"Physics of Auroral Phenomena", Proc. XXXIII Annual Seminar, Apatity, pp. 63 - 66, 2011

Polar
Geophysical
Institute

CALCULATION OF THE MAGNETOPAUSE STAND-OFF DISTANCE

A.E. Levitin, L.I. Gromova, L.A. Dremukhina, E.G. Avdeeva, A.U. Burtsev (*Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Troitsk, Moscow region, Russia)*

Abstract. Two magnetopause stand-off distance R_0 models using statistics of the dayside magnetopause locations deduced from the satellite measurements in crossing of the magnetopause, and basing on balance of the solar wind plasma's pressure and that of the Earth's magnetic field, are examined. Results predicted according to different models have been compared with satellite measurements of the magnetopause crossings close to the subsolar point. A discrepancy between the models become more significant, when R_0 becomes less than 7 Re. As data set of satellite crossings of the magnetopause close to the subsolar point don't contain IMF and the solar wind parameters that are typical for strong magnetic storms, analytical models of the magnetopause stand-off distance don't allow to calculate R_0 reliably, when R_0 becomes less than 7 *Re*.

Introduction

The magnetopause stand-off distance (R_0) is an important input parameter of the modern magnetospheric magnetic field models. The R_0 calculating can be based either on the dynamic balance of the solar winds plasma's pressure and that of the Earth's magnetic field or can response on statistics of the dayside magnetopause location deduced from the satellite measurements. Choosing the first option, it's necessary to calculate the near-Earth's magnetic field taking into account the instant spatial-temporal distribution of the basic magnetosphere current systems. However in this case, a reliable conclusion is hardly achievable. In the other way, the analytical relations between R_0 and parameters of the solar wind and interplanetary magnetic field fixed by patrol satellites should be applied.

These relations are deduced from statistics of satellite crossing of the dayside magnetopause and transfer the crossing points into initial point of the geometry figure describing the model magnetopause (ellipsoid, paraboloid and others). Data of satellite crossings of the dayside magnetopause, especially close to the subsolar point, are few. As the magnetospheric disturbances occur rather rarely satellites cross the magnetopause under quiet or moderate magnetospheric conditions substantially. Correspondingly, statistical data sets used for constructing R_0 analytical models don't practically contain great amplitudes of the southern IMF component *Bz* and the solar wind dynamic pressure. Therefore such models don't allow to calculate the magnetopause stand-off distance R_0 reliably, when R_0 becomes less than 7 *Re*.

We have presented short description of modern R_0 models and comparison of their results with satellite measurements of the magnetopause crossings close to the subsolar point under different magnetospheric conditions.

Model calculation of the magnetopause stand-off distance

In magnetospheric physics, it is important to have an accurate model for the determination of the size and shape of the magnetopause. In the absence of solar wind coupling to the magnetosphere, these parameters could be predicted by the dynamic and static pressures of the solar wind and the magnetic pressure of the magnetosphere. Based on this assumption, various models have been developed. The earlier statistical study and following empirical model of the average magnetopause shape and size was carried out by *Fairfield* in 1971. Other empirical models followed; Formisano in 1979 adopted Fairfield's approach and used nearly all magnetopause crossings available at that time to develop a new model. Detailed studies of magnetopause processes have shown that dayside reconnection leads to the changes of the magnetopause shape and location. For this reason, *Sibeck et al.* (1991) fitted magnetopause crossings as either a function of dynamic pressure or as a function of the *Bz* component of the interplanetary magnetic field (IMF) and *Petrinec et al.* (1991) fitted the magnetopause as a function of dynamic pressure for strongly northward and strongly southward IMF separately.

Further empirical magnetopause models are already bivariate with respect to both dynamic pressure and IMF *Bz* (e.g. *Roelof and Sibeck*, 1993; *Petrinec and Russel,* 1993, 1996; *Kuznetsov and Suvorova*, 1998; *Shue et al.*, 1997). The *Petrinec and Russell* (1996) model of the nightside magnetopause use inverse trigonometric functions. The other mentioned models adopted either the general equation of an ellipsoid with two parameters (eccentricity and standoff distance) or the general quadratic equation; *Shue et al.* (1997) used the standoff distance and the level of tail flaring. From this short survey, it follows that these models use various functional forms to represent the shape and location of the magnetopause and are usually parametrized by solar wind dynamic pressure and IMF *Bz*. The basic findings of these studies were that the magnetopause scales are roughly with pressure as $p^{-1/6}$ ($p^{-1/6.6}$ *in Shue et al.*, 1997) and that for decreasing IMF *Bz*, the magnetopause displaces inward near the nose and outward down the tail.

