MAKING USE OF SPACECRAFT-PLASMA INTERACTIONS: DETERMINING TENUOUS PLASMA WINDS FROM WAKE OBSERVATIONS AND NUMERICAL SIMULATIONS

Anders I. ERIKSSON (1), Erik ENGWALL (1,2), Ram PRAKASH (1),
Lars K. S. DALDORFF (1,2), Roy TORBERT (3), Iannis DANDOURAS (4) and Klaus TORKAR (5)

(1) Swedish Institute of Space Physics, Uppsala, Sweden
(2) Department of Astronomy and Space Physics, Uppsala University, Sweden Stockholm, Sweden
(3) Space Science Center, University of New Hampshire, Durham, NH, USA
(4) Centre d'Etude Spatiale des Rayonnements/Centre National de la Recherche Scientifique, Toulouse, France
(5) Space Research Institute, Austrian Academy of Sciences, Graz, Austria

For in situ plasma measurements, effects of a wake forming around the spacecraft are usually regarded only as a source of measurment errors. However, as the wake properties depend on the plasma density, temperature and flow velocity, an observation of the wake can be used to infer such plasma parameters. We present electric field observations from the Cluster satellites in the tail lobes of the Earth's magnetosphere, showing a wake with potentials of order of a volt or less. Simulations using the PicUp3D and SPIS codes verifies the understanding of the wake structure.

1. INTRODUCTION

In this paper, we will review and summarize work performed in the last years aiming at understanding and making use of the signatures of very wide (enhanced) wakes detected by the electric field instruments on the Cluster satellites in the magntosphere tail lobes and the over the pola cap. This has been presented in the following papers:

1) In *Electric field measurements on Cluster: comparing the double-probe and electron drift techniques* [1] we found that the two techniques complement each other very well, having very different limitations. While the electron drift instrument cannot follow rapid E-field variations and requires sufficient magnetic field strength, the double-probes will be sensitive to effects of spacecraft-plasma interaction effects. In particular, this was shown to happen in the polar caps and tail lobes of the magnetosphere, where enhanced wakes were detected and found to be common.

2) In *Double-probe measurements in cold tenuous space plasma flows* [2], we presented details of the EFW spin signature in the regions of enhanced wakes, establishing means to identify them in EFW data alone, and showed some simulation data.

3) The paper *Wake formation behind positively charged spacecraft in flowing tenuous plasmas* [3] concentrates on the physical understanding of the enhanced wake, by means of general arguments and detailed numerical simulations using the PicUp3D code.

4) In *Low-energy (order 10 eV) ion flow in the magnetotail lobes inferred from spacecraft wake observations* [4] we established how we can make use of the wake for deriving new scientific data on the tenuous plasma flows causing them.

These results were summed up and discussed in detail in Erik Engwall's licentiate thesis [5], where also some first statistical results of applying the wake technique to the polar wind were included. Initial stages of the work have also been reported at previous Spacecraft Charging Technology Conferences [6, 7] and elsewhere [8].

In this report, we summarize the results from these papers, adding some material on recent and ongoing simulation efforts. After briefly discussing the instrumentation in Section 2, we consider the data signatures of the enhanced wakes in Section 3. Simulations are presented in Section 4, and the use of the data for polar wind studies follows in Section 5. We end by summing up the main conclusions in Section 6.

2. INSTRUMENTS

Each of the four Cluster satellites [9] carries two instruments dedicated to electric field measurements: the double-probe Electric Fields and Waves (EFW) instrument, using four spherical electrostatic probes, symetricaly mounted on four wire booms in the spin plane [10, 11, 12], and the Electron Drift Instrument (EDI), emitting a beam of electrons and detecting them upon their return by the magnetic field [13, 14, 15]. EFW directly measures the voltage between the probes, which are kept close to the local plasma potential by use of a bias current, getting the electric field after division by the boom length. The fundamental quantity measured by EDI is the drift step, directly giving the electron gyroradius and finally the electric field when combined with the magnetic field data from the Cluster Flux Gate Magnetometer instrument [16, 17]. In addition, electric fields can often be derived from the velocity moment from the Cluster Ion Spectrometer (CIS) data [18, 19] combined with FGM magnetic field data. The merits and limitations of each technique are discussed in detail in Paper [1].

3. POLAR WIND WAKE SIGNATURES IN DATA

Narrow wake structures seen in the solar wind can easily be identified in the EFW data alone, as reported elsewhere in this volume [20]. The large wakes to be discussed here, enhanced by the high positive potential of the spacecraft, is less conspicuous as it is broader and hence looks like some imperfection of the sinusoidal spin frequency signature of a natural electric field in the plasma. Figure 1 shows one such spin of EFW data [7, Fig. 8]; similar data are also shown in Paper [2]. The EFW data, obtained at 25 samples/s and hence with 100 data points during the 4 s spin period, are shown as blue dots. The electric field measured by EDI is shown as a blue curve. An inferred signal resulting from asymmetric photoemission is shown as a black curve. The green curve is the remnant field, i.e. the part of the measured EFW data not due to neither the natural field seen by EDI nor the signal due to photoemission asymmetries. As will be seen, this field is due to a large wake, and obviously is the dominant signal in the EFW data at this time.

