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Another way of deriving the ring current decay time during disturbed periods

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Abstract
Coupling parameter, ϵ, and the total energy dissipated by the magnetosphere, U_T, are determined for six disturbed periods, following three known criteria for U_T computation. It is observed that U_T exceeds ϵ for $Dst < -90$ nT, for all models. Differences between models reside on the estimated values for the particles' life time in the equatorial ring current. The values of τ_R, used in the models, are small during the main phase of the disturbance, in disagreement with the charge exchange life time of the majority species, H^+ and O^+. Based on this conclusion, a different criterion to calculate τ_R is proposed, differentiating the different stages of the perturbation. τ_R is calculated, for the main phase of the storm, from the rate of energy deposition estimation, Q, in the ring current. For Dst recovery phase, the values are obtained from a ring current decay law computation. The U_{TNU} calculated, physically more coherent with the processes occurring during the event, is now smaller than expected. In this sense, it is understood that the power generated by the solar wind-magnetosphere dynamo, should also be distributed in the inner magnetosphere, auroral zones and equatorial ring current, as in the outer magnetosphere, plasmoids in the tail shot in antisolar direction. A further adjustment of ϵ, with the Chapman-Ferraro distance, l_0, variable, has been made. Although the results, improve the estimation of ϵ, they are still smaller than U_T, except U_{TNU}, for some disturbed periods. This result indicates the uncertainty in the computation of the input energy, by using the many expressions proposed in the literature, which are always presented as laws proportional to a given group of parameters, with an unknown factor of proportionality, which deserves more detailed physical analysis.

Key words *magnetosphere – substorms – ring current – plasmoids*

1. Introduction

The solar wind energy input generated by the solar wind-magnetosphere dynamo coupling can be estimated using several functions. One of those was introduced by Perreault and Akasofu (1978) as the parameter ϵ given by

$$\epsilon = vB^2 \sin^4 (\Theta/2)\, l_0^2 \qquad (1.1)$$

where v is the solar wind speed, B the interplanetary magnetic field (IMF) magnitude, Θ the polar angle of the IMF projected on the Y-Z plane in the GSM coordinate system, and $l_0 = 7$ R_E (R_E = Earth radius).

The total magnetospheric energy dissipation parameter, U_T, is given by different processes. Part of the energy dissipated in the inner magnetosphere, is deposited in the ring current belt, U_R. Another part is partially dissipated as joule heating energy, U_J, and partially as auroral particles injection, U_P (Perreault and Akasofu, 1978). According to Akasofu (1981), U_T may be written as

$$U_T = \alpha(\partial D/\partial t + D/\tau_R) + \beta AE \qquad (1.2)$$

where D is the absolute value of the Dst index corrected for the solar wind dynamic pressure changes, τ_R is the ring current decay time, *AE* the auroral electrojet index, and α and β are constants equal to 4×10^{20} erg $(\mathrm{nT})^{-1}$ and 3×10^{15} erg $(\mathrm{nT\ s})^{-1}$, respectively.

The most uncertain parameter in U_T formulation, is τ_R. Several methods have been suggested to introduce τ_R in that equation. We will only mention three of them; the first due to Akasofu (1981), who considers τ_R depending on $\in$, the second due to Vasyliunas (1987), who makes τ_R independent of $\in$ but a function of magnetospheric energy output U_T, and the last due to Gonzalez *et al.* (1989) who assume τ_R depending on *Dst*.

In this paper, we first assume that the coupling function $\in$ with l_0 constant, is a good estimation of the energy input and we handle the above three methods for six selected disturbed periods, together with the new proposed criterion, here introduced, to calculate τ, aiming at a better agreement with experimental results.

As a second step, we consider that l_0 in $\in$ function is not a constant. According to Roederer (1987):

$$l_0 = \{M_E^2 / \mu_0 \rho v^2\}^{1/6} \qquad (1.3)$$

where M_E is the earth magnetic momentum and ρv^2 is the solar wind dynamic pressure.