However, the various models have different ranges of validity (both spatially and in control parameters) because, among other things, the data sets used for their development were different. Moreover, the data sets used for the development of models usually contained a rather small number of high-latitude magnetopause crossings. *Sotirelis and Meng* in 1999 presented a calculation where the shape of the magnetopause is computed from the requirement that the pressure in the magnetosheath is balanced by magnetic pressure inside the magnetosphere. The authors found changes in the shape of the magnetopause with varying dipole tilt angle. The magnetotail and standoff location shifted vertically, in opposite directions, for nonzero dipole tilt. The vertical offset of the standoff location from the Earth-Sun line varies linearly with dipole tilt angle, reaching 3 R_e for maximum of the tilt. Today for magnetopause crossings, most people have computed the predicted magnetopause positions according to following models:

Shue et al. [1997]: $R_0 = 11.4 + 0.013Bz)(Dp)^{-1/6.6}$, for $Bz > 0$;
$R_0 = 11.4 + 0,14Bz)(Dp)^{-1/6.6}$, for $Bz < 0$;

Shue et al. [1998]: $R_0 = \{10.22 + 1.29tanh[0.1849Bz + 8.14)]\}(Dp)^{-1/6.6}$;

Kuznetsov and Suvorova [1998]: $R_0 = 8.6(1 + 0.407exp(- (|Bz| - Bz)^2/(200*p^{0.15}))Dp^{-0.19})$.

Here Bz (nT) is interplanetary magnetic field z-component is GSM coordinates and Dp (nPa) is the solar wind dynamic pressure.

We propose to estimate R_0 by basing on the dynamic balance of the solar wind plasma pressure Dp and magnetic pressure $B^2/2\mu_0$, that is calculated according to some magnetospheric magnetic field model. We have used Paraboloid Model (PM) [*Feldstein et al.*, 2005] and show that our model (PM-used procedure) results practically coincide with R_0 predicted according to different analytical models. But our procedure of R_0 estimation is preferable during magnetic storms when the southern IMF component Bz becomes rather strong.

The PM model has been named as paraboloid since the magnetopause, representing the paraboloid of revolution geometrically, is the essential element of the model. PM reflects both the physical and analytical description of the geomagnetic field within the whole magnetosphere. On the basis of physical ideas of the character of large-scale magnetospheric current systems and their magnetic fields, analytical relationships were obtained, which make it possible to calculate the geomagnetic field vector at any point in the magnetosphere as a function of input parameters of the model for magnetic storms of any intensity.

The representation of the magnetic field in the modeling region is based on the modular principle, according to which the total magnetic field $B(t)$ is represented as the sum of contributions from major magnetospheric field sources (modules). Every module is an independent current system and each current system has its own intrinsic relaxation and inertia time scales. The magnetic field of each current system depending on its own input parameters is calculated separately. During the magnetic storm intervals the large-scale current systems are influenced not only by the current state of the interplanetary medium, but also its time history during the previous hours. These effects, as well as the non-linear character of the magnetospheric response to the extreme condition in the solar wind are taken into account in PM using model input parameters that specify the magnitude and evolution of important magnetospheric quantities. These input parameters are based on observed conditions in the magnetosphere during the entire course of the magnetospheric disturbances from magneto-quiet conditions to intense magnetic storms. Until recently only a handful of empirical models of the large-scale magnetospheric magnetic field were available. These models were built on the basis of fitting satellite magnetic field measurements in the magnetosphere to various sets of approximating mathematical functions.

PM uses physical notions of the possible character of the magnetospheric currents to select basis functions for these systems. For example, in contrast to the empirical models, the coefficients in the expansion of the potential for the magnetospheric magnetic field (B_T) due to the tail current system are determined on the basis conditions that $B_{TN} = 0$ (B_{TN} is the component of the magnetic field B_T normal to the magnetopause). As a result the tail plasma sheet current closes along the whole magnetopause, including its day sector. This is a key feature distinguishing PM from other magnetic field models, which has important consequences for the location of the magnetopause (since the inner part of the magnetotail current closes through the subsolar magnetopause) and for the contribution of magnetopause currents to *Dst*. For every magnetic field source, PM assumes a zero value of the normal component of the magnetic field on the magnetopause. The continuity equations for the magnetic field and electric current density, $div\ \mathbf{B} = 0$ and $div\ \mathbf{j} = 0$ in the magnetosphere outside the region of the current source location are valid as well.