If such data are used to produce spin resolution electric field data by means of sinusoidal fits to the spinning data, as is common practice for double-probe instruments [21], we get a result as illustrated in Figure 2, showing simultaneous spin resolution EFW and EDI data from the Cluster 1 and Cluster 3. The top panels gives the EFW probe-to-spacecraft potential, V_{ps} (black), which can be taken as a measure of the negative of the spacecraft potential (the relation between the two quantities is linear, with about a 20% difference between them, as

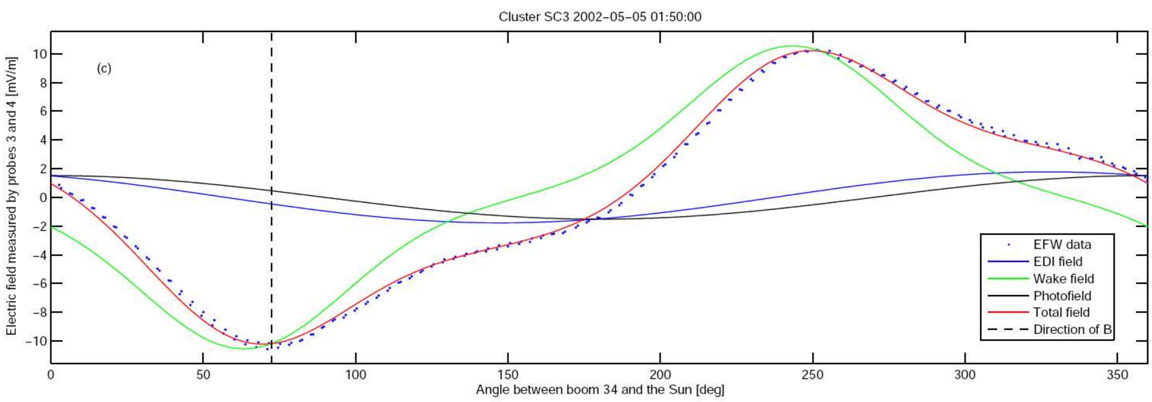

Fig. 1. Example of full time resolution Cluster EFW data from one probe pair, in the spinning reference frame. Adapted from Paper [2].

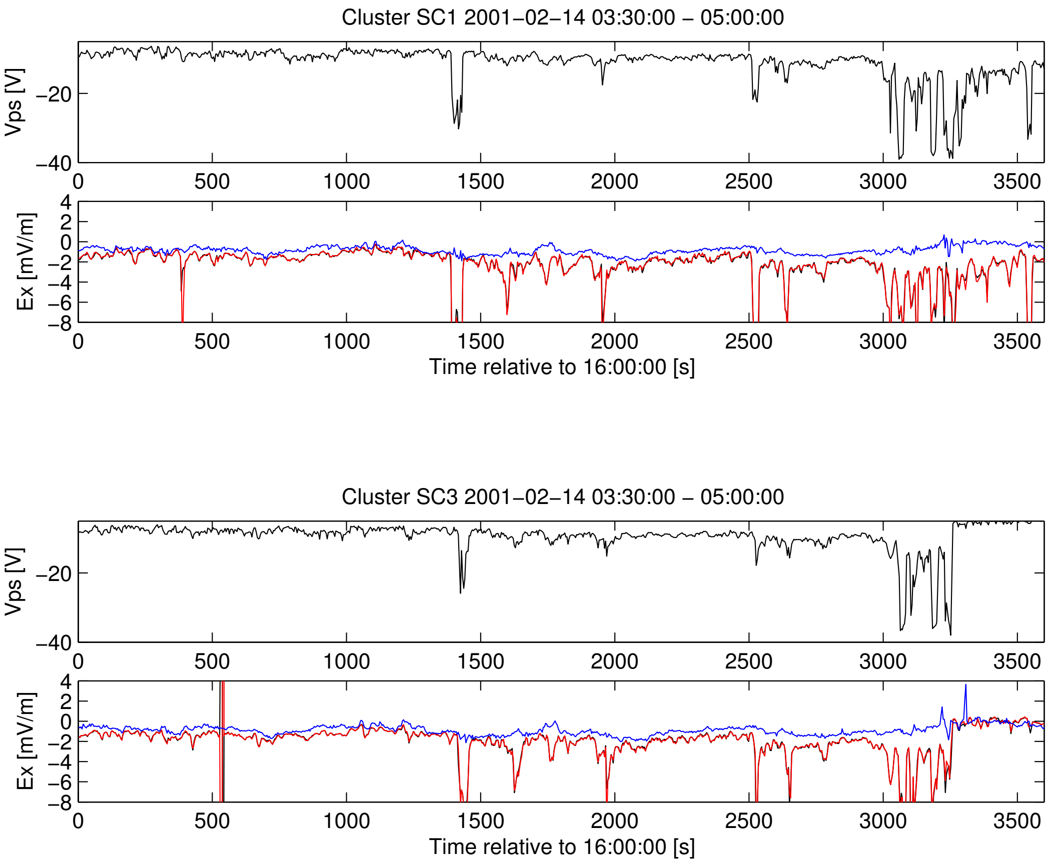

Fig. 2. Example of spin-resolution data showing discrepancy between EFW and EDI data.