2. Models and results

According to Zwickl *et al.* (1987), Akasofu's criterion to introduce τ_R is given by

$$\begin{array}{ll} \tau_R = 20\ \mathrm{h} & \in \leq 10^{18}\ \mathrm{erg\ s^{-1}} \\ \quad = 2 & 10^{18} < \in \leq 5\times10^{18} \\ \quad = 1 & 5\times10^{18} < \in \leq 10^{19} \\ \quad = 0.5 & 10^{19} < \in \leq 5\times10^{19} \\ \quad = 0.25 & 5\times10^{19} < \in \end{array}$$

Vasyliunas (1987), considering that there is a range of $\in$ for which τ_R tends to a power law, reformulates τ_R as a function of U_T instead of $\in$, but for $\nu = 1/\tau_R$:

$$\begin{array}{ll} \nu = 0.05\ \mathrm{h^{-1}} & U_T \leq 10^{18}\ \mathrm{erg\ s^{-1}} \\ \quad = 0.33\ [U_T/10^{18}]^{0.6} & 10^{18} < U_T \leq 6.4\times10^{19} \\ \quad = 4 & 6.4\times10^{19} < U_T \end{array}$$

Gonzalez *et al.* (1989) assume three domains of *Dst* in order to search for the best values of τ_R from the correlation study between U_T and different coupling functions. The chosen *Dst* intervals are:

$$\begin{array}{r} Dst \geq -\ 50\ \mathrm{nT} \\ -120\ \mathrm{nT} \leq Dst < -\ 50\ \mathrm{nT} \\ Dst < -120\ \mathrm{nT} \end{array}$$

The authors worked with different sets of τ_R values: 1) τ_R constant for different *Dst* ranges, resulting in very low correlation coefficients (< 0.5); 2) sets of τ_R values decreasing when $|Dst|$ increases. In this case, all coupling functions show the best correlation coefficients for the sets of τ_R values (4, 0.5, 0.5) and (4, 0.5, 0.25). Gonzalez and co-workers restricted this analysis to the main phase of the disturbance.

In this paper, six disturbed periods have been analyzed (table I). The parameter U_T has been calculated for the above methods, *i.e.* Akasofu's (U_{TAK}), Vasyliunas' (U_{TVAS}) and that suggested by Gonzalez and co-workers (U_{TGON}). The results of the application of these methods are compared with each other and with $\in$.

Figures 1a-f show the results in the different

Table I. Disturbed periods analyzed in this paper.

January 29-31, 1978	$Dst < -100$ nT
August 29-30, 1979	$Dst < -150$ nT
October 20-23, 1981	$Dst < -200$ nT
March 1-2, 1982	$Dst < -220$ nT
November 23-25, 1982	$Dst < -220$ nT
February 10-13, 1984	$Dst < -\ 60$ nT

