Cold magnetospheric plasma flows and spacecraft wakes: PicUp3D simulations and Cluster data

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Cold tenuous plasmas are difficult to study with conventional ion instruments onboard magnetospheric spacecraft, as the spacecraft potential often is so high that the ions cannot reach the spacecraft. If the plasma is flowing, a wake is created behind the spacecraft. This wake can give a detectable or even dominating contribution to the data from a conventional double-probe electric field instrument. While this is a contamination to the measurement of the natural electric field, it is also potentially useful to derive flow properties like velocity and temperature. In order to understand the problems and exploit the possibilities of this effect, we have used the PicUp3D code to perform PIC simulations. We present the simulation results and compare them to data from the Cluster spacecraft, whose comprehensive instrument payload is quite ideal for studies of this character.

1. Introduction

Cold ions with temperatures of a few eV are common in the magnetosphere. However, they are difficult to measure with conventional ion instruments, since the spacecraft potential of a sunlit spacecraft in a tenuous plasma often is of the order of several tens of volts, preventing the cold ions from reaching the spacecraft. Recent studies have been able to detect cold ions for high ion drift velocities or with spacecraft equipped with artificial spacecraft potential control. Su et al [3] have been able to measure the properties of the cold flowing polar wind with the POLAR spacecraft, equipped with the ion instrument TIDE and the artificial plasma source instrument PSI, which brings the spacecraft potential as low as 1 V. Sauvaud et al. have performed measurements with the ion spectrometer CIS onboard Cluster, which detected cold ions accelerated by an intermittently moving magnetopause [1] and fast flowing cold ions in the magnetotail [2].

Cold flowing plasmas form a wake behind the spacecraft. Signatures of this wake can be seen in the data from a double-probe electric field instrument like the EFW instrument on Cluster. The wake signature is mostly seen as a contamination of the real electric field which the instrument aims at observing, but if properly understood, the wake signature holds a potential for deriving properties of the cold flowing plasma. We have therefore performed simulations of the wake formation using the code package PicUp3D [4], and present simulation results as well as real spacecraft data.

2. Evidence of spacecraft wake in Cluster data

The Cluster satellites are equipped with two instruments for electric field measurements using different techniques: the Electric Fields and Waves instrument (EFW) [5] and the Electron Drift Instrument (EDI) [6]. EFW uses the well-known and conceptually simple technique of two spherical probes measuring the potential difference in the plasma. The probes are separated by 88 m thin wire booms. EDI measures the electric field by determining the drift of high-energetic electrons in a magnetized plasma. Both techniques have their own weaknesses and merits [7]. When operating in cold flowing plasmas, a direct interpretation of EFW data gives an electric field estimate differing from what is observed by EDI. An example from the polar wind is shown in figure 2. In this figure it can also clearly be seen that the problems grow when the spacecraft potential is high.

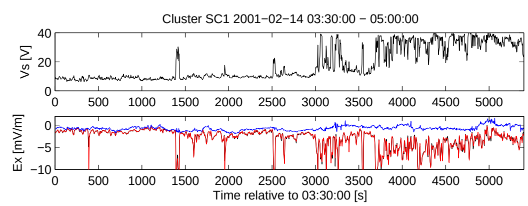

Fig. 1. EFW and EDI electric field data from Cluster 1. The top panel shows the spacecraft potential V_s, while the lower panel displays the EDI (blue) and EFW (red, black) estimates of the GSE X component of the electric field. Strong discrepancies between the EDI and EFW electric field estimates can be seen when V_s is high.

The explanation to the spurious electric field is that an enhanced wake is formed behind the spacecraft [7]. This wake will be much larger than expected from the geometrical size of the spacecraft, if the spacecraft potential is larger than the supersonic flow energy of the ions, i.e. if the following inequality is satisfied

$$KT_{\mathrm{i}} < E_{\mathrm{k}}^{\mathrm{i}} < eV_{\mathrm{s}}, \tag{1}$$

where KT_{i} and V_{s} are the ion thermal energy and the spacecraft potential, respectively. For such conditions, the ions will be deflected by the potential structures rather than the geometrical shape of the spacecraft. In addition, not only the spacecraft body will contribute to the wake, but also the thin wire booms, since their effective size will grow from a few millimeters to the order of meters.