shown by Cully et al. [22]). The $V_{\rm ps}$ voltage also is a useful proxy for the plasma density [23, 24]. The lower panels, for each spacecraft, show the X component of the spin resolution electric field in the GSE coordinate system, red for EFW and blue for EDI. At the start of the interval, $V_{\rm ps}$ is around -10 V, corresponding to a spacecraft potential of the same magnitude and opposite sign and a plasma density of several particles per cubic centimetre, and EFW and EDI are in reasonable agreement (blue and red curves). Starting around 1400 s into the plot, and more frequent from 3000 s, intervals of lower density appear, where $V_{\rm ps}$ drops to around -40 V, corresponding to densities on the order of 0.1 cm^{-3}. At these times, large differences appear between EFW and EDI electric fields. On Cluster 3, the ASPOC artificial spacecraft potential controller is turned on 3250 s into the plot, immediately stabilizing the potential as is obvious from the $V_{\rm ps}$ measurement. At this time, the EFW-EDI difference almost disappears, showing that the discrepancy was not related to the low density as such, but rather to the high value of the spacecraft potential. In Section 4, we will show that this behaviour is fully consistent with the EFW-EDI difference being due to a wake forming behind the spacecraft, visible to EFW but not to EDI.

4. MODEL AND SIMULATIONS

Figure 3 shows two sketches of wake formation in different plasma regimes. The upper one shows the narrow wake formed in e.g. ionospheric or solar wind [20] conditions. The sketch leaves out features like Mach cones and wake filling, but illustrates the basic point: the transverse dimensions of the wake are set by the physical size of the spacecraft. Such a wake will be narrow and easily identifiable in the data, as shown for Cluster solar wind measurements elsewhere in this volume [20]. The lower sketch shows the completely different situation arising if the plasma is so tenuous that energy necessary for the ions to reach the spacecraft is much higher than the ion kinetic energy. In these situation, the ions scatter off the potential structure caused by the spacecraft,

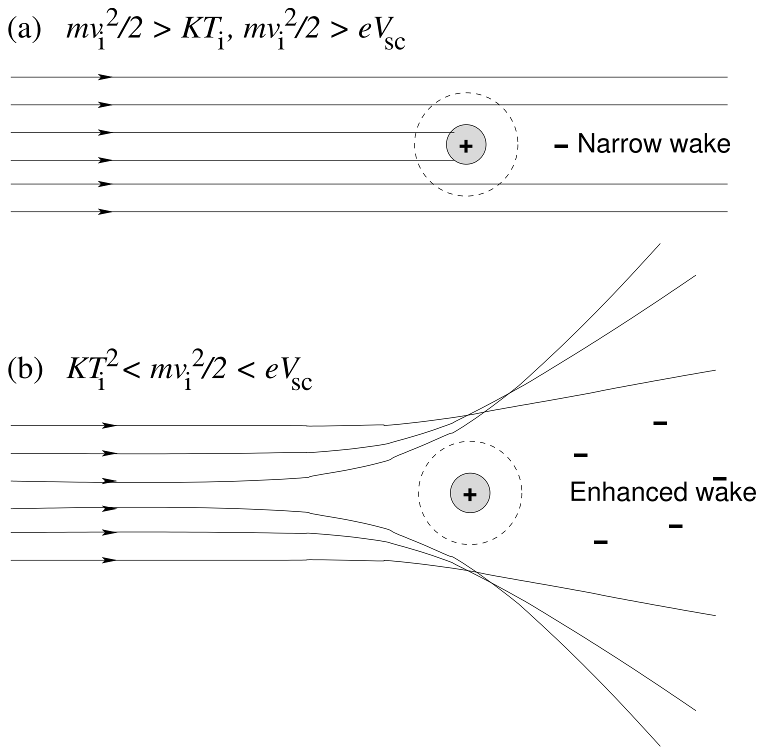

Fig. 3. Sketch of wake formation for different plasma flow regimes. Adapted from Paper [1].

[h]

never reaching the satellite itself. The result is a wake of dimensions that can be much above the characteristic physical size of the spacecraft. This is particularly so for the wire booms, whose physical width is only a few millimeters but whose potential field extends for meters.

This of course requires the presence of a flow of ions with flow kinetic energy per charge below the spacecraft potential, and also with thermal energy below the flow energy (as otherwise no wake would form). For spacecraft potentials of a few tens of volts, this translates to energies in eV of lower magnitudes. Do such flows exist? Yes, they do, and in exactly the regions where EFW-EDI differences like those in Figures 1 and 2 are observed. This flow is the polar wind, flowing upward along the geomagnetic field lines from the ionosphere with temperatures of a few eV and flow kinetic energy per particle of a few eV to a few tens of eV [25]. The polar wind has been well mapped at lower altitudes, but less well in the tenuous plasmas encountered outside a few Earth radii geocentric distance because of the obvious problem with the high spacecraft potential stopping the ions from reaching the spacecraft. The best available measurements are from the POLAR satellite, where an artificial plasma source made it possible to bring down the spacecraft potential to a few volts [26, 25].