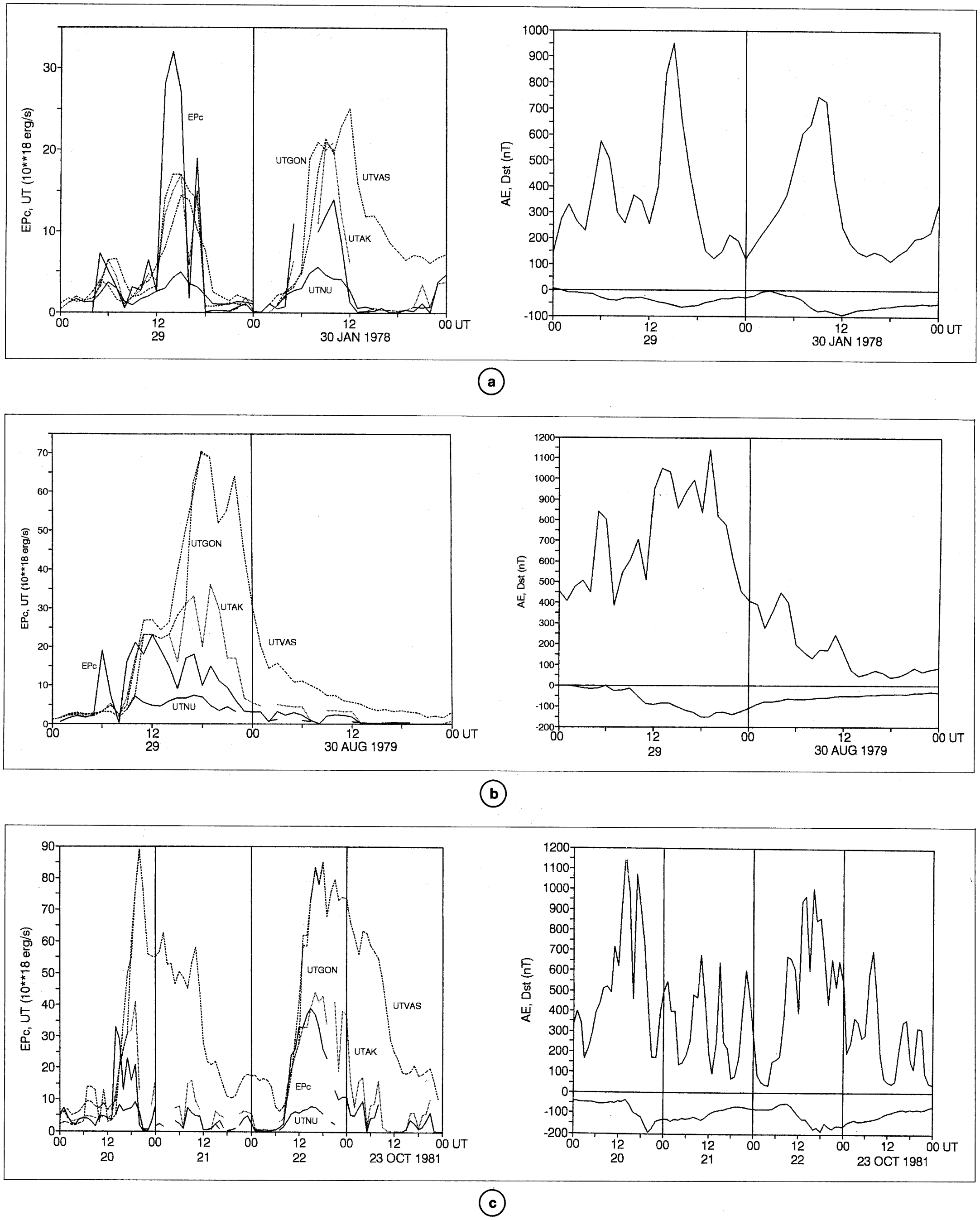
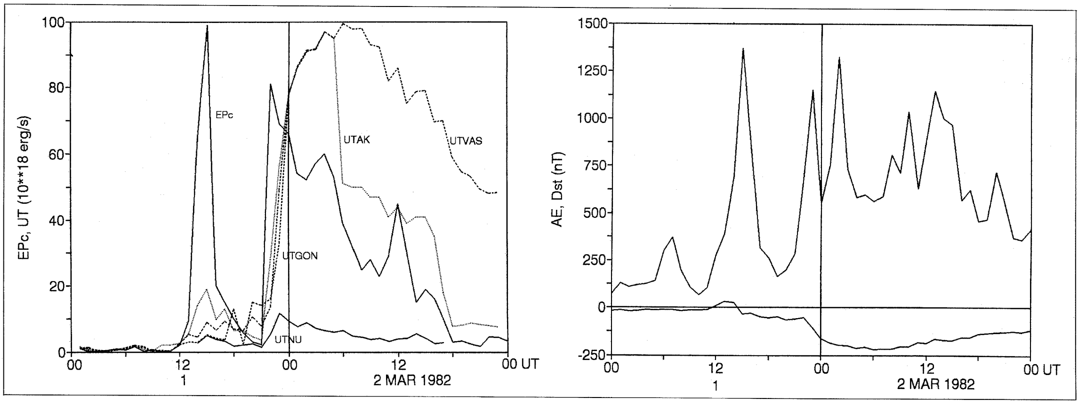


Fig. 1a-c. ε (EP_c), the total magnetospheric dissipation parameter U_T, using the four methods indicated, *AE* and *Dst* geomagnetic indices for: a) January 29-30, 1978; b) August 29-30, 1979; c) October 20-23, 1981.



