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THE POYNTING FLUX INTO EARTH'S MAGNETOSPHERE IN MODEL WITH IONOSPHERIC ELECTRIC FIELD SATURATION

Yu. V. Kuzminykh, Yu. A. Karavaev, and V. M. Mishin (*Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia)*

Abstract. [1] The literature-known methods of calculating the Poynting flux ε from solar wind into the Earth's magnetosphere either do not take into account magnetospheric parameters and, therefore, give predicted, not real value of the Poynting flux, or use constant calibration coefficients which actually are not constant and can be calculated only with poor accuracy at present. Besides, these methods do not take into account effects of saturation of the convection electric field transferred into the magnetosphere from solar wind as well as dynamic pressure P_d. The goal of this paper is to develop a new method to calculate ε=ε* which takes into account the mentioned effects. The initial testing of the obtained results was carried out using the ring current decay time of the 20 Nov 2003 superstorm data. The test results testify in favor of the new method stated here.

1. Introduction

[2] Empirical calculations of electromagnetic energy flux ε into the magnetosphere is one of the traditional problems for physics of magnetosphere. One of the most known methods to calculate ε or equivalent "coupling functions" using observational data is the Perreault-Akasofu method, in which the Poynting vector flux is $\varepsilon=\varepsilon_A(W)=(4\pi/\mu_0)\cdot V_{SW}\cdot B^2\cdot \sin^4(\theta/2)\cdot l_0^2$, where $\mu_0=4\pi\cdot 10^{-7}$ H/m; V_{SW} is solar wind velocity; B is the strength of the interplanetary magnetic field (IMF); θ is the clock-angle of the IMF orientation, in the GSM coordinate system; the factor l_0 denotes the linear dimension of an ''effective cross-sectional area'' of the magnetosphere determined empirically to $l_0 = 7\ R_E$ [Perreault and Akasofu, 1978].

[3] In another known method, the solar wind electric field is calculated, $E_{SW}(B/m)=V_{SW}\cdot B_Z$, where V_{SW} is solar wind velocity; B_Z is the IMF southern component. The electric field E_{SW} is used as "solar wind - magnetosphere coupling" function.

We note that the two mentioned methods calculate the ε_A and E_{SW} coupling functions, using solar wind parameters, disregarding the ε_A and E_{SW} response dependence from the magnetosphere's state.

[4] In the papers [Mishin et al., 2000 and references therein] there was proposed the method $\varepsilon=\varepsilon'=(\Psi_1^2 \cdot V_{SW})/(\mu_0\cdot S_L)$, where $\Psi_1=\langle B_L\rangle\cdot S_L/2$ is a variable portion of the open magnetic flux through the polar cap, calculated on the MIT-2 basis from ground-based observations. The S_L calibration coefficient in the formula for ε′ was determined empirically by Mishin et al. [2006].

[5] The two first methods give predicted, rather than real, value of the Poynting flux; in the third one the constant calibration coefficient is used, which is not actually constant and can be calculated only with poor accuracy at present. All the three mentioned, as well as other known, methods do not take into account the strong effect of saturation of the convection electric field transported into the magnetosphere from solar wind, and effect of dynamic pressure, Pd [Hill et al., 1976, 1984; Siscoe et al., 2002a, b, c; 2004; Shepherd et al., 2002; Hairston et al., 2005; Ebihara et al., 2005].

These are the main disadvantages of even the most popular empirical methods for calculating ε that stimulates the search of a new method to which the present paper is dedicated. The goal of the paper is to develop the method of calculating ε from the observational data available, using the magnetogram inversion technique and measuring solar wind parameters. The new method, unlike the known ones, should take into account the saturation effect mentioned above.

2. Calculating ε with the electric field saturation

[6] Strong saturation of the main magnetospheric and ionospheric electric field with growth of E_{SW} and the corresponding saturation of the ΔU_{pc} potential difference on the polar cap boundary was described by [Hill et al., 1976; 1984]. Now, the saturation effect theory has extensive literature [e.g., Boyle et al., 1997; Shepherd et al., 2002; Shepherd et al., 2002; Hairston et al., 2005]. The MHD model of saturation was developed by Siscoe et al. [2002b; c; 2004]. The alternative version was proposed by McDougal and Jayahandran [2006; 2007]. We note that the known relation of Kan and Lee [1979] also supposes saturation of the Poynting input flux.