3. Simulations of the wake

To study the wake formation behind Cluster and the effect on EFW, we have performed two types of simulations with

PicUp3D for typical polar wind conditions[1]: The wake effect behind a) one pair of the wire booms only, and b) the spacecraft body only. This division is made to simplify the simulations, but also to better understand the contributions to the wake from different parts of the spacecraft system. The simulations with the booms have indeed shown that they can by themselves create a wake giving rise to a spurious electric field of over 5 mV/m, assuming the probes perfectly couple to the plasma [8]. This is comparable to the spurious electric field in EFW data of 5-10 mV/m.

In figure 3 the ion density from one of the simulations with the spacecraft only is displayed, showing a clear depletion behind the spacecraft. This ion wake will to a large extent be filled with the subsonic electrons creating a negatively charged wake behind the spacecraft. The effect on the double-probe instrument mounted on a spinning spacecraft for different plasma parameters is shown in figure 3, which should be compared to the signatures from the EFW instrument in regions of spurious electric fields. These signatures show indeed the same overall shape as the signatures obtained in the simulations (see the plotted example in figure 3). From the simulations, it is evident that size of the wake, as well as the signatures are dependent on the plasma parameters. Thus, by careful examination of the signatures of the spurious EFW signal in combination with the simulation results, there is a potential to derive properties of the flowing plasma. By another method, it is possible to calculate the flow velocity only from comparison between EFW and EDI data, providing that certain conditions apply. From the sounding experiment WHISPER on Cluster as well as from measurements of the spacecraft potential, the plasma density can be estimated. The remaining two free parameters, the electron and ion temperatures, could possibly be obtained by careful examination of the signatures of the spurious EFW signal in comparison with the simulation results.

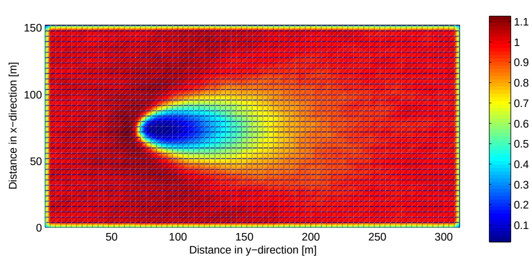

Fig. 2. Ion density around the spacecraft, which is situated at x=78 m and y=78 m.

4. Conclusions

The main conclusions of the current study are:

1) An enhanced wake forms behind a spacecraft in a flowing plasma, when the condition $KT_\mathrm{i} < E_\mathrm{k}^\mathrm{i} < eV_\mathrm{s}$ is satisfied. Such a wake will affect a double-probe electric field instrument significantly.

2) Simulations with PicUp3D have permitted to quantify the effect on the double-probe electric field instrument, assuming that the probes perfectly couple to the plasma. The magnitude as well as the spin dependence of the wake field is in good agreement with Cluster data.

[1] E_k^i=10 eV, KT_i=1-2 eV, KT_e=1-2 eV, n_0=0.2 cm^{-3}, V_s=35 V.

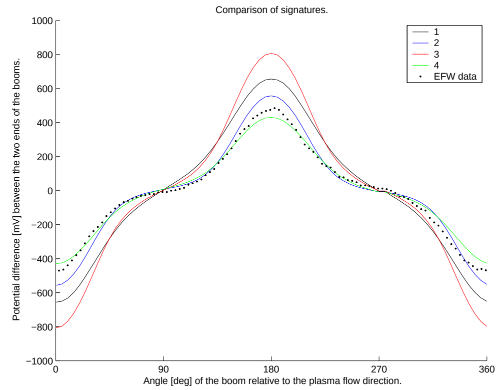

Fig. 3. Comparison of signatures from EFW data with four simulations with the spacecraft. The signatures show the potential difference between the probes at different angles of the boom relative to the flow. The EFW data is taken from the pair of probes 34 of the EFW instrument on Cluster 3 during one spin period (4 s) starting at 2002-02-13 01:48:06. In the simulations the spacecraft potential and density are constant, V_s=35 V and n_0=0.2 cm^{-3}, while the temperatures are varied: 1. $KT_e = KT_i = 2$ eV. 2. $KT_e = KT_i = 1$ eV. 3. $KT_e = 2$ eV, $KT_i = 1$ eV. 4. $KT_e = 1$ eV, $KT_i = 2$ eV. The amplitude of the spurious electric field varies from 4-10 mV/m.

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