The wake will charge negatively due to electrons, for whom the flow is subsonic, entering it. When the EFW probes traverse the wake during the spin, they will therefore detect a potential difference that could conceivalbly look like the data seen in Figure 1, which after spin fitting without any cleaning of the data would give results like these shown in Figure 2. This idea is confirmed by the numerical simulations to which we now turn.

For simulations, we have mostly used the particle-in-cell code PicUp3D [27, 28]. PicUp3D uses a fixed rectangular grid, limiting the possibilities for simulating structures like the narrow wire booms carrying the EFW probes. We have therefore started simulations using SPIS [29, 30, 31], also a particle-in-cell code but with more flexible modelling capabilities, and a lot of other features as well. We will not go into details of the simulations here: the reader is refered to Paper [3] and other references to our numerical work [6, 8, 7, 5]. Basically, we have performed two kinds of simulations: with only the spacecraft (no booms), represented as a cube (PicUp3D) or a cylinder (SPIS), or with booms only, represented as a series of points in PicUp3D. We

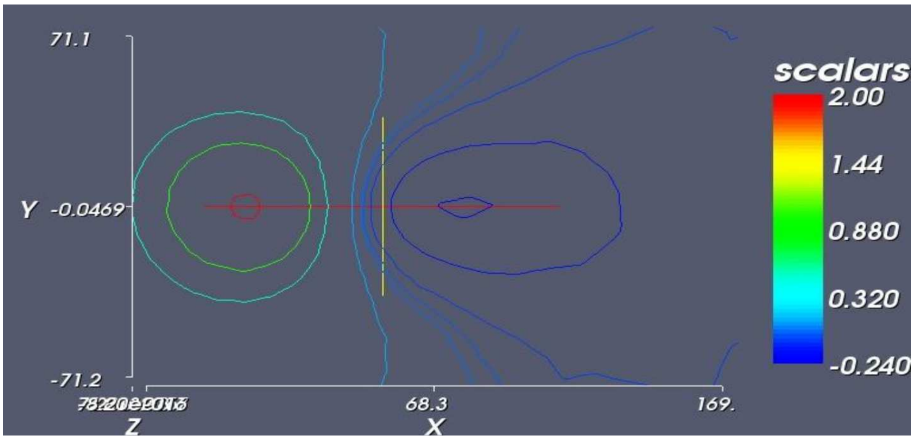

Fig. 4. SPIS simulation of wake potentials behind the spacecraft, not taking the booms into account. Colour scale is in volts, and the axis length scales are in meters.

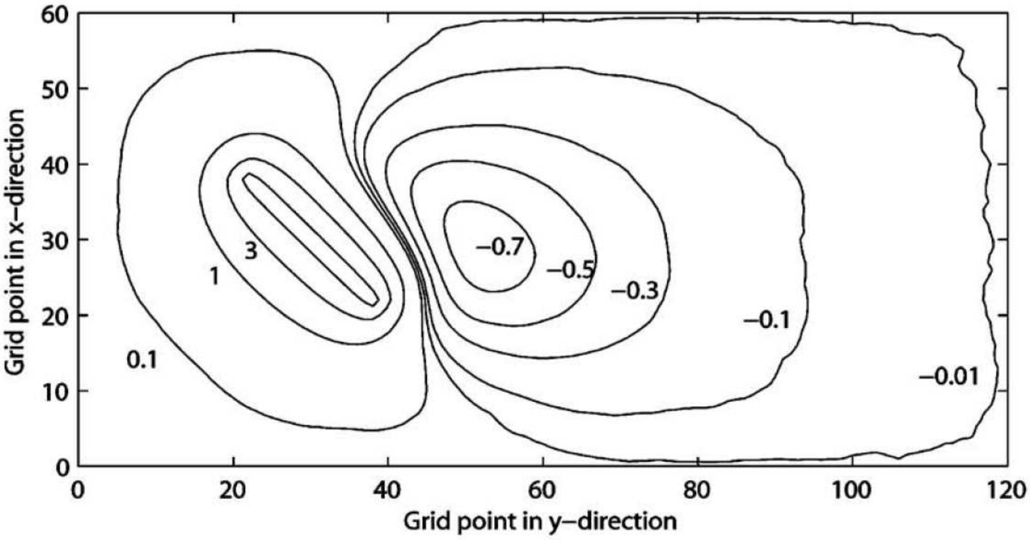

Fig. 5. PicUp3D simulation of wake potentials behind the EFW wire booms. Adapted from Paper [3]. The grid resolution is 4 m.

are currently implementing studies of proper cylinders in SPIS. Interestingly, the spacecraft-only and boom-only simulations give quite similar results, though the wake is deeper for the booms only simulations. Figure 4 shows a typical potential pattern from a spacecraft-only simulation, this time using SPIS and with the spacecraft represented as a cube in order to compare to similar PicUp3D results. Figure 5 displays similar results from a PicUp3D simulation run with the EFW booms only. These simulation runs assume all ions are protons, a plasma density of 0.2 cm^{-3}, electron and ion temperatures of 2 eV. The ion flow kinetic energy is 10 eV, and the spacecraft and booms are at potential $+20$ V. Simulations like these verify the general idea of wake formation.