[7] Below we propose the method of calculating ε = ε* based on using the modified equation [Kan and Lee, 1979] and the known ΔU_{PC} potential difference on the polar cap boundary. We entered the modified Kan and Lee equation as

$$\Delta U_{PC}= \Phi_{PC} = c[(\mu_0\cdot\varepsilon^*\cdot V_{SW})/(4\cdot\pi)]^{0,5}, \qquad (1)$$

where $\Delta U_{PC} = \Phi_{PC}$ is the potential difference in the polar cap ionosphere calculated with the saturation effect taken into account [Hill et al., 1976; Siscoe et al., 2002b; Ober et al., 2003]; V_{SW} is solar wind velocity. The non-dimensional coefficient is $c \neq 1$ unlike the Kan and Lee equation where the value of c = 1 is postulated. From (1) the equation for the Poynting flux ε=ε* follows:

$$\varepsilon^* = (4\cdot\pi\cdot \Phi_{PC}^2)/(c^2\cdot \mu_0\cdot V_{SW}). \qquad (2)$$

[8] We calculated the constant coefficient c in (2) empirically, accepting $\varepsilon^*=2Q_{DR}+Q_I$, where two summands of the right side are the Q_{DR} ring current power and the Joule ionosphere heating power Q_I (it includes also the power of auroral particle precipitation into the ionosphere [Turner et al., 2001; Ostgaard et al., 2002; Karavaev et al., the present collected papers]).
Assuming $Q_I >> Q_{DR}$ at low activity (AE ≤ 100 nT), we obtain the relation

$$\varepsilon^* \approx Q_I. \qquad (3)$$

The Q_I values used in this paper are calculated by means of the magnetogram inversion technique (MIT) [Mishin, 1990; Kamide and Baumjohann, 1993]. Equating the right sides of formulas (2) and (3) for intervals with low activity ($Q_I >> Q_{DR}$), and using time-average values within these intervals, we obtain the value of c=0.38. The test results (see further) show that, as initial estimate, it is possible to assume the c value in the formula (2) constant for all studied interval UT.
[9] The ε* values plot, calculated by means of (2) according to the 20 Nov 2003 superstorm data, is given in Figure 1. There the ε_A plot is also shown.

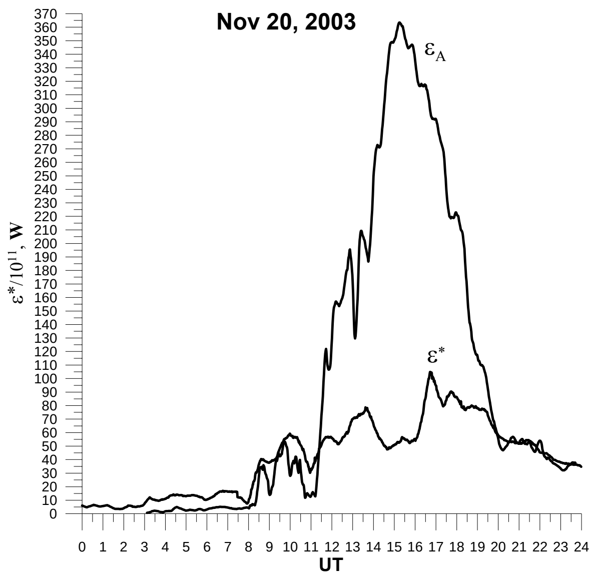

Figure 1. The Poynting flux during the 20 Nov 2003 superstorm: ε_A - after Perreault and Akasofu [1978]; ε* – (with saturation taken into account) according to the authors of this paper. The difference of the two curves (for ε_A and ε*) illustrates the impact of the mentioned saturation effect.