The total magnetic field vector $B(t)$ for any point (x, y, z) in the magnetosphere in the solar-magnetospheric coordinate system and for the time t is:

$$B(t) = B_d(y) + B_{CF}(y, R1) + B_T(y, R1, R2, F) + B_R(y, b_r) + B_{SR}(y, b_r, R1) + B_{FAC}(y, R1, J_0),$$

where:

$B_d(y)$ is the Earth´s dipole field;

$B_{CF}\,(y, R1)$ is the field of currents on the magnetopause shielding the dipole field;
$B_T\,(y, R1, R2, F)$ is the field of the tail current system (cross-tail current and its closure magnetopause current);
$B_R\,(y, b_r)$ is the field of the ring current;
$B_{SR}\,(y, b_r, R1)$ is the field of currents on the magnetopause shielding the ring current field;
$B_{FAC}\,(y, R1, J_0)$ is the field due to field-aligned currents.

Table 1 shows magnetopause stand-off distance R_0 predicted according to following models: *Shue et al.* [1997] *Kuznetsov and Suvorova* [1998] and PM-used procedure during strong disturbed IMF conditions when model input parameters increases to values specifying strong magnetic storms.

Table 1. R_0 (Re) predicted according to different models under strong disturbed IMF conditions : $Dp > 10$ nPa, $Bz < -10$ nT.

Bz, nT Dp, nPa	-10	-20	-30	Model
10	6.91	6.32	6.30	*Shue et.al* [1998]
	6.10	5.56	5.55	*Kuznetsov et al.* [1998]
	7.74	7.66	7.74	PM-used-procedure
15	6.50	5.95	5.93	*Shue et al.* [1998]
	5.69	5.15	5.14	*Kuznetsov et al.* [1998]
	7.31	7.22	7.30	PM-used-procedure
20	6.22	5.69	5.67	*Shue et al.* [1998]
	5.42	4.88	4.87	*Kuznetsov et al.* [1998]
	7.10	6.94	7.02	PM-used-procedure
25	6.01	5.50	5.48	*Shue et.al.* [1998]
	5.22	4.68	4.67	*Kuznetsov et al.* [1998]
	6.89	6.74	7.10	PM-used-procedure
30	5.85	5.35	5.33	*Shue et al.* [1998]
	5.06	4.52	4.51	*Kuznetsov et al.* [1998]
	6.75	6.58	6.63	PM-used-procedure

Results predicted according to analytical models *of Shue et.al,* [1998] and *Kuznetsov et al.* are sufficiently close and differ from results based on the dynamic balance of the solar winds plasma's pressure *Dp* and PM magnetic pressure $B^2/2\mu_0$ by 1-2 Re because of the statistical set of initial data doesn't practically contain measurements under great amplitudes of the southern IMF component *Bz* and the solar wind pressure.

Table 2 shows R_0 predicted according to different models according to following models: *Shue et al.* [1997], *Shue et al.* [1998], *Kuznetsov and Suvorova* [1998] and PM-used-procedure for specific events when geostationary satellite was located close to the magnetopause, and therefore R_0 should be equal to 6.6 Re. Note, that at $Bz = -27$ nT only R_0 predicted by PM-used-procedure is approximately equal to 6.6 Re(bold in the Table 2).

Table 3 shows R_0 predicted according to the same, as in Table 2, models for specific events that have been examined by team of IKI RAN. R_0 measured by IKI team are presented in the last column of the Table 3. During these events difference between results of analytical models and PM-used-procedure increases under strong negative IMF *Bz*.

Conclusion

Analytic models for estimation of the magnetopause stand-off distance R_0 [*Kuznetsov and Suvorova*, 1998; *Shue et al.* 1997, 1998] are rather reliable if input data for model calculating correspond to the statistical set of initial data that doesn't practically contain measurements under great amplitudes of the southern IMF component *Bz* and the solar wind pressure *Dp*. R_0 estimation basing on balance of the solar wind plasma's pressure *Dp* and magnetic pressure $B^2/2\mu_0$ calculating according to paraboloidal model of the magnetoshperic magnetic field [*Feldstein et al.*, 2005] gives good agreement with analytic model results. But it would be preferable to choose PM-use-procedure during magnetic storms when the southern IMF component *Bz* becomes rather strong (-30 nT < *Bz* < -20 nT).