Simulations can also give more details for comparison to actual measurements. Figure 6 shows the signal EFW would detect during a full spin according to several PicUp3D simulations at some different plasma parameters, together with an example of actually measured data. One should here note that the the actual plasma parameters corresponding to the example data are not known to any accuracy: the temperatures for the simulations are simply assumed values. If the simulation was trusted as representative, a comparison of data and simulation could presumably give constraints on the temperatures, for example the $T_\mathrm{i}/T_\mathrm{e}$ ratio. However, the simulation used here is a spacecraft-only simulation, and comparison to boom-only simulations suggest that the booms are more important for the wake formation. Reliable boom simulations at varying angle of attack requires use of

SPIS, and we have only started on such simulations at this stage.

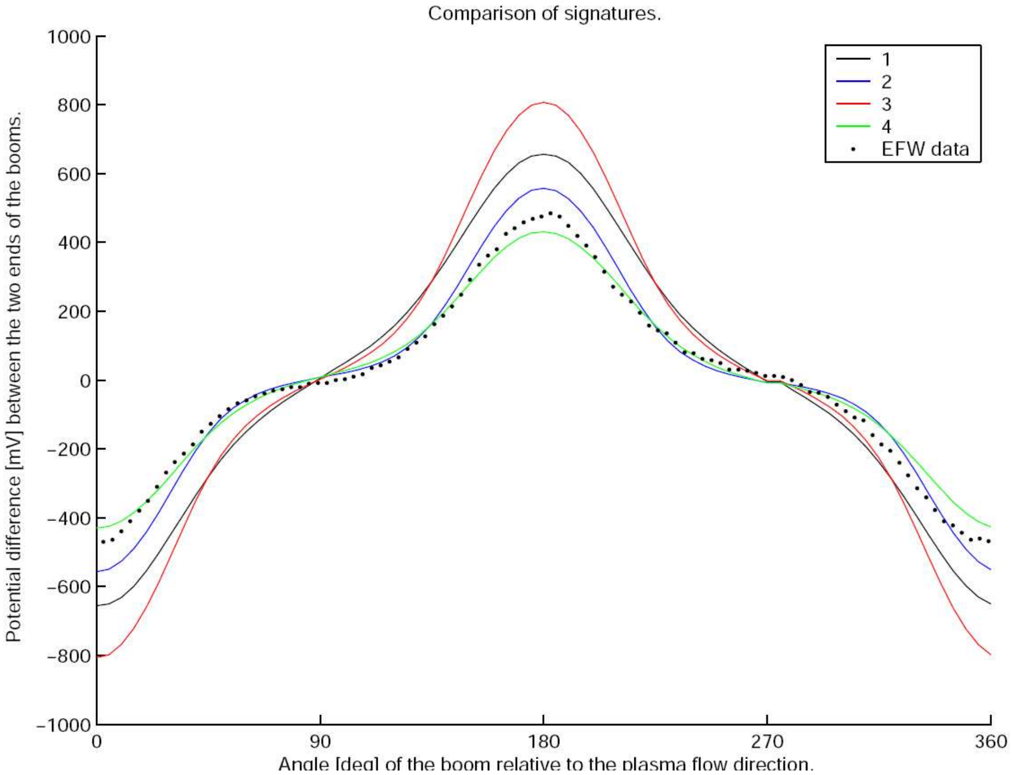

Fig. 6. Comparison of simulated (in colour) wake signatures and actual Cluster EFW measurement during one spin. Colours refer to different plasma temperature combinations: $KT_e = KT_i = 2$ eV (black), $KT_e = KT_i = 1$ eV (blue), $KT_e = 2$ eV, $KT_i = 1$ eV (red), $KT_e = 1$ eV, $KT_i = 2$ eV (green). Adapted from Paper [3].

5. DERIVING PLASMA FLOW FROM WAKE OBSERVATIONS

While the simulations show general agreement with the observations, it still remains to verify the identification of the wake mechanism with independent data. This was done in Paper [4], and in the process we developed a scientifically useful method for measuring cold ion flows.

The basis of the method is as follows. EDI reliably measures the plasma drift velocity component perpendicular to the magnetic field, so the velocity of the ions in this direction is known. As magnetization effects will be negligible on the wake length scale, the wake will extend in the direction parallel to the total ion flow, i.e. to the vector sum of its parallel and perpendicular components. The direction of the wake projection in the spin plane is found from the EFW and EDI data, i.e. from the peak of the green curve in Figure 1, and the perpendicular flow component in the spin plane is known from EDI data. From this information, we can reconstruct the ion flow velocity along the magnetic field. The metod, described in more detail in Paper [4], works as long as the flow direction is not too far from the spin plane.

