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Study of Magnetosphere Dynamics under Various Alfven Mach Numbers for the Northward IMF Condition: 3D Global PIC Simulations

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Abstract

For a long time, the interactions of the solar wind with the Earth's magnetosphere have been analyzed with the help of three-dimensional (3D) global particle-in-cell (PIC) simulation where the interplanetary magnetic field (IMF) is steadily northward. Yet the Earth's magnetosphere and the Kelvin-Helmholtz Instability (KHI) in a global, dayside and nightside magnetotail configuration using the 3D PIC simulations has not been well examined. In this work, we compared the simulation results for both high and low Alfven Mach numbers of MA=5 and MA=1, respectively. Our results show diverse magnetospheric dynamics by taking into account the various Alfvenic Mach conditions. The relationship between the upstream magnetohydrodynamic (MHD) turbulence in the solar wind and Earth's magnetosphere behavior is investigated. In both the meridian and equatorial planes, the effects of Alfven Mach number on magnetospheric characteristics such as electron/ion densities and current densities are explored. The structure of the magnetosphere is also investigated at high and low Alfven Mach numbers. The solar-terrestrial interaction as a result of various solar activities is investigated in this work utilizing a large-scale global three-dimensional PIC simulation.

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Keywords: Northward IMF, Kelvin-Helmholtz Instability, Magnetosphere dynamics, 3D PIC simulation, Alfven Mach number.

1- Introduction:

The interplanetary magnetic field (IMF) has long been believed to play a huge rule in the solar wind interactions with the Earth's magnetosphere. Beyond the Earth magnetosphere, particles entering the Earth's surface may have a wide range of impacts on our daily lives. The magnetic fields of the Sun are primarily triggered the activity of the solar cycle effects on the Sun's surface like sunspots. The amount of activity on the Sun's surface changes as the magnetic fields change. The Earth may be affected by this activity such as, the eruptions can cause lights in the Earth's magnetosphere called aurora. The radio communications and even the electricity grids on Earth may be affected by the extreme eruptions and avalanches of high-energy particles reaching the Earth's surface during the high solar activity. Aerosols are the primary constituents of clouds and are formed by energetic particles trapped by the Earth's magnetosphere. Bow shock is formed on the dayside at (11-14) R_E when the solar wind strike against the Earth's magnetosphere, where R_E is the Earth radius. Lugaz et al. [2016] studied that a bow shock will occur when the solar wind's magnetosonic Mach number is larger than one. The Earth's magnetosphere encompasses different regions, for instance, the radiation belts, Van Allen bands, plasmasphere, and ionosphere. However, all these magnetosphere's boundaries would be affected by the solar wind's magnetic field, dynamic pressure, and number density, which are all associated to the Alfven Mach number. Several Mach regimes have been used to study the interaction of the solar with the Earth (Farrugia et al. 1995; Lavraud

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& Borovsky 2008). Most prior investigations have been concluded that the magnetopause location is determined by the solar wind's dynamic pressure. Fairfield (1971) and Shue et al. found the influence of the IMF orientation on the location of the magnetopause.

In this paper, the 3D PIC simulation has been performed to investigate the effect of different Alfven Mach numbers (MA=1 and 5) on the general shape, size, ion/electron concentrations, currents, and overall dynamics of the magnetosphere. We also compared the findings of the 3D PIC simulation to the results of the MHD simulation (Lavraud & Borovsky 2008).

2. Simulation Model

The basic MHD equations are as follows.

$$\frac{\partial B}{\partial t} = -c\nabla \times E \quad (1)$$

$$\frac{\partial E}{\partial t} = c^2\nabla \times B - \frac{1}{\varepsilon_o} J \quad (2)$$

$$m_{i,e}\frac{dv_{i,e}}{dt} + q_{i,e}\left(E + v_{i,e} \times B\right) \quad (3)$$

where B represents the magnetic field, E is the electric field, J is the current density and v is the charged particle velocity. Furthermore, c is the speed of light, q is the particle charge, and m is the particle mass while the subscripts i and e stand for ions and electros, respectively.

2-1 Initial parameters:

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In this paper, the typical values of the Mach numbers, MA=1 and MA=5 are used to examine the Earth's magnetospheric dynamics. Alfven Mach number is the ratio of the bulk velocity to the Alfven velocity $MA = V_{Bulk} / V_{Alfven}$ where $V_{Alfven} = B / \sqrt{\mu_o \rho}$ with B is the magnetic field (here B is considered as IMF magnetic field), μ_o is the vacuum permeability and ρ is the charge density. For this simulation, we used the latest version of the 3D Stanford PIC code (Tristan code) (Buneman et al. 1992; Buneman 1993; Cai et al. 2015). A 3D electromagnetic complete particle global simulation model is also used in this study. This simulation model divides the temporal sequence of IMF rotations into two phases (i) the Earth’s magnetosphere is produced by a magnetic dipole field from time step 0 to 1500, during which there is no IMF (ii) a northward IMF (Bz=0.215) gradually activates from the step 1501 to 1800. The IMF then remains unchanged until the time step reaches to 3000 (Esmaeili & Kalaee 2017).