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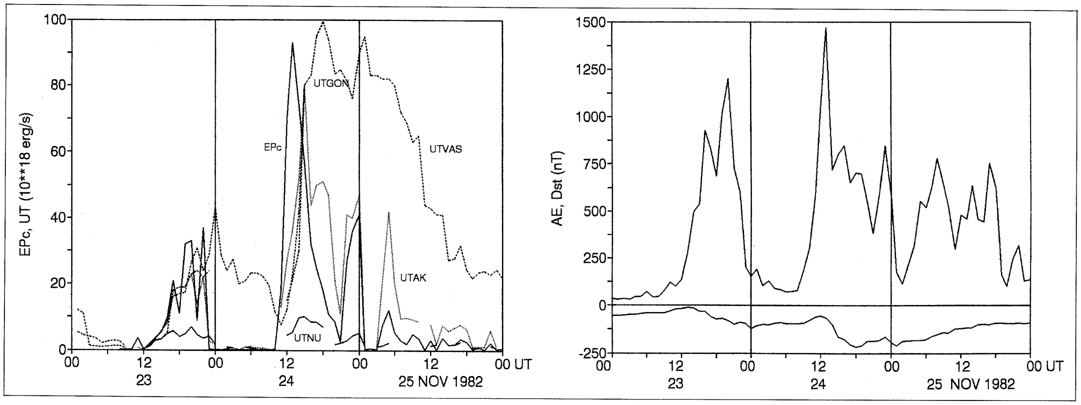

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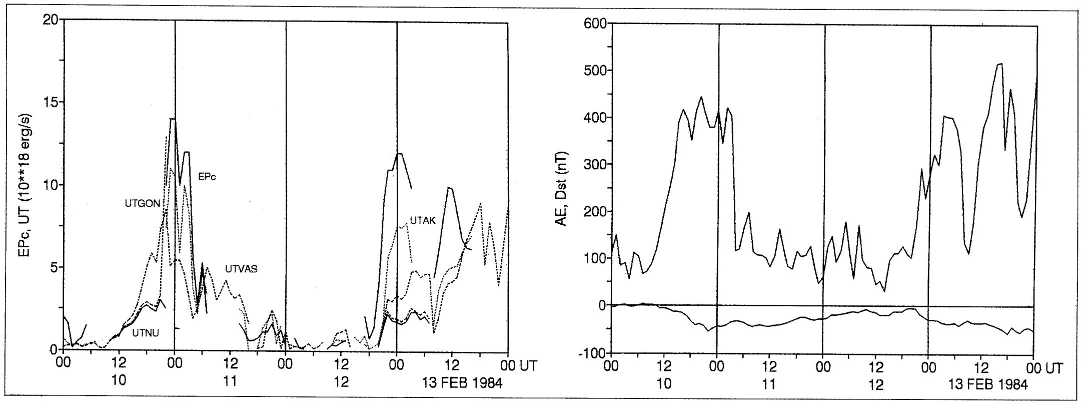

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Fig. 1d-f. ε (EP_c), the total magnetospheric dissipation parameter U_T, using the four methods indicated, *AE* and *Dst* geomagnetic indices for: d) March 1-2, 1982; e) November 23-25, 1982; f) February 10-13, 1984.

disturbed periods, respectively. These figures also show the variation of the equatorial geomagnetic index, *Dst*, for the same periods. It can be clearly seen that for $|Dst| < 90$ nT, the three methods give values of U_T smaller than ϵ, but when *Dst* goes below −90 nT, U_T «jumps» to unexpected values much greater than ϵ. This result, very difficult to justify from a physical point of view, could be related to two possible reasons: first, a fault in the modeling of τ_R implicating the need for a revision of criteria to derive this parameter, and second, no consideration is taken of the substantial part of the magnetospheric energy dissipated tailward from the plasmasheet reconnection region with the generation of the so-called plasmoids (Mishin, 1991).

