Penetration electrid field and the formation of plasmaspheric shoulders and notches

J. Goldstein[1], R. W. Spiro[1], R. A. Wolf[1], P . H. Reiff[1], J. W. Freeman[1], B. R. Sandel[2], W. T. Forrester[2], D. L. Gallagher[3], R. L. Lambour[4]

Abstract.
Sudden changes in solar wind (SW) and IMF allow outer magnetospheric E-fields to penetrate past the inner magnetosphere's shielding layer. The intensity of this "penetration E-field" is concentrated in MLT: "active regions" (AR) are found in the pre-dawn (PD) and pre-noon (PN) local times. A comparison study showing good agreement between simulations and IMAGE EUV data, establishes the connection between penetration and "shoulders" and "notches" that form in the PDAR, where penetration-induced plasma motion is most pronounced. Detailed analysis of EUV-observed plasmapause motion also shows both a pronounced PDAR concentration and a strong correlation with rapidly-changing SW/IMF.

The extreme ultraviolet (EUV) instrument on the IMAGE satellite [*Burch*, 2000] is the first mission to provide full global images of the plasmasphere on a routine basis [*Sandel et al.*, 2000a, 2001]. EUV detects resonantly scattered solar 30.4 nm radiation, and produces images with 0.1 R_E spatial resolution (or better) every 10 minutes, allowing detailed observation of a number of meso-scale plasmaspheric features such as convection tails, "bite-outs" (or "plasma voids"), "fingers" and "shoulders" [*Sandel et al.*, 2001; *Burch et al.*, 2001a, b; *Goldstein et al.*, 2002]. Plasmaspheric tails, predicted by *Grebowsky* [1970] and *Chen et al.* [1975], appear in in-situ data as "detached plasma regions" [*Carpenter et al.*, 1993; *Moldwin et al.*, 1994; *Carpenter and Lemaire*, 1997]. The other features are not as easily spotted in single-point measurements, and therefore, it is only with the advent of the EUV instrument that attention is being focused on them.

The plasmaspheric shoulder can be understood as a consequence of penetration electric field, triggered by changes in the solar wind (SW) and interplanetary magnetic field (IMF). The inner magnetosphere tends to maintain a so-called "shielding layer," a protection against the effects of the (sunward) SW/IMF-driven magnetospheric plasma convection. The penetration of outer magnetospheric convection into the inner magnetosphere occurs in two instances, both when convection changes more rapidly than the shielding layer can compensate. If convection strengthens rapidly (e.g., after a sudden southward turning of the IMF), the shielding layer will be temporarily inadequate, and "undershielding" occurs in which a generally sunward plasma flow is imposed upon the inner magnetosphere. In the other case, a sudden weakening in convection (e.g., after a northward IMF turning) creates an "overshielding" condition, where the shielding layer overcompensates, and its "anti-sunward push" is no longer balanced by convection. As a result, overshielding imposes a net anti-sunward push on the inner magnetospheric plasma. The combination of the inner-magnetospheric anti-sunward flow, and the outer-magnetospheric sunward flow, creates a two-cell mini-convection (or "eddy flow") pattern in the inner magnetosphere [*Goldstein et al.*, 2002]. Plasma flows radially outward in the pre-dawn (PD) region, and is then pulled along with the outer-magnetospheric flow field, flowing eastward around the dawnside and westward around the dusk side. The two streams of deflected plasma then re-join on the dayside to flow radially inward in the pre-noon (PN) region. The stronger eddy flow occurs on the dawnside. It was shown by *Goldstein et al.* [2002], that the PD outward flow region, or "active region" (AR), was most likely responsible for the creation of the plasmaspheric shoulder of May 24, 2000 [*Burch et al.*, 2001a, b; *Goldstein et al.*, 2002].