In this paper, we adopt the same simulation model with dimensions (x=215, y=145, z=145) that has previously been used by Esmaeili & Kalaee [2017] and Esmaeili et al. [2020]. In the simulation, 1 equals to $0.5\,R_E$ where $1\,R_E$ is approximately 6400 km. The 1000 simulation time step would be roughly 26 minutes if we take a typical value of 400 km/s for solar wind velocity and each grid spacing (Need to be rephrased). In this work, a magnetic field is normalized to the reference magnetic field which is equal to, in which is the electron mass and is the electron plasma frequency and e is the electron charge.

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Alfven Mach number is the ratio of the bulk velocity to the Alfven velocity (). Alfven velocity is defined as, whereas *B* is the magnetic field (here is the magnetic field of IMF) and is the vacuum permeability and is the density. For this simulation, we used the latest version of the 3D Stanford PIC code (Tristan code) (Buneman et al. 1992; Buneman 1993; Cai et al. 2015-

2-2 MA effects on the general shape of magnetosphere during northward IMF direction in the meridian plane (Section Name is Confusing):

2-2 Effect of MA on the Structure of Earth's Magnetosphere

The solar-terrestrial total magnetic field during the northward IMF direction is depicted in Figure 1. The near-Earth cusp axis is perpendicular to the magnetopause of the magnetospheric flanks as shown in Figure 1. The cusp axis is tilted sunward using the typical value of MA(=5). In this case, the reconnection ~~zone~~ region is relocated to the lower latitude, almost above the cross-section of the cusp axis with the magnetopause.

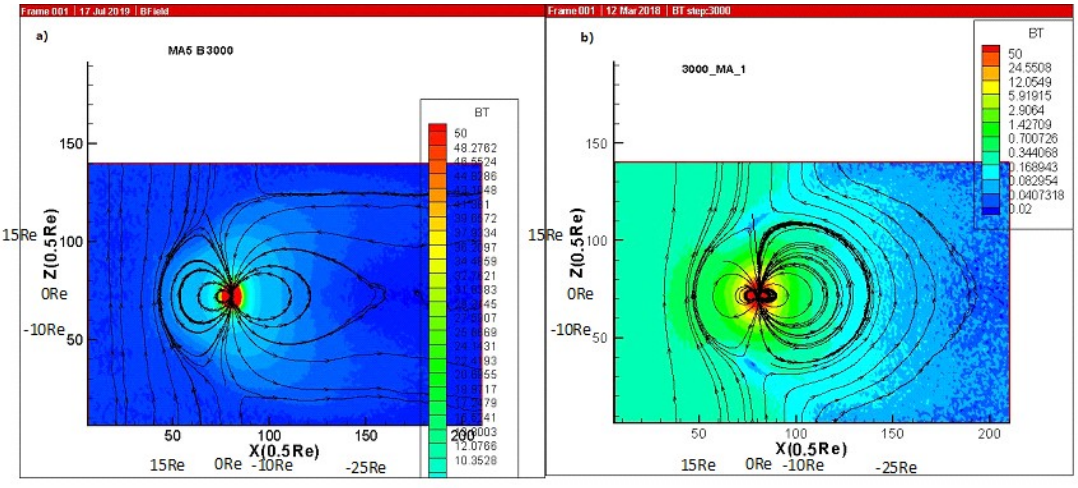

Fig.1 General magnetospheric shapes in the meridian plane, during northward IMF condition for (a) MA=5, (b) MA=1 (compared to figure 3, Lavraud & Borovsky 2008), Black lines in a) and b) represents the cusp axis.

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This is in good agreement with MHD simulation results by Lavraud & Borovsky (2008). In addition, a more compact magnetosphere configuration is produced using the typical value of MA(=1). However, we observed the closed magnetic field lines in the near-Earth magnetotail about X=180 while the magnetosphere is opened in the tail ward using MA=5 as depicted in Figure 1b. This agrees well with the ~~of the~~ MHD simulation results (Lavraud & Borovsky 2008, Figure 3).

