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On the stability of rotational discontinuities: One- and two-dimensional hybrid simulations

H. Karimabadi, D. Krauss-Varban, and N. Omidi[1]

Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla

Abstract. Studies of rotational discontinuities (RDs) and their role in affecting the magnetic field rotations at the magnetopause have been generally conducted using one-dimensional simulations and for RDs in isolation from external perturbations. The conditions at the magnetopause are, however, often turbulent with large Alfvénic and mirror mode fluctuations. Here, previous calculations are extended to two-dimensions using the hybrid code and the effect of external perturbations on the stability of both isotropic and anisotropic RDs is examined for the first time. As in the one-dimensional simulations and in agreement with observations at the magnetopause, RDs are found to satisfy the minimum shear condition (rotation angles less than or equal to 180°) and have gradient scale half-widths of the order of $1-4$ ion inertial lengths. In addition, RDs are found to be quite stable even when large amplitude mirror and Alfvén waves impinge upon them. No evidence for two-dimensional (e.g., surface or shear) instabilities were found. Although simulations show the presence of a coherent wavetrain for some of the RDs, the observations of RDs at the magnetopause have not identified any wavetrain. It is shown that under the turbulent conditions prevalent at the magnetopause, the detection of wavetrain in the data would most likely require multispacecraft measurements.

1. Introduction

In ideal, one-dimensional MHD, rotational discontinuities (RDs) constitute one of the four allowed propagating steady state discontinuities. Two of the distinguishing characteristics of an RD in fluid theory are that the flow speed both upstream and downstream of it is equal to the intermediate speed, and the fact that it can rotate the transverse component of the magnetic field. One of the regions in space plasmas where RDs have been reported to exist is at the magnetopause during reconnection events [e.g., *Sonnerup et al.*, 1981; *Berchem and Russell*, 1982; *Gosling et al.*, 1991]. The above observations revealed several important properties of RDs that needed to be explained by the subsequent theories. First, the magnetic field rotation always showed a minimum shear (i.e., rotation angle less than 180°) and both senses of field rotations were observed. Secondly, the thickness of RDs is observed to be within a few ion inertial lengths. Although the conditions at the magnetopause consist of a turbulent, high beta and anisotropic ($T_\perp/T_\parallel > 1$) plasma with significant levels of Alfvénic and mirror mode fluctuations, most studies of RDs [e.g., *Swift and Lee*, 1983; *Goodrich and Cargill*, 1991; *Krauss-Varban*, 1993; *Vasquez and Cargill*, 1993; *Krauss-Varban et al.*, 1995] have been performed in the limit of an isotropic plasma, in isolation from external perturbations. Despite their limitations, the above studies have had considerable success in explaining the observed properties of RDs. In particular, the kinetic simulations of RDs in the high beta regime and for a small normal component of the ambient magnetic field (typical situation at the magnetopause) [*Krauss-Varban et al.*, 1995] showed that an RD with the minimum shear is stable and has a gradient scale halfwidth of $1-4$ ion inertial lengths, both in agreement with observations.

The effect of temperature anisotropy, which is a common feature of the magnetosheath plasma, on the above results has also been explored by several authors [e.g., *Omidi*, 1992; *Lin and Lee*, 1993; *Karimabadi*, 1995]. In addition to the field rotation, an RD in an anisotropic plasma can affect finite jumps in the plasma quantities [e.g., *Hudson*, 1971; *Chao*, 1970]. However, the properties of the RD regarding its stability, minimum shear and its thickness remain essentially the same as in the isotropic limit. One significant difference between the RD in isotropic plasma as compared to the anisotropic plasma is in regards to the number of reflected ions. The number of reflected ions from an RD is typically a few percent for the isotropic case, but can be much larger for the anisotropic case [*Karimabadi*, 1995]. This fact may play a role in the understanding of the magnetopause crossings where a large number of reflected ions are observed [e.g., *Fuselier*, 1994, and references therein].