This is verified in Figure 7, showing ion flows derived by the wake method and from ion measurements. This would not be possible on a single spacecraft, as either the spacecraft potential is lower than the ion flow energy, in which case the ions reach the spacecraft and can be measured by the ion detectors but no wake forms, or the spacecraft potential is higher than the ion energy, in which case the wake method works but the ions cannot be seen by an instrument on the spacecraft. For this particular event, the ASPOC artificial spacecraft controller [32] was in operation on Cluster 4, and the ion flow had sufficiently high energy to overcome the remnant spacecraft potential still left despite ASPOC (which is not usually the case). The top panel shows the ion flow velocity component parallel to the magnetic field as derived from the wake method using data from from Cluster 3, where ASPOC was not operating and the spacecraft potential thus was high, marked with blue dots

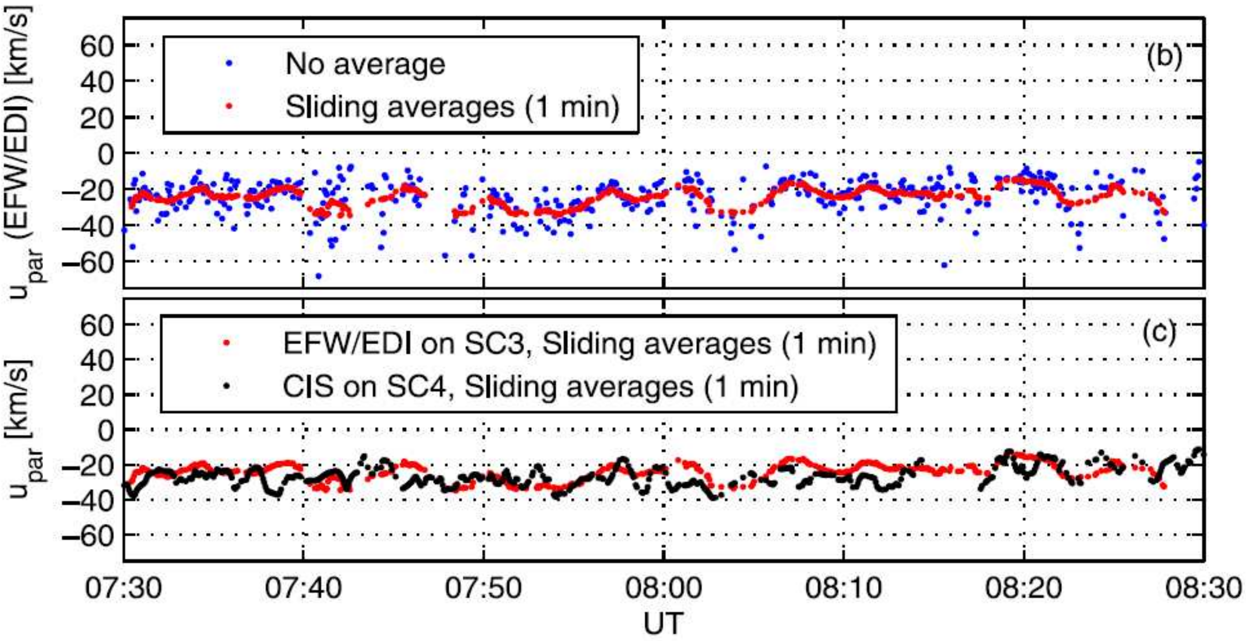

Fig. 7. Comparison of wake-derived parallell ion flow velocity on Cluster 3 to the same quantity derived from CIS ion data on Cluster 4. This comparison was possible because of operation of the ASPOC artificial spacecraft potential controller on Cluster 4, in combination with a higher than usual ion flow energy. Adapted from Paper [4].

for each spin with a red curve when averaged to one minute time resolution. The lower panel shows this sliding average, still in red, together with the parallell flow velocity from the CIS particle instrument on Cluster 4. The measurements agree as well as could be expected for a spacecraft separation of about 0.5 R_E. This verifies our interpretation of the EFW data as a wake signature, and provides us with a method to study the otherwise elusive polar wind ion flow.

6. CONCLUSION

Our principal results can be summarized as follows:

1) Combining data from two electric field instruments based on very different principles, we can determine the existence of wakes caused by a flowing ion poulation hidden to the particle detectors because of the high spacecraft potential.

2) The wake formation has been verified using the particle in cell simulation codes PicUp3D and SPIS, giving good agreement to observed data.

3) The wake formation has also been verified by comparing to direct ion measurements in a rare case where the ions could be detected on one Cluster satellite, with its potential stabilized by artificial means, and the wake on another of the Cluster satellites.

4) The wake method can be used for studying the flow of ions of very low energy that are otherwise hidden to particle instruments because of high spacecraft potentials.

Spacecraft wakes may thus be useful as a means for deriving plasma properties, and not only be seen as a contamination to measured data.

Acknowledgements

Many people have been involved in the studies presented here: thanks to Goetz Paschmann, Per-Arne Lindqvist, Jack Quinn Arne Pedersen, Forrest Mozer and many others for good cooperation and fruitful discussions. We wish also to thank the PicUp3D and SPIS developers, the SPIS sponsor ESA and the SPINE network for creating not only the SPIS code but also a stimulating scientific and human environment around it. In particular, thanks are due to Julien Forest, Alain Hilgers and Jean-François Roussel for a lot of help in the initial stages of our simulations.

References

[1] A. I. Eriksson, M. André, B. Klecker, H. Laakso, P.-A. Lindqvist, F. Mozer, G. Paschmann, A. Pedersen, J. Quinn, R. Torbert, K. Torkar, and H. Vaith. Electric field measurements on Cluster: comparing the double-probe and electron drift techniques. *Ann. Geophysicae*, 24:275–289, 2006.

[2] E. Engwall and A. I. Eriksson. Double-probe measurements in cold tenuous space plasma flows. *IEEE Trans. Plasma Sci.*, 34:2071–2077, doi:10.1109/TPS.2006.883375, 2006.