The pre-dawn active region (PDAR) is really just the narrow range of magnetic local time (MLT) where the radial flows caused by overshielding (or undershielding) are strongest. Its counterpart, the pre-noon active region (PNAR), is weaker, more spread-out in MLT. Thus, undershielding (i.e., some penetration of the external convection past the shielding layer) triggers the formation of an indentation ("notch") in the PDAR, and a small bulge in the PNAR. In the opposite case, overshielding causes a shoulder in the PDAR and a small dent in the PNAR. Simulation results of the data-driven Magnetospheric Specification Model (MSM) [*Freeman et al.*, 1993; *Wolf et al.*, 1997; *Weiss et al.*, 1997; *Lambour et al.*, 1997] show the rough spatial and temporal characteristics of the flows imposed on the inner magnetosphere by penetration E-fields. The validity of the MSM's penetration flow field is subject to testing via comparison with EUV global images. The severity of the PDAR shoulder or notch is naturally dependent upon the particular SW/IMF conditions driving the system. On May 24, 2000 and July 29, 2000, PDAR shoulders were created that were comparable in size to the plasmasphere itself [*Burch et al.*, 2001a; *Goldstein et al.*, 2002]. In several other examples, although there is good agreement between MSM and EUV (in support of the hypothetical connection between overshielding and PDAR shoulders), the shoulders observed and simulated are smaller, less pronounced than those of May and June 2000.

The opposite situation, undershielding, is also testable via MSM-EUV comparison. On March 19, 2001, a sudden increase in SW dynamic pressure produced a very pronounced PM notch in the MSM's plasmapause. Although the subsequent time evolution of this notch shows a gradual "blurring" of the originally sharp indentation, the MSM plasmapause still bears a large (greater than 0.5 R_E) U- or V-shaped scar hours later when EUV data are available. Side-by-side comparisons of MSM and EUV plasmapauses show excellent agreement.

[1] Department of Physics and Astronomy, Rice University, Houston, TX 77005 USA
[2] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 USA
[3] National Space Science and Technology Center NASA Marshall Space Flight Center, Huntsville AL 35812 USA
[4] 244 Wood Street, Lexington, MA 02420 USA

Paper number p0386

Finally, from successive EUV images, the time-dependent position of the plasmapause can be analyzed to infer an equatorial penetration E-field along this boundary. In a number of cases where EUV observes large-scale motion of the plasmapause, plots of penetration field intensity versus MLT and time can be created. These plots show that the penetration field is most pronounced in the PD and PN sectors, and that it is triggered by rapid changes in the SW/IMF.

Acknowledgments. We thank F. Rich of AFRL (ABI) and M. Hairston of U.T. Dallas (PCP); and the Kyoto WDC-C2 ($D_{\rm st}$), NGDC ($K_{\rm p}$), and NSSDC OMNI-Web (SW/IMF) sites, and D. Carpenter (comments). Work at Rice supported by NASA contract NAS5-96020 with SwRI, in part by NASA SEC Theory grant NAG5-8136 and NSF-ATM-9802744. Work at U. Arizona funded by Contract 83818 from SwRI, a subcontract under NASA NAS5-96020.

References

Boyle, C. B., P. H. Reiff, and M. R. Hairston, Empirical polar cap potentials, *J. Geophys. Res.*, *102*, 111, 1997.

Burch, J. L., IMAGE mission overview, *Space Sci. Rev.*, *91*, 1, 2000.

Burch, J. L., D. G. Mitchell, B. R. Sandel, P. C. Brandt, and M. Wüest, Global dynamics of the plasmasphere and ring current during magnetic storms, *Geophys. Res. Lett.*, *28*, 1159, 2001a.

Burch, J. L., et al., Views of Earth's magnetosphere with the IMAGE satellite, *Science*, *291*, 619, 2001b.

Carpenter, D. L., and R. R. Anderson, An ISEE/Whistler model of equatorial electron density in the magnetosphere, *J. Geophys. Res.*, *97*, 1097, 1992.

Carpenter, D. L., and J. Lemaire, Erosion and recovery of the plasmasphere in the plasmapause region, *Space Sci. Rev.*, *80*, 153, 1997.