In an effort to examine the structure and stability of RDs under conditions typical at the magnetopause, we extend the above studies to two dimensions and take into account stability of an RD in response to external perturbations. We address the question of whether an RD can remain stable in interacting with large amplitude mirror and AIC waves which are typically present at the magnetopause. Since RDs in 1-D are quite thin, it is also important to determine whether they are subjected to any instabilities in two dimensions.

The outline of the paper is as follows. After a brief description of the simulation model, we present the first two-dimensional simulations of RDs and compare their structures with the corresponding solutions in 1-D. We also make suggestions regarding the type of satellite measurements that would be required if some features of the RD such as its wavetrain are to be detected. The summary and discussion of results and their relevance to observations of RDs at the magnetopause are given in the last section.

[1]Also at California Space Institute, University of California, San Diego, La Jolla.

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2. Simulation Model

The simulation codes used are the 1-D [*Winske and Omidi*, 1993] and 2-D electromagnetic hybrid codes which treat the electrons as an adiabatic fluid and ions as kinetic macroparticles. The piston method is used to form the RD, where the plasma is injected from the left end and reflected from the right end of the simulation box [e.g., *Karimabadi*, 1995]. The upstream magnetic field lies in the $x-y$ plane and makes an angle θ_{BN} with the $x-$axis. The simulations are performed in the rest frame of the downstream plasma and the fields on the right boundary in x are set according to Rankine-Hugoniot relations. We use periodic boundary conditions for the particles and fields in the $y-$direction. Time is normalized to proton gyrofrequency (Ω), x to c/ω_p and velocity to Alfvén speed V_A. Here, ω_p is the proton plasma frequency.

3. Results

We start with a simpler case of an RD in an isotropic plasma. Since the observed field rotations at the magnetopause are almost always less than 180°, we consider noncoplanar RDs here. We should point out that the results obtained here for RDs are expected to apply to weak ISs as well. For a rotation angle of 180°, the weak ISs and RDs have very similar structures and are almost indistinguishable in a high beta plasma. The main distinction between an RD and a weak IS occurs at noncoplanar angles where weak ISs are time dependent whereas an RD is stable [e.g., *Karimabadi and Omidi*, 1992; *Karimabadi et al.*, 1995].

3a. Isotropic Case

Since the plasma quantities as well as the magnitude of the magnetic field do not change across an RD in the isotropic limit, no injection of plasma is required

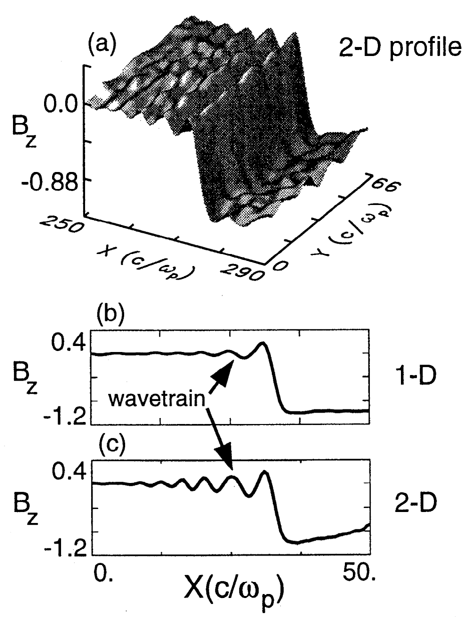

Figure 1. (a) Two-dimensional hybrid simulation of an RD in an isotropic plasma. (b)-(c) Plots of B_z versus x from the 1-D and 2-D simulations, respectively. In (c), the B_z is averaged over all y.