[3] E. Engwall, A. I. Eriksson, and J. Forest. Wake formation behind positively charged spacecraft in flowing tenuous plasmas. *Phys. Plasmas*, 13:062904, 2006.

[4] E. Engwall, A. I. Eriksson, M. André, I. Dandouras, G. Paschmann, J. Quinn, and K. Torkar. Low-energy (order 10 ev) ion flow in the magnetotail lobes inferred from spacecraft wake observations. *Geophys. Res. Lett.*, 33:L06110, doi:10.1029/2005GL025179, 2006.

[5] Erik Engwall. Cold magnetospheric plasma flows: Properties and interaction with spacecraft. Licentiate thesis, Department of Astronomy and Space Physics, Uppsala University, Sweden. Available at http://space.irfu.se, 2006.

[6] E. Engwall, A. I. Eriksson, A. Pedersen, J. Forest, G. Paschmann, J. Quinn, R. Torbert, and K. Torkar. Wake effects on positively charged spacecraft in flowing tenuous plasmas: Cluster observations and modelling. In *Proceedings of the 8th Spacecraft Charging Technology Conference, Huntsville, October 2003*. NASA, 2004.

[7] E. Engwall and A. I. Eriksson. Cold magnetospheric plasma flows and spacecraft wakes: PicUp3D simulations and Cluster data. In *Proceedings of the 9th International Spacecraft Science Technology Conference (SCTC-9)*. Japan Aerospace Exploration Agency, 2005.

[8] E. Engwall and A. I. Eriksson. Cold magnetospheric plasma flows and spacecraft wakes: PicUp3D simulations and Cluster data. In *Proceedings of the 7th International Symposium for Space Simulations (ISSS-7)*, 2005.

[9] C. P. Escoubet, A. Pedersen, R. Schmidt, and P. A. Lindqvist. Density in the magnetosphere inferred from ISEE 1 spacecraft potential. *J. Geophys. Res.*, 102:17595–17610, 1997.

[10] G. Gustafsson, R. Boström, B. Holback, G. Holmgren, A. Lundgren, K. Stasiewicz, L. Ahlén, F. S. Mozer, D. Pankow, P. Harvey, P. Berg, R. Ulrich, A. Pedersen, R. Schmidt, A. Butler, A. W. C. Fransen, D. Klinge, M. Thomsen, C.-G. Fälthammar, P.-A. Lindqvist, S. Christenson, J. Holtet, B. Lybekk, T. A. Sten, P. Tanskanen, K. Lappalainen, and J. Wygant. The electric field and wave experiment for the Cluster mission. *Space. Sci. Rev.*, 79:137–156, 1997.

[11] A. Pedersen, F. Mozer, and G. Gustafsson. Electric field measurements in a tenuous plasma with spherical double probes. In J. Borovsky, R. Pfaff, and D. Young, editors, *Measurement Techniques in Space Plasmas: Fields (AGU Geophysical Monograph 103)*, pages 1–12. American Geophysical Union, 1998.

[12] G. Gustafsson, M. André, T. Carozzi, A. I. Eriksson, C.-G. Fälthammar, R. Grard, G. Holmgren, J. A.

Holtet, N. Ivchenko, T. Karlsson, Y. Khotyaintsev, S. Klimov, H. Laakso, P.-A. Lindqvist, B. Lybekk, G. Marklund, F. Mozer, K. Mursula, A. Pedersen, B. Popielawska, S. Savin, K. Stasiewicz, P. Tanskanen, A. Vaivads, , and J-E. Wahlund. First results of electric field and density observations by Cluster EFW based on initial months of operation. *Ann. Geophys.*, 19:1219–1240, 2001.

[13] G. Paschmann, F. Melzner, R. Frenzel, H. Vaith, P. Parigger, U. Pagel, O.H. Bauer, G. Haerendel, W. Baumjohann, N. Scopke, R.B. Torbert, B. Briggs, J. Chan, K. Lynch, K. Morey, J.M. Quinn, D. Simpson, C. Young, C.E. McIlwain, W. Fillius, S.S. Kerr, R. Mahieu, and E.C. Whipple. The electron drift instrument for Cluster. *Space Science Reviews*, 79:233–269, 1997.

[14] G. Paschmann, C. E. McIlwain, J. M. Quinn, R. B. Torbert, and E. C. Whipple. The electron drift technique for measuring electric and magnetic fields. In J. Borovsky, R. Pfaff, and D. Young, editors, *Measurement Techniques in Space Plasmas: Fields (AGU Geophysical Monograph 103)*, pages 29–38. American Geophysical Union, 1998.

[15] G. Paschmann, J. M. Quinn, R. B. Torbert, H. Vaith, C. E. McIlwain, G. Haerendel, O. H. Bauer, T. Bauer, W. Baumjohann, W. Fillius, M. Förster, S. Frey, E. Georgescu, S. S. Kerr, C. A. Kletzing, H. Matsui, P. Puhl-Quinn, and E. C. Whipple. The electron drift instrument on Cluster: overview of first results. *Ann. Geophys.*, 19:1273–1288, 2001.

