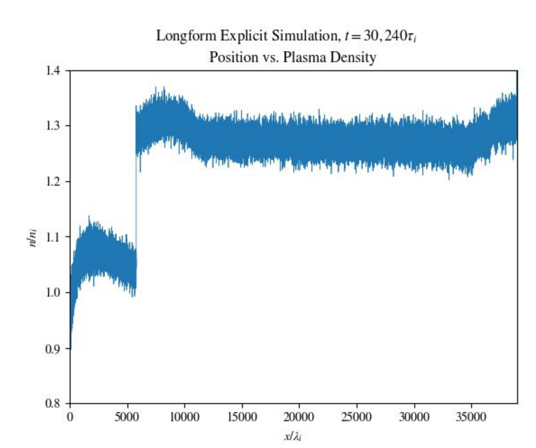

Figure 2: Position vs. Density after 30,240 ion cyclotron periods (τ_i). Position is normalized to the ion inertial length (λ_i); density is normalized to the initial upstream state (n_i).

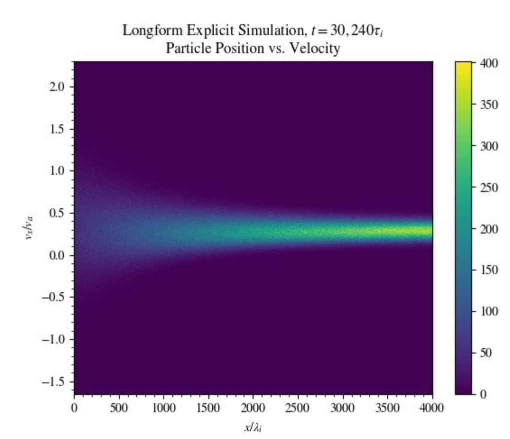

Figure 3: Particle Position vs. Velocity histogram with 500 bins. Taken from the same data as figure 2, near the left boundary of the simulation area.

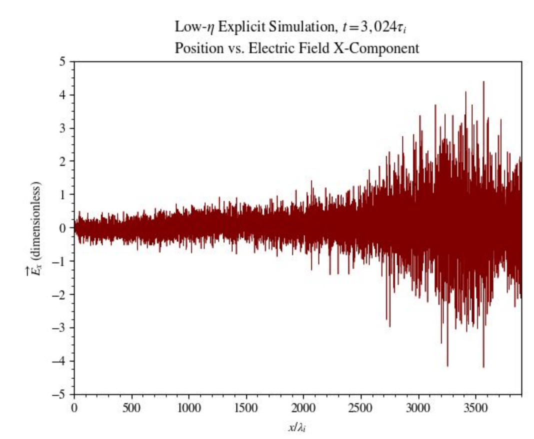

Figure 4: Position vs. Electric Field X-Component after 3,024 ion cyclotron periods during a low-resistivity test of the explicit simulation's capabilities.

The Semi-Implicit Model

To eliminate the concerns with the explicit model as discussed above, we propose further developing the plasma simulation used to study the *IBEX* ribbon by Florinski *et al.* (2016). It is a semi-implicit model using periodic boundaries, which we project to greatly reduce the numerical noise, rendering the numerical resistivity unnecessary. The periodic boundary conditions mean we cannot introduce a shock by reflecting the ions, so we instead propose introducing a fast magnetosonic wave which can be expected to steepen into a shock. We produce the wave using the procedures of Lembege & Dawson (1984), who suggest adding a "driving current" during the early stages of the simulation and then removing it, allowing the wave to develop over time. The driving current is defined as follows:

$$j_d = j_0 \sin(kx - \omega t) \qquad (2)$$

The driving current is applied for the first 5 ion cyclotron periods before being switched off. Figure 5 shows an example of the system's state after running for a total of 20 ion cyclotron periods, once the wave has visibly developed. We have not yet been able to observe the wave steepening into a shock; in our early tests the wave collapses inward as shown in Animation 1. However, development of this method is in its early stages, and we are confident that this simulation model will be applicable to the study of shocks in weakly collisional plasmas. We have also run long simulation tests to confirm that the electric field does not explode as it does in the explicit model. See Figure 6 for a good example of this result.