The Earth's magnetotail acts as a reservoir for the energy that is extracted from the interaction between the solar wind and the Earth's magnetosphere. A portion of that energy is released through a violent process known as a magnetospheric substorm. Behind the Earth, the solar wind extends the magnetosphere away from the Earth on the nightside forming the magnetotail. The magnetotail contains two lobes, such as northern and southern tail lobes which are separated by a plasma sheet (it is an area where the magnetic field is weaker). The magnetic field lines looks dipolar in the near-Earth magnetotail (MA=1) while the field lines are stretched by increasing the value of MA(=5) as shown in Figure 1. Furthermore, the thin current sheet region is formed by increasing the MA value.

Next, we will compare the previous MHD simulation findings are on the equatorial plane with our results which are obtained for the meridian plane. The resemblance of the MHD simulation results with the current equatorial plane findings will be investigated in the following sections.

2-3 Total electron/ion current density in the equatorial plane:

Figure 2 shows the total electron current densities in the equatorial plane both for MA=5 and MA=1:

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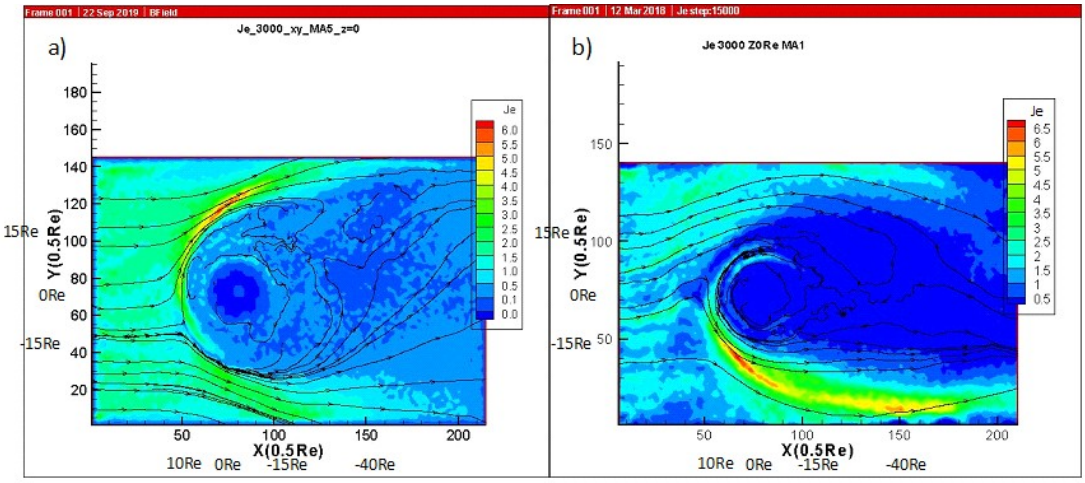

Fig.2 Total electron current densities in the equatorial plane, during northward IMF condition for (a) MA=5, (b) MA=1

In the higher MA case, we can see more intense and turbulent currents around the Earth than in the lower MA counterpart. A ring current is the result of trapping the charged particles in a Earth's magnetosphere and this ring current is larger for MA=5 case (Fig. 1a) (The figure cite here maybe wrong). For the case of MA=5, we observed a maximum current density area in the dusk-side of the Earth (about Y=120 in Fig 2a) and a similar area in the dawn-ward of the Earth (around Y=50 in Fig 2b) for the MA=1 case.

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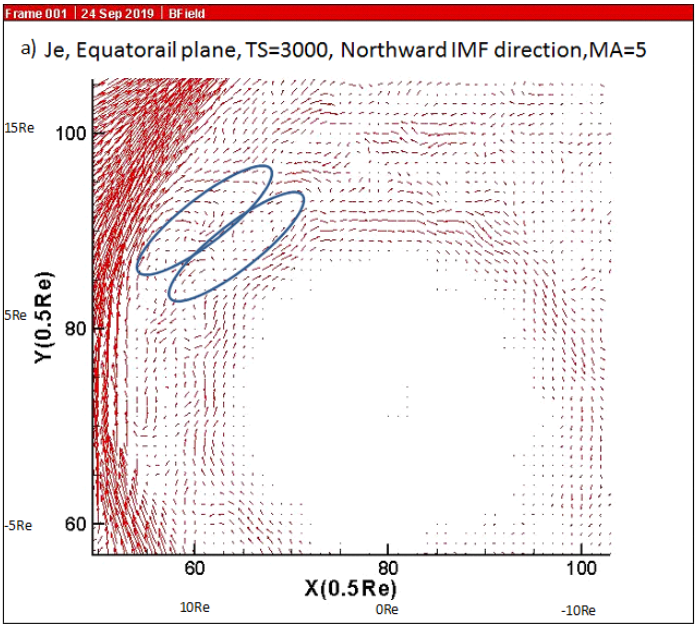