The ring current decay time values, τ_R, proposed by the different models, are small at the time of maximum disturbance. Those values do not agree with the charge exchange lifetimes (predominant loss process) of the major species in the equatorial ring current: H^+ and O^+ (table II).

3. A new approach

Based on those results, in this paper we analyze the ring current decay time, τ, during the

Table II. Charge exchange lifetimes in hours (from Hamilton *et al.*, 1988).

R (R_E)	Neutral density (cm^{-3})	H^+			
		50 keV	75 keV	100 keV	125 keV
2.0	1938	4.72	11.7	25.5	50.6
2.5	891	10.3	25.4	55.4	110
3.0	514	17.8	44.0	96.0	191
3.5	310	29.5	73.0	159	316
4.0	204	44.9	111	242	481
5.0	106	86.4	214	467	926
6.0	64	144	356	778	1540
7.0	42	219	543	1190	2350

R (R_E)	Neutral density (cm^{-3})	O^+			
		50 keV	75 keV	100 keV	125 keV
2.0	1938	3.34	2.77	2.50	2.34
2.5	891	7.37	6.03	5.43	5.08
3.0	514	12.6	10.4	9.4	8.8
3.5	310	20.9	17.3	15.6	14.6
4.0	204	31.8	26.4	23.7	22.2
5.0	106	61.2	50.8	45.7	42.8
6.0	64	102	84.7	76.2	71.4
7.0	42	155	129	116	109

Charge exchange cross-sections were taken from Smith and Bewtra (1978). Neutral hydrogen density was calculated from the Chamberlain model using the best fit parameters of Rairden *et al.* (1986). $T = 1050$ K, exobase density equal to 44000 cm^{-3}; $r_c = 1.08\ R_E$; $r_{sc} = 3.0\ r_c$ (from Hamilton *et al.*, 1988).

different phases of geomagnetic disturbances, considering different criteria for each phase. Pudovkin *et al.* (1988) studied *Dst* variation and its dependence on solar wind parameters, and the difference in the decay time τ, for each geomagnetic storm phase. We use their criteria to estimate τ in the main phase of the disturbance when there is an energy input to the ring current; we consider then values of the ring current decay computation (*Dst* index recovery) to calculate τ in the recovery phase.

Pudovkin and co-workers have calculated the rate of energy input to the ring current, Q $(= \partial D / \partial t + D / \tau)$ in the main phase and compared Q with the injection functions corresponding to the E_Y-component of the solar wind electric field: $v(0.5\ \sigma - B_Z)$ (v is the solar wind speed, B_Z is the north-south component of the IMF, and σ is the IMF variability). Then they obtain the respective dependence between Q and the injection function; at last, using the fact that at the moment of the *Dst* maximum intensity, $dD/dt = 0$ and then $Q = |D|_{\max} / \tau_m$, where τ_m is the characteristic decay time.

For this purpose, during the six periods indicated in table I, 79 2-h intervals in the main phase were selected. The Q values and the injection function, determined for a 1-h prior period, were estimated for those periods. The respective dependence is:

$$Q = 4.87 + 3.49\ v(0.5\,\sigma - B_z)\,10^{-3} \qquad (3.1)$$

where v is in km s^{-1}, B_z and σ are in nT, $v(0.5\,\sigma - B_z)$ is in mv/m and Q is in nT/h. Then we calculated Q an hour prior to the $|D|_{\max}$ and we found τ_m for the different main phase disturbance periods. Figure 2 shows the ring current decay time in the main phase vs. $|D|_{\max}$ and it can be seen that τ_m is practically independent of $|D|_{\max}$ its mean value being around 5.5 h for $|D|_{\max} > 80$ nT.