Animation 1: Scan the code to the left to see a video of how the magnetosonic wave evolves over time using the present model.

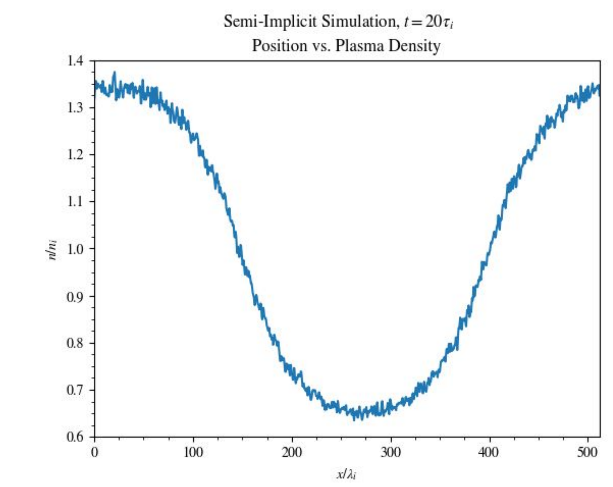

Figure 5 (left): A current-induced magnetosonic wave observed while testing the semi-implicit plasma model.

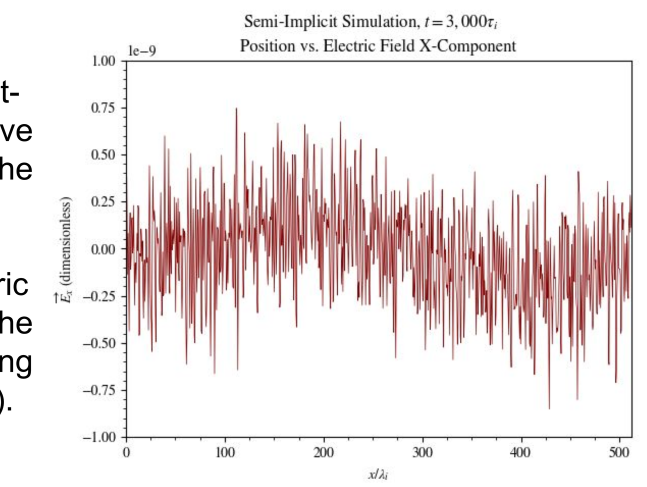

Figure 6 (right): The electric field distribution in the semi-implicit model after a long "stress test" simulation ($\eta = 0$).

Conclusions and Future Work

After rigorous testing of the previously discussed explicit model, we conclude that it is unfortunately not well-suited to examine weak collisional effects within VLISM plasma. We also recommend that any model which requires a high level of numerical resistivity to yield accurate results be treated with caution within this domain. Our findings suggest that high values of numerical resistivity "drown out" the effects of weakly collisional particle interactions, making them difficult if not impossible to use meaningfully in our application. We further present a promising semi-implicit model currently under development to address these issues. This model is favored for its periodic boundary conditions and increased numerical stability, which should allow us to eliminate numerical resistivity from the model altogether. This in turn completely removes the "anomalous" electron-ion collisions described by Winske & Omidi (1991) so that attention can be focused completely on the effects of infrequent ion-ion collisions. We present preliminary results from the adaptation of this simulation to model a shock, showcasing a fast magnetosonic wave induced by an external current as in Lembege & Dawson (1984).

Moving forward, we first aim to continue fine-tuning our techniques to introduce a wave that steepens into a shock, rather than collapsing inward as it does at present. Once this is accomplished, we will turn our attention to implementing a collision system within the simulation. The model is at present fully collisionless, as this was sufficient to conduct the investigation in Florinski *et al.* (2016). We plan to implement collisions using the grid-based approach described by Jones *et al.* (1996), in a similar manner to that used by the explicit model. Once this development of the code is finished, we can apply the fully developed model to analysis of the VLISM using a high number of simulated particles to maximize accuracy. In particular, we aim to determine whether the results obtained by Mostafavi & Zank (2018) using a steady-state model are consistent with results from a time-variant hybrid model of VLISM plasma. The finished model could also have further uses; we take care to make it generalizable to other cases, so it could be used to verify results or draw new conclusions regarding collisional space plasmas even beyond the VLISM.

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