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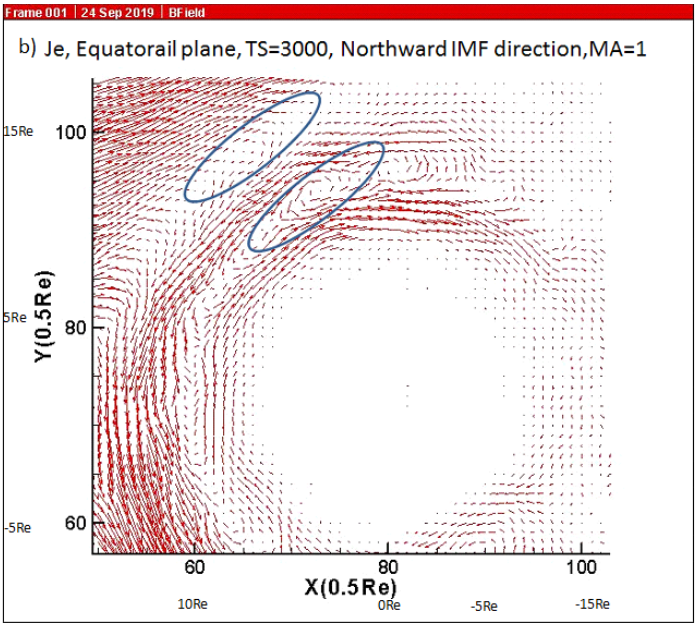

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141Fig.3 Total electron current density vectors in the equatorial plane, Z=0Re, during
142northward IMF condition for (a) MA=5, (b) MA=1

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The velocity shear on the magnetosphere's boundary layer can trigger the Kelvin-Helmholtz Instability (KHI, vortexes in the ovals in Fig 3a, b) , which is important to physicists because it could be the potential candidates for mass and energy transfer from the solar wind to the magnetosphere. Using their three-dimensional MHD code, Merkin and his colleagues (2013) evaluated the magnetopause's stability in terms of KHI growth rate. The velocity shear between the magnetospheric plasma (which is essentially stagnant) and the magnetosheath flow drives this growth rate (These sentences are confusing). They discovered that magnetic tension is critical in the stabilization of oscillation growth rates (One can't state the stabilization of the growth rates, this is misleading) . Matsumoto & Seki (2007) used 3D MHD simulation to examine KHI under various beta conditions, where beta is the ratio of plasma pressure to magnetic pressure. They changed the beta parameter to investigate the effect of magnetic field intensity on the KHI's 3D nonlinear evolution. They have found ~~discovered~~ that the vortex shape is unstable at high beta and more stable at low beta. In addition, using a 2D MHD code, Samtaney (2003) demonstrated the magnetic field's ability to inhibit Ritchmaier-Meshkov instability (This sentence is confusing. I think, the work 2003 should be cited earlier than 2007). In terms of the more stabilised condition under lower MA = 1 case, our 3D PIC simulation results are in good agreement with the 3D MHD simulation results obtained by Merkin et al. [2013]; Matsumoto & Seki [2007]; and Samtaney [2003]. The vector plot of electron current density is shown in Figure 3. For both Ma=5 and Ma=1, it seems similar to the to Figure 2. In the case of MA=5, there are more turbulent currents around the plasmasphere (Figure 3a). However, for the lower

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Alfven Mach number case, the two layers of Kelvin-Helmholtz instability (Ovals in the plots) are more apparent.

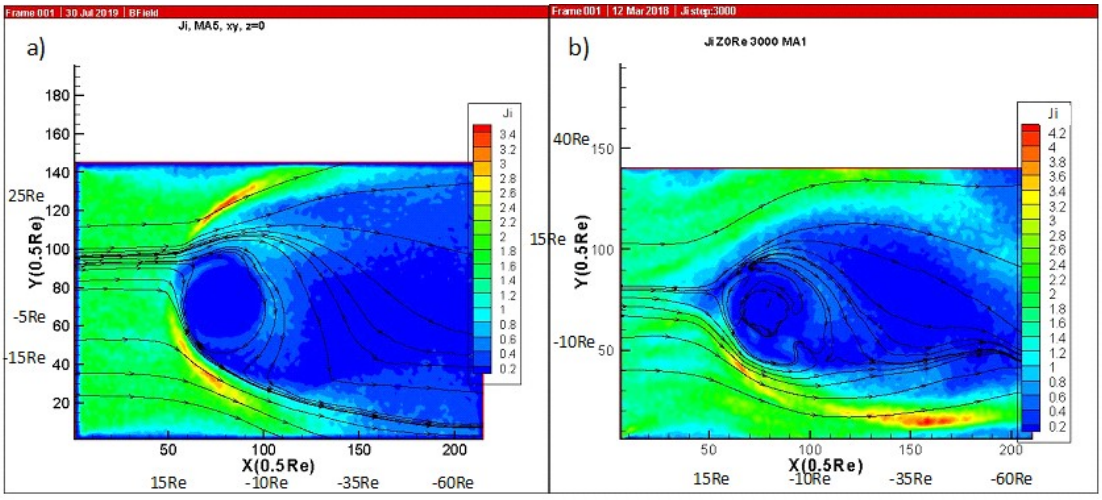

Fig.4 Total ion current densities in the equatorial plane, Z=0Re, during northward IMF condition for (a) MA=5, (b) MA=1