For the recovery phase of the different disturbances we calculated τ, τ_R, using the values of the ring current decay calculation (*Dst* index recovery):

$$D = A\, e^{-t/\tau_R}$$

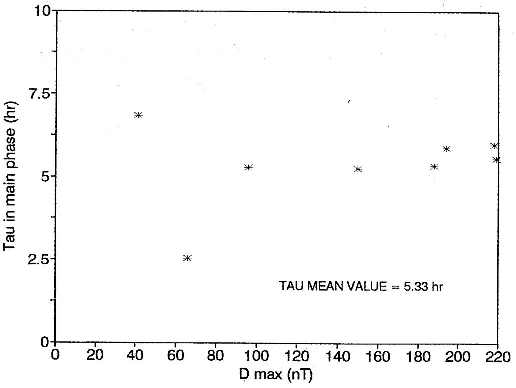

Fig. 2. The ring current decay time in the main phase vs. $|Dst|_{\max}$.

from which we obtain,

$$\tau_R = (t_2 - t_1) / \ln (D_1 / D_2)\,.$$

Using these criteria, we estimated the ring current decay time for the disturbed periods indicated in table I. Afterwards we calculated the parameter U_T (U_{TNU}). U_{TNU} was not calculated for periods where, 1) we did not have enough data, or 2) there was additional energy input to the ring current in the recovery phase.

Figures 1a-f also show U_{TNU}. It can be seen that U_{TNU} values are smaller than $\in$ for all periods. The new τ estimated values are indicated in table III. Those values are comparable with O^+ and H^+ charge exchange lifetimes (table II).

So far, we have only taken into account the structure of U_T, without considering if $\in$, as given by (1.1), is formed by parameters that have been correctly estimated. Looking at (1.1), it is reasonable to believe that the weakest point resides in the estimation of l_0, the Chapman-Ferraro distance. In an additional approach, and following Roederer (1987), we calculated $\in$ for a l_0 variable and given by (1.3). The new values of $\in$ (EP_v), together with those for l_0 = constant (EP_c) and U_{TVAS} are presented in fig. 3a-f. Now, EP_v is greater than EP_c, approaching more to U_{TVAS} but farther from U_{TNU}.

Table III. Estimated τ values using the proposed criteria.

Disturbance	Phases	Periods (U_T)	τ (h)
29-30/1/1978	Main	01TU-16TU	5.3
	recovery	17TU-03TU	3.3
30-31/1/1978	Main	03TU-12TU	5.3
	recovery	12TU-14TU	8.1
		14TU-22TU	21.8
29-30/8/1979	Main	09TU-18TU	5.3
	recovery	19TU-20TU	6.6
		21TU-02TU	10.4
		02TU-24TU	26.0
20-22/10/1981	Main	14TU-20TU	5.9
	recovery	20TU-22TU	6.3
		22TU-08TU	65.4
		11TU-20TU	15.8
		01TU-05TU	110.0
		05TU-09TU	9.0
22-23/10/1981	Main	09TU-18TU	5.3
	recovery	19TU-24TU	37.0
01-02/3/1982	Main	14TU-06TU	5.6
	recovery	07TU-24TU	9.0
23-24/11/1982	Main	13TU-00TU	5.3
	recovery	00TU-05TU	17.4
		06TU-09TU	92.5
		09TU-12TU	5.5
24-25/11/1982	Main	12TU-18TU	5.3
	recovery	19TU-23TU	15.7
		24TU-17TU	26.7
		17TU-24TU	63.0
10-11/2/1984	Main	10TU-22TU	5.3
	recovery	24TU-05TU	17.0
12-13/2/1984	Main	20TU-07TU	5.3
	recovery	Not calculated. There is additional energy input	

4. Conclusions

In this preliminary paper a few methods of ring current decay time computation were examined and compared with a new proposal. This new method comes from the need to eliminate the discrepancy between $\in$ and U_T values, whose computation gives unreasonable results from a physical point