Table 2. R_0 (Re) predicted according to different models for events when geostationary satellite was located close to the magnetopause.

Date	*Bz,* nT	*N,* cm^{-3}	*Dp,* nPa	R_0, Re *Shue et al.* [1997]	R_0, Re *Shue et al.* [1998]	R_0, Re *Kuznetsov et al.* , [1998]	R_0, Re PM-used
21.02.79	2.2	22.8	10.74	7.98	7.99	7.71	7.92
25.07.81	-27.0	21.8	21.87	4.77	5.60	4.79	**6.23**
11.11.83	2.6	12.6	6.11	8.71	8.71	8.58	8.55
12.06.91	17.6	22.2	27.29	6.97	6.97	6.46	6.65
21.02.92	-9.4	17.4	5.94	7.58	7.58	6.78	8.29

Table 3. R_0 (Re) predicted according to different models for events that have been examined by team of IKI RAN.

Date	*Bz,* nT	*N,* cm^{-3}	*Dp,* nPa	R_0, Re *Shue et al.* [1997]	R_0, Re *Shue et al.* [1998]	R_0, Re *Kuznetsov et al.*	R_0 ,Re PM-used	R_0, Re IKI
07.06.81	-11.0	34.0	14.40	6.58	6.41	6.45	7.19	6.4
25.07.81	-15.3	10.0	10.90	6.45	6.34	6.82	7.04	6.6
24.05.83	-15.1	15.0	13.31	6.16	6.16	6.16	6.88	6.5
11.12.83	-5.0	7.0	2.95	9.25	9.25	9.32	9.24	6.4

Note that reliable comparison model R_0 with satellite measurements could not realizable as a satellites cross the magnetopause in the solar point during a magnetospheric disturbance very rarely. Besides, the magnetopause stand-off distance R_0 should not be estimated rather accurately due to permanent moving of the magnetopause.

Acknowledgments. This study is supported by RFBR grants 08-05-00896.

References

Fairfield, D.N., Average and unusial locations of the Eath's magnetopause and bow shock, , *J. Geophys. Res.*, 76, 6700, 1971.

Feldstein, Y. I., Levitin, A.E.; Kozyra, J. U., et al., Self-consistent modeling of the large-scale distortions in the geomagnetic field during the 24–27 September 1998 major magnetic storm, *J. Geophys. Res.,* 110, A11, A11214 10.1029/2004JA010584, 2005.

Kuznetsov, S.N., and A.V. Suvorova, An empirical model of the magnetopause for broad ranges of solar wind pressure and *Bz* IMF, in *Polar Cap Boundary Phenomena,* edited by J. Moen et al., Kluwer Acad., Norwell, Mass., 51, 1998.

Petrinec, S. M., and C. T Russell, Factors which control the size of the magnetosphere, in *Solar Terrestrial Predictions IV, vol. 2, edited by J. Hruska et al.*, pp. 627-635, Natl. Oceanic and Atmos. Admin. Environ. Res. Lab., Bolder, Colo.,1993.

Petrinec, S. M., and C. T Russell, Near-Earth Magnetotail shape and size as determined from magnetopause flaring angle, *J. Geophys. Res.*, 101,137-152, 1996.

Petrinec, S. M., Song, P., and C. T Russell,., Solar cycle variations in the size and shape of the magnetopause, *J. Geophys. Res.*, 96, 7893, 1991.

Roelof, E. C., and D. G. Sibeck, Magnetopause shape as a bivariate function of interplanetary magnetic field Bz and solar wind dynamic pressure, *J. Geophys. Res.,* 98, 21421, 1993.

Sibeck, D. G., Lopez, R. E., and Roelof, E. C.: Solar wind control of the magnetopause shape, location, and motion, *J. Geophys. Res.*, 96, 5489, 1991.

Shue, J.-H, J. K. Chao, H. C. Fu, et al, A new functional form to study the solar wind control of the magnetopauses ize and shape, *J. Geophys. Res.,* 102, 9497, 1997.

Shue, J .-H., et al., Magnetopause location under extremes solar wind conditions, *J. Geophys. Res.*, 103, 17, 691, 1998.

Sotirelis, T., and Meng, C-I, Magnetophause from pressure balance, *J. Geophys. Res.,* 104, 6889, 1999.