The total ion current density in the equatorial plane for the two situations of Mach Alfven numbers is shown in Figure 4. For the situation of MA=5 in Fig.4a, we have a wider eye structure of the ion current density in the equatorial plane. However, the eye shape is twisted Sunward when MA=1 as depicted in Figure 4b. The Alfven Mach number has a significant influence on various dynamics as well as the topologies of the Earth's magnetosphere, as shown in Figure 4.

2-4 Electron/ion number densities:

Figure 5 illustrates the electron number densities for both Mach numbers of MA= 1 and MA = 5 in the meridian plane. In the case of MA=5, electrons accumulated in the cusp area at higher altitudes, as well as near the magnetosheath, as seen in Fig. 5a. In addition, in Fig. 5b, the double cusp structure can be seen for MA=1, but it is not visible for

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MA=5. In addition, when the Mach number becomes larger, the magnetosheath structure appears to be smaller.

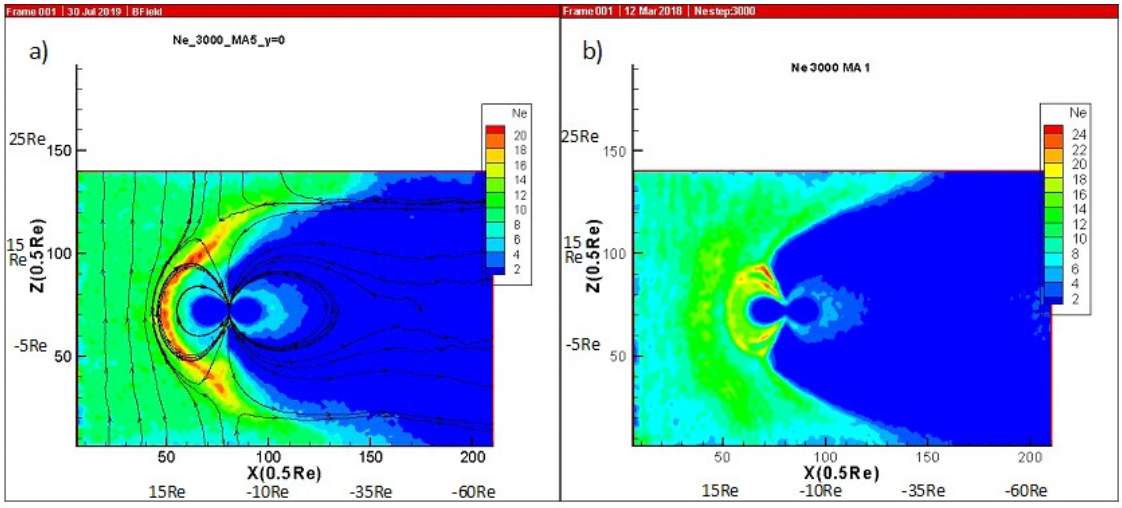

Fig.5 Total electron number densities in the meridian plane during northward IMF condition for (a) MA=5, (b) MA=1

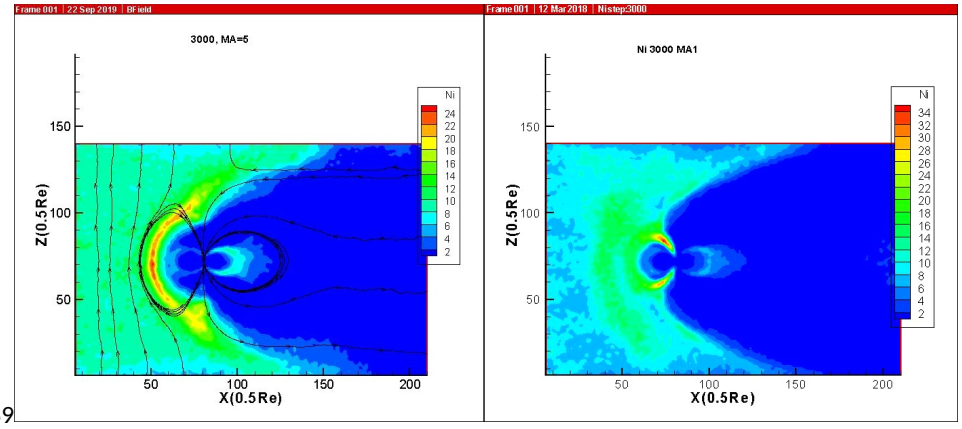

Fig.6 Total ion number densities in the meridian plane during northward IMF condition for (a) MA=5, (b) MA=1