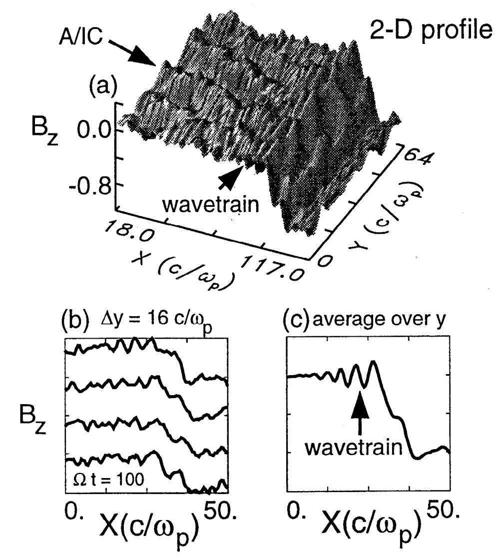

Figure 2. (a) Two-dimensional hybrid simulation of an RD in an anisotropic plasma. (b) Cuts of B_z at four different values of y. (c) B_z averaged over all y versus x.

from the left boundary [*Karimabadi and Omidi*, 1992; *Krauss-Varban et al.*, 1995]. Figure 1a shows the two-dimensional profile of the B_z component for a noncoplanar RD with $\theta_{Bn} = 80°$, $\beta_i = 1.0$, $\beta_e = 0.2$, and $\omega_p/\Omega = 4000$. The rotation angle ϕ is set such that $B_{z1} = -B_{y0}$, and $B_{y1} = 0$. The subscripts 0 and 1 refer to values upstream and downstream, respectively. Note that in the piston method, setting ϕ still allows two different field rotations. For instance, for the above choice of downstream field components, the field rotation can be either $-270°$ (electron sense) or $+90°$ (ion sense). In the present case, the RD starts with and maintains a rotation with minimum shear ($\phi = -90°$). The simulation box is a rectangle $300 \times 64c/\omega_p$ which is divided into 600×64 cells, with 50 particles per cell. A timestep of 0.05Ω was used. Upstream of the RD, there exists a coherent Alfvén/ion cyclotron (A/IC) wavetrain with the propagation angle along the RD normal direction. Aside from the wavetrain, we have found no evidence of wave activity along the RD front by the end of simulation ($\Omega t = 300$), and there is no significant broadening of its thickness. Thus, we conclude that the RD is stable in this case.

Figures 1b and 1c show a comparison between the one- and two-dimensional structure of the RD. The profile of B_z in the 2-D case is obtained from averaging over all y. There is no appreciable differences between the RD structure in the two cases.

3b. Anisotropic Case

Our second example involves an RD in an anisotropic plasma. In order to examine the stability of RDs to external perturbations, we choose a large upstream anisotropy of 3.15 so that large amplitude Alfvén and/or mirror modes would be excited. Figure 2a shows the two-dimensional profile of B_z for an RD with the above upstream anisotropy and $\theta_{Bn} = 78°$, $\beta_{\|i} = 0.75$, $\beta_e = 0.41$ and a rotation angle of $\phi = -90°$. The downstream plasma parameters based on the Rankine-Hugoniot relations are $B_1 = 0.858B_0$, $N_1 = 1.2N_0$, and $T_\perp/T_\| = 1.4$. The simulation box is a rectangle $400 \times 64c/\omega_p$

which is divided into 800 × 64 cells, with 50 particles per cell. The timestep is 0.05Ω. Unlike the isotropic case, plasma has to be injected from the left boundary, much like in simulations of shocks. The presence of a strong wave activity upstream of the RD is clearly evident in Figure 2a. There is also some evidence of "rippling" of the RD front in this figure. We will discuss the origin of this latter effect shortly. By conducting a detailed analysis, we have established that there are three types of waves upstream. One is a coherent Alfvénic wavetrain generated by the RD. Due to the presence of other waves, it is very hard, if not impossible, to identify the wavetrain in Figure 2a. This may explain why no clear examples of RDs with wavetrains have been observed at the magnetopause. To further illustrate this point, we show y–slices of B_z as a function of x in Figure 2b. Each slice may be similar to the type of measurement that would be made with a single satellite. The presence of a wavetrain is only evident after we average B_z over all y as in Figure 2c. This suggests that some features of RD such as its wavetrain can only be identified using multi-spacecraft measurements as in the CLUSTER mission.