[16] A. Balogh, M. W. Dunlop, S. W. H. Cowley, D. J. Southwood, J. G. Thomlinson, K.-H. Glassmeier, G. Musmann, H. Lühr, M. H. Acuña H. Fairfield, J. A. Slavin, W. Riedler, K. Schwingenschuh, and M. G. Kivelson. The Cluster magnetic field investigation. *Space. Sci. Rev.*, 79:56–91, 1997.

[17] A. Balogh, C. M. Carr, M. H. Acuña, M. W. Dunlop, T. J. Beek, P. Brown, K.-H. Fornaçon, E. Georgescu, K.-H. Glassmeier, J. Harris, G. Musmann, T. Oddy, and K. Schwingenschuh. The Cluster magnetic field investigation: overview of in-flight performance and initial results. *Ann. Geophysicae*, 19:1207–1217, 2001.

[18] H. Rème *et al.* The Cluster Ion Spectrometry (CIS) Experiment. *Space Sci. Rev.*, 79:303–350, January 1997.

[19] H. Rème et al. First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment. *Ann. Geophysicae*, 19:1303–1354, 2001.

[20] A. I. Eriksson, Y. Khotyaintsev, and P.-A. Lindqvist. Spacecraft wakes in the solar wind. In *Proceedings of the 10th International Spacecraft Charging Technology Conference (SCTC-10)*, 2007.

[21] P.-A. Lindqvist, Y. Khotyaintsev, M. André, and A. I. Eriksson. EFW data in the Cluster active archive. In K. Fletcher, editor, *Proceedings of the Cluster and Double Star symposium: 5th anniversary of Cluster in space*, page 68.1. ESA SP-598, European Space Agency., 2006.

[22] C. Cully, R. E. Ergun, and A. I. Eriksson. Electrostatic structure around spacecraft in tenuous plasmas. *J. Geophys. Res.*, accepted for publication, June 2007.

[23] A. Pedersen. Solar wind and magnetosphere plasma diagnostics by spacecraft electrostatic potential measurements. *Ann. Geophysicae*, 13:118–129, 1995.

[24] A. Pedersen, P. Decreau, P. Escoubet, G. Gustafsson, H. Laakso, P.-A. Lindqvist, B. Lybekk, F. Mozer, and A. Vaivads. Four-point high time resolution information on electron densities on Cluster. *Ann. Geophys,*, 19:1471–1481, 2001.

[25] Y.-J. Su, J. L. Horwitz, T. E. Moore, L. Giles, M. O. Chandler, P. D. Craven, M. Hirahara, and C. J. Pollock. Polar wind survey with the thermal ion dynamics experiment/plasma source instrument suite aboard POLAR. *J. Geophys. Res.*, 103:29305–29337, 1998.

[26] T. E. Moore, C. R. Chappell, M. O. Chandler, P. D. Craven, B. L. Giles, C. J. Pollock, J. L. Burch, D. T. Young, J. Hunter Waite, J. E. Nordholt, M. F. Thomsen, D. J. McComas, J. J. Berthelier, W. S. Williamson, R. Robson, and F. S. Mozer. High-altitude observations of the polar wind. *Science*, 277:349–351, 1997.

[27] J. Forest, L. Eliasson, and A. Hilgers. A new spacecraft plasma simulation software, PicUp3D/SPIS. In *Proc. 7th Spacecraft Charging Technology Conference*, volume ESA SP-476, pages 515–520, 2001.

[28] J. Forest, A. Hilgers, B. Thiebault, L. Eliasson, J.-J. Berthelier, and H. De Feraudy. An open-source spacecraft plasma interaction simulation code picup3d: Tests and validations. *IEEE Proc. Plasma Sci.*, 34:2103–2113, doi:10.1109/TPS.2006.883402, 2006.

[29] J.-F. Roussel, F. Rogier, D. Volpert, J. Forest, G. Rousseau, and A. Hilgers. Spacecraft plasma interaction software (SPIS): Numerical solvers - methods and architecture. In *Proceedings of the 9th International Spacecraft Science Technology Conference (SCTC-9)*. Japan Aerospace Exploration Agency, 2005.

[30] J. Forest, J.-F. Roussel, A. Hilgers, B. Thiébault, and S. Jourdain. SPIS-UI, a new integrated modelling environment for space applications. In *Proceedings of the 9th International Spacecraft Science Technology Conference (SCTC-9)*. Japan Aerospace Exploration Agency, 2005.

[31] A. Hilgers, B. Thiébault, J.-F. Roussel, J. Forest, and E. Engwall. Test and validation of a new spacecraft plasma interaction software, SPIS. In *Proceedings of the 9th International Spacecraft Science Technology Conference (SCTC-9)*. Japan Aerospace Exploration Agency, 2005.

[32] K. Torkar, W. Riedler, C. P. Escoubet, M. Fehringer, R. Schmidt, R. J. L. Grard, H. Arends, F. Rüdenauer, W. Steiger, B. T. Narheim, K. Svenes, R. Torbert, M. André, A. Fazakerley, R. Goldstein, R. C. Olsen, A. Pedersen, E. Whipple, and H. Zhao. Active spacecraft potential control for cluster - implementation and first results. *Ann. Geophysicae*, 19:1289–1302, 2001.