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193Ion number densities ~~in~~ at the meridian plane for various Alfven Mach numbers in 194northward IMF direction are shown in Figure 6. The different field topologies of the 195magnetosphere alter with the ion distributions in the magnetosphere (Fig. 6a, b). Ions 196appear to be accumulating in the magnetosheath mostly around the Sun Earth line with 197MA=5 rather than its lower counterpart.

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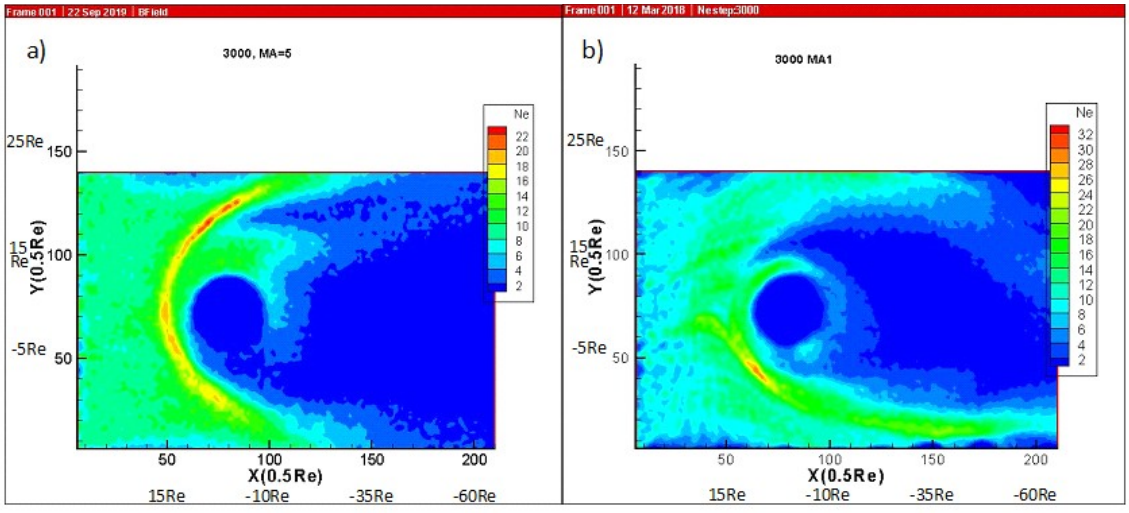

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200Fig.7 Total electron number densities in the equatorial plane during northward IMF
201condition for (a) MA=5, (b) MA=1

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204The electron densities in the equatorial plane are shown in Figure 7 for both high and low 205Alfven Mach numbers. In the event of a higher MA, we can witness more electrons 206accumulating near the Earth than in the case of a lower Alfven Mach number. From the 207dawn to the dusk ward of the Earth, increasing density of electrons may be seen in Fig. 2087a. Only in the dawn-ward region of the Earth does Fig 7b exhibit high quantities of

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electrons. Furthermore, the maximum number density areas in both MA=5, 1 match to the maximum current areas in Figures 2-a, b.

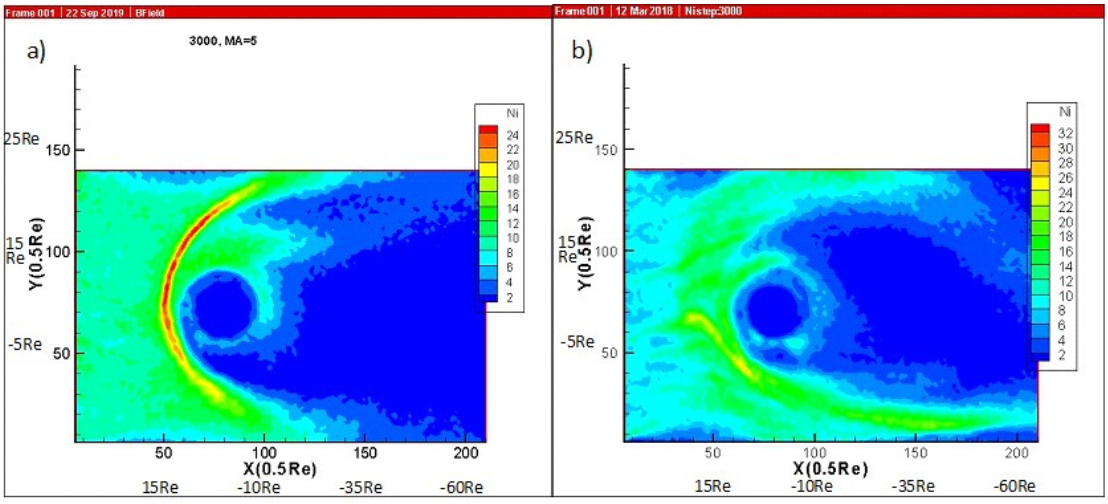

Fig.8Total ion number densities in the equatorial plane during northward IMF condition for (a) MA=5, (b) MA=1

In the equatorial plane, the maximum ion density can be seen in the dusk-side of the Earth for MA=5 in figure 8a, compared to the dawn-side of the Earth for MA=1 in figure b. The electron and ion densities have nearly identical behavior as the values of Mach number increases.

4-Simulation benchmarks

The current results using the 3D global PIC simulations has an extensive benchmark with the experimental results from the CLUSTER satellite and also benchmark with the previous 3D MHD findings obtained by Cai et al [2015]. Also, for the case shown in figure 1, we have showed the good agreement with the previous MHD results (e.g. see figure 3, in Lavraud 2008) for the general shape of magnetosphere due to the different

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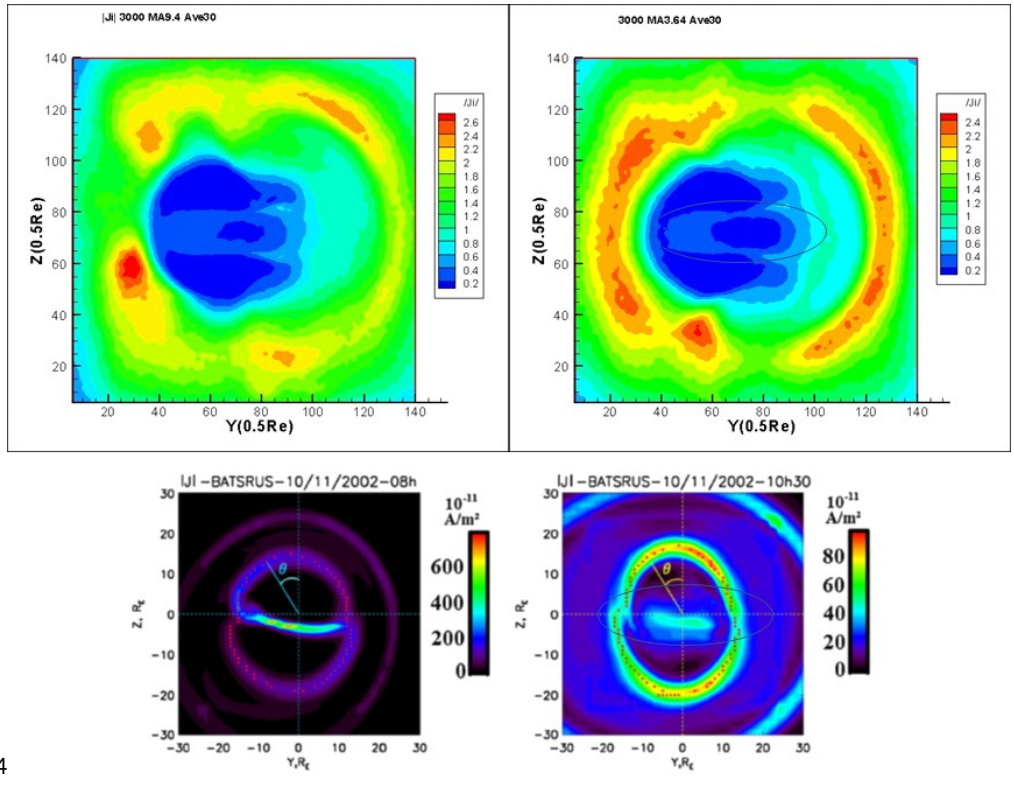
226MA numbers. Also, cusp axis sunward tilt in Figure 1b using MA=5 is in a good 227agreement with MHD results (e.g. see Lavraud & Borovsky 2008). Higher values of the 228Alfven Mach number shift magnetic reconnection to a lower altitude, which is consistent 229with previous MHD simulation findings by Lavraud & Borovsky [2008]. The less 230turbulent vortices of Kelvin Helmholtz instability inside the Earth's magnetosphere using 231MA=1 in Fig 3b has also good agreement with the MHD results ~~from~~ by Merkin et al 232[2013], Matsumoto & Seki [2007] and Samtaney [2003]. Figure 9 shows the PIC 233simulation results and MHD results in the lower row for both MA =3.64 and MA=9.4:



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235Fig.9 current densities in the YZ plane and the results from the MHD simulation. a, b) are 236the results from 3D PIC simulation for MA=9.4 and 3.64 respectively. C, d) are the 237results from 3D MHD simulation (Lavraud et al 2013) for MA=9.4, 3.64 respectively.