Carpenter, D. L., B. L. Giles, C. R. Chappell, P. M. E. Decreau, R. R. Anderson, A. M. Persoon, A. J. Smith, Y. Corcuff, and P. Canu, Plasmasphere dynamics in the dusk-side bulge region: a new look at an old topic, *J. Geophys. Res.*, *98*, 19243, 1993.

Chen, A. J., J. M. Grebowsky, and H. A. Taylor Jr., Dynamics of mid-latitude light ion trough and plasma tails, *J. Geophys. Res.*, *80*, 968, 1975.

Fejer, B. G., R. W. Spiro, R. A. Wolf, and J. C. Foster, Latitudinal variation of perturbation electric fields during magnetically disturbed periods: 1986 SUNDIAL observations and model results, *Ann. Geophys.*, *8*, 441, 1990.

Freeman, J. W., et al., Magnetospheric Specification Model development code and documentation. Report for USAF contract F19628-90-K-0012, Rice University, Houston, TX, 1993.

Goldstein, J., R. W. Spiro, P. H. Reiff, R. A. Wolf, B. R. Sandel, J. W. Freeman, and R. L. Lambour, IMF-driven overshielding electric field and the origin of the plasmaspheric shoulder of May 24, 2000, *Geophys. Res. Lett.*, *accepted April*, 2002.

Grebowsky, J. M., Model study of plasmapause motion, *J. Geophys. Res.*, *75*, 4329, 1970.

Gussenhoven, M. S., D. A. Hardy, and N. Heinemann, Systematics of the equatorward diffuse auroral boundary, *J. Geophys. Res.*, *88*, 5692, 1983.

Kavanagh, L. D., J. W. Freeman Jr., and A. J. Chen, Plasma flow in magnetosphere, *J. Geophys. Res.*, *73*, 5511, 1968.

Lambour, R. L., et al., Global modeling of the plasmasphere following storm sudden commencements, *J. Geophys. Res.*, *102*, 24351, 1997.

Moldwin, M. B., et al., An examination of structure and dynamics of the outer plasmasphere using multiple geosynchronous satellites, *J. Geophys. Res.*, *99*, 11475, 1994.

Nishida, A., Formation of plasmapause, or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail, *J. Geophys. Res.*, *71*, 5669, 1966.

Sandel, B. R., R. A. King, W. T. Forrester, D. L. Gallagher, A. L. Broadfoot, and C. C. Curtis, Initial results from the IMAGE extreme ultraviolet imager, *Geophys. Res. Lett.*, *28*, 1439, 2001.

Sandel, B. R., et al., The extreme ultraviolet imager investigation for the IMAGE mission, *Space Sci. Rev.*, *91*, 197, 2000a.

Sandel, B. R., et al., Extreme ultraviolet imager investigation for IMAGE mission, *Space Sci. Rev.*, *91*, 197, 2000b.

Spiro, R. W., R. A. Wolf, and B. G. Fejer, Penetration of high-latitude-electric-field effects to low latitudes during SUNDIAL 1984, *Ann. Geophys.*, *6*, 39, 1988.

Weiss, L. A., R. L. Lambour, R. C. Elphic, and M. F. Thomsen, Study of plasmaspheric evolution using geosynchronous observations and global modeling, *Geophys. Res. Lett.*, *24*, 599, 1997.

Wolf, R. A., et al., Modeling convection effects in magnetic storms, in *Magnetic Storms*, edited by B. T. Tsurutani, p. 161, AGU, Washington, D. C., 1997.

J. Goldstein, R. W. Spiro, R. A. Wolf, P. H. Reiff, J. W. Freeman, Dept of Physics & Astron, Rice Univ, Houston, TX 77005 USA (jerru@hydra.rice.edu)

B. R. Sandel, W. T. Forrester, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 USA

D. L. Gallagher, NASA Marshall Space Flight Center, NSSTC Huntsville, AL 35812 USA

R. L. Lambour, 244 Wood Street, Lexington, MA 02420 USA