In addition to the wavetrain, there are two other types of waves upstream. By performing a Fourier analysis of the upstream, we found two peaks in the power, one at propagation angle of 0° and the other at 68°. The Fourier transform of the field at these two angles is shown in Figure 3. We have verified that both peaks are due to the presence of the temperature anisotropy which gives rise to generation of A/IC and mirror modes. The fact that the mirror mode and A/IC have their maximum growth at 68° and 0°, respectively, is also consistent with linear theory. Most of the power lies on the A/IC branch due to the larger growth rate of A/IC waves as compared to the mirror mode. Figure 3b shows the presence of A/IC waves propagating in both directions relative to the RD. The downstream moving A/IC waves are the source of "ripples" seen along the RD front in Figure 2a. Aside from the effects of these waves, we have found no evidence for any other (surface or shear) instabilities that would disrupt the RD, and no widening of RD takes place in time. In fact, given the presence of large amplitude A/IC waves that crash into the RD, the RD remains remarkably stable.

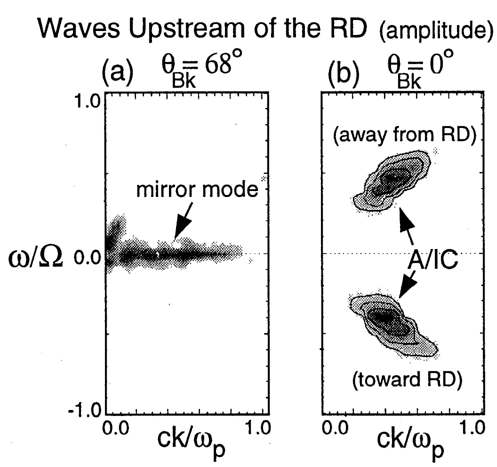

Figure 3. Fourier transform of the magnetic field upstream of the RD in Figure 2. (a)-(b) Wave spectrum at two propagation angles.

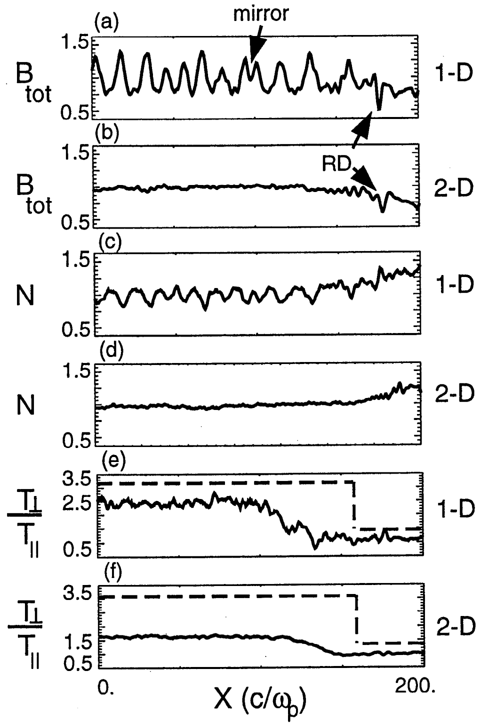

Figure 4. One- and two-dimensional simulations of an RD with an initial upstream anisotropy of 3.15. Dashed lines in (e)-(f) are anisotropy profiles at $t = 0$

Figure 4 shows the magnetic field, density and temperature anisotropy as a function of x from 1-D and 2-D simulations. The plots from the 2-D simulation are averaged over all y. Since we start the simulations with an upstream anisotropy of 3.15, which is unstable to both A/IC and mirror modes, the RD that is formed in the 1-D case is not the same as that formed in 2-D. The reason is that in 1-D, only waves excited at an angle given by the RD normal can be excited upstream. Since A/IC growth rate drops sharply at oblique angles, it is mainly the mirror mode that grows in 1-D. The situation is reversed in 2-D where all propagation angles are possible and A/IC dominates due to its largest growth rate. This, together with the fact that the mirror mode is not as effective in reducing the temperature anisotropy as the A/IC mode, results in a different level of upstream temperature anisotropy, which in turn affect the type of RD that is formed. However, the question that we want to address here is in regards to the stability of the RD under the influence of external perturbations. Our 1-D simulation is useful in determining the effect of the large amplitude mirror modes on the RD whereas the 2-D simulations help address the effect of A/IC waves. The real situation at the magnetopause is somewhere between the two cases shown in Figure 4, where due to processes that are still subject of active research both A/IC and mirror modes coexist and can have comparable amplitudes.

In Figure 4a, the mirror mode clearly has grown to large amplitudes and has fluctuations in amplitude that are comparable, if not larger, than that associated with the jump in the field across the RD as well as the field depression within the RD. Examination of jumps across the RD as well as its thickness showed no significant change in time, after the initial transitory stage. Thus, in spite of such large perturbations, the RD remains intact. The RD shows the same robustness in 2-D (Figure 4b) and remains stable during the run ($\Omega t = 200$). The drop in the magnetic field across the RD is evident in Figure 4b but the A/IC waves are best seen in a plot of B_z (Figure 2b). This is because A/IC waves are only slightly compressional and do not generate large fluctuations in the total magnetic field or density. Figures 4c and 4d show the increase in the plasma density across the RD as expected for an anisotropic RD. Although it is also possible to form RDs that reduce the density, we will not consider them here. Finally, in Figures 4e and 4f we show the temperature anisotropy as a function of x. Also shown in each figure, as a dashed line, are the initial values of upstream and downstream anisotropies, based on the Rankine-Hugoniot relations. The fact that the jump in the temperature anisotropy (Figures 4e and 4f) occurs before the jump in the magnetic field is due to the presence of a large number of backstreaming ions. As expected (see above), the upstream anisotropy in the 2-D case is reduced more from its initial value than in the 1-D case. Initially, while the waves grow and reduce the anisotropy upstream, the RD adjusts itself so that the jumps in quantities such as density and the magnetic field remain essentially unchanged. This ability of the RD to adjust to changing plasma parameters and exist in the presence of large amplitude waves is remarkable but is clearly needed if it is to survive under conditions prevalent at the magnetopause.

3. Summary

We investigated the stability of both isotropic and anisotropic RDs in two-dimensions and under the influence of external perturbations and changing upstream plasma parameters. In the isotropic case, we found no significant changes in the solutions between 1-D and 2-D simulations. In the anisotropic case, there can be differences between the one- and two-dimensional simulations if the plasma anisotropy, either upstream or downstream, is large enough so that the plasma is unstable to generation of A/IC and mirror modes. In such cases, the onset of instability results in the modification of local plasma conditions which in turn changes the type of RD that will result. Since the details of the temperature anisotropy instability are different in 1-D and 2-D, different RDs would form in 1-D and 2-D. Aside from this effect, we have not found any significant differences in the RD structure in 1-D and 2-D simulations. In general, we found RDs to be quite stable which is undoubtedly one reason why they can form at the magnetopause as well as many other space plasmas. Although we did not find any evidence for two-dimensional instabilities (e.g., surface or shear instabilities), they cannot be ruled out for parameter regimes other than the ones examined here.

One puzzle regarding the observation of RDs has been the lack of evidence for a coherent wavetrain. On the other hand, kinetic simulations have shown that in many cases RDs do possess a wavetrain. Here we showed that under the turbulent conditions at the magnetopause the detection of a wavetrain with a single spacecraft measurement is extremely difficult, if not impossible. Multispacecraft measurements such as the CLUSTER mission are required to identify such kinetic signatures as well as to determine accurate scale sizes.

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H. Karimabadi, D. Krauss-Varban, and N. Omidi, Department of Electrical and Computer Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0407.

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