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239The MA=9.4 case has a higher current density (slightly bigger color scale), and both PIC 240and MHD findings have the same structures. We do not see the current sheet bending for 241~~the~~ MA=9.4 due to the resolution of the simulation.

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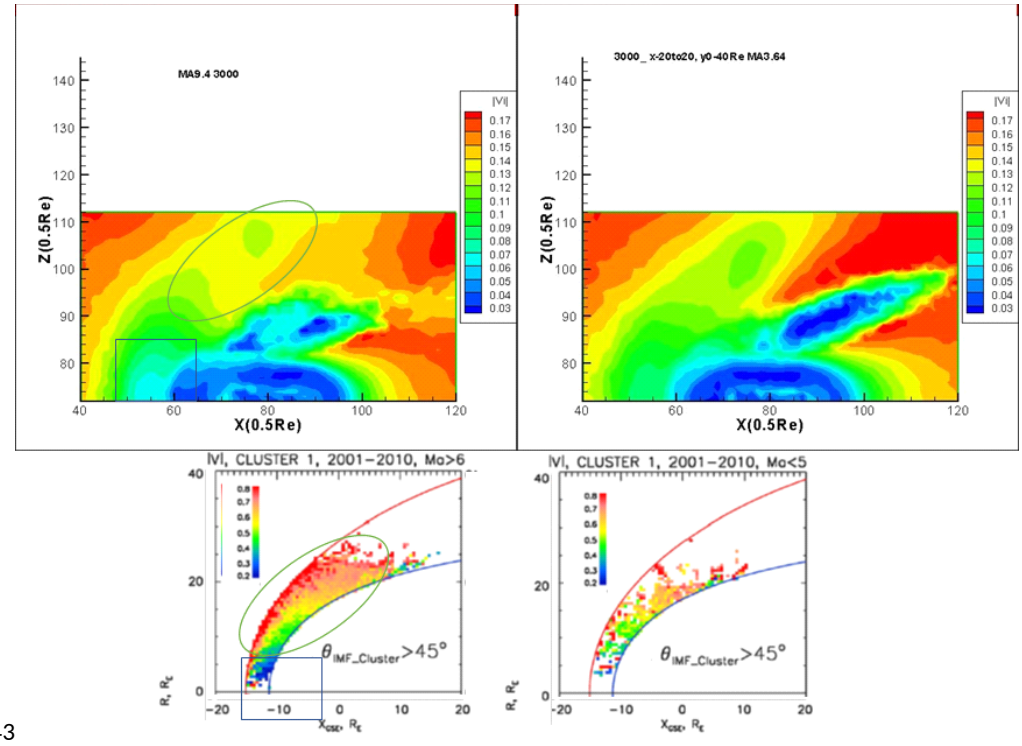

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244Fig.10 Abstract value of ion velocity in the meridian plan. a, b) the results from 3D PIC 245simulation for MA=9.4, 3.64 respectively. c, d) the observational data from CLUSTER 246satellite (Lavraud et al 2013) for MA >6, MA<5 respectively.

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248**3-Summary and conclusion**

249The effects of Alfven Mach number on the general shape and size of the magnetosphere 250on both meridian and equatorial planes were the focus of this paper. Furthermore, we 251looked into the effects of various Alfven Mach numbers on the cusp area. We explored

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distinct MA impacts on the emergence of Kelvin-Helmholtz instability layers around the Earth in the equatorial plane. During the higher scenario of MA = 5, we noticed a narrower distance between two KHI layers, larger particle current densities, and more turbulent currents centered near the Earth. In this paper, we have reported the results for electron and ion behavior (currents and densities) under various Alfven Mach numbers. For the northward IMF example, we found that a greater Alfven Mach number has a significant impact on the structure and dynamics of the Earth's magnetosphere. We compared the results from our 3D PIC simulation with the results from the MHD results for magnetospheric dynamics at various Alfven Mach numbers. Our findings indicated good agreement with the MHD community for the compared cases. (This sentence needs to be rephrased). This could be due to the cusp~~'s~~ which is shifted sunward morphology at higher Alfven Mach numbers. This confirms our prior findings (Esmaeili & Kalaee 2017), that ~~we~~ can only be detected double or triple cusp in a few rare circumstances. This is consistent with the observation of a double/triple cusp during various satellite missions. Due to the varied magnetospheric conditions, certain satellite missions do not report double cusp. The double cusp region study will be worth exploring using the 3D PIC global simulation.

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