3. Testing

[10] The initial testing of the obtained results was carried out using the calculated data of the ring current decay time τ_T of the 20 Nov 2003 superstorm (see Figure 2 and designations therein).

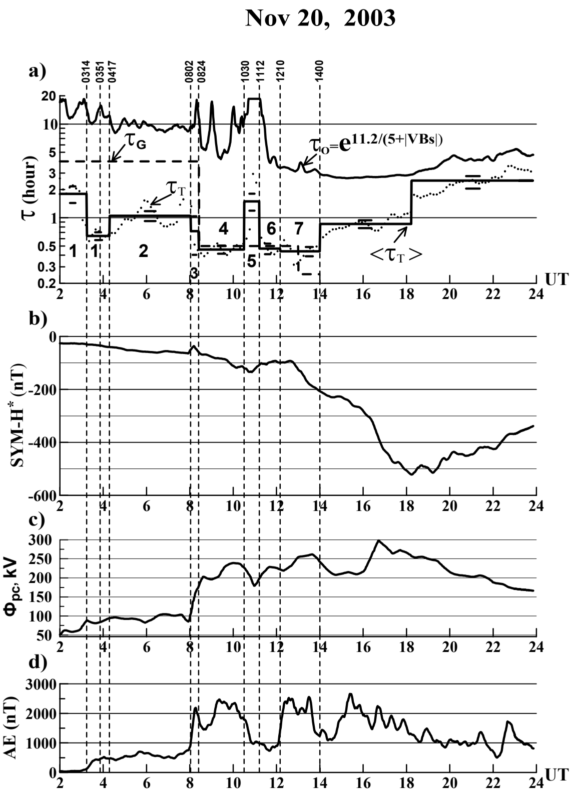

Figure 2. The D_R-current decay time: τ_O – after O'Brien and McPherron, τ_G – after Gonzalez et al., τ_T and $\langle\tau_T\rangle$ – dotted line and solid line, that is averages for each substorm's regime marked 1 to 7 (a); SYM-H* – index corrected for solar wind dynamic pressure (b), Φ_{PC} – the polar cap potential drop with saturation taken into account [Ebihara, et al., 2005] (c); AE – auroral activity index (d).

It is evident that the τ_T values (unlike τ_O and τ_G) distinctly change on the boundaries each of the superstorm's 7 regimes listed above, which were timed independently [Mishin et al., 2007]. The mean-square deviations of the τ_T value from the means for each regime are also shown. We note that mean-square spread of the calculated τ_T values is significantly lower than in the early papers by the these authors where either ε_A [Perreault and Akasofu, 1978] or ε' [Mishin et al., 2000] was used instead of ε*. The τ_T characteristic values (in hours) for the first 7 timed regimes are the following: 1.8-0.64; 1.05; 0.72; 0.46; 1.5; 0.47; 0.44.
[11] For comparison we give in the same figure the τ_O [O'Brian et al., 2000] and τ_G [Gonzalez et al., 1989] values, when calculating which, other methods of calculating the energy entering the magnetosphere were used. From Figure 2 it follows that the τ_O and τ_G values differ from τ_T by far, even sharper they differ between themselves, and their changes during the superstorm (especially τ_O) do not correlate with the observed changes of the substorm's regimes.

Thus, introducing the new method of calculating the Poynting flux ε* provided calculating the τ scale, which takes into account different regimes of magnetospheric disturbance, in a quality way for the first time.

4. Conclusion

[12] We proposed the method of calculating the Poynting flux ε=ε* based on applying the modified equation [Kan and Lee, 1979] and given potential difference $\Delta U = \Phi_{PC}$ on the polar cap boundary [Hill et al., 1976; Siscoe et al., 2002b; Ober et al., 2003]. We made the initial testing of the proposed method by calculating the ring current decay time $\tau=\tau_T$ of the 20 Nov 2003 superstorm. The testing results showed that introducing the new method of calculating the Poynting flux ε* with due regard for the saturation effect provided calculating the τ scale, which takes into account different regimes of magnetospheric disturbance, in a quality way for the first time [Karavaev et al., 2008 (see the present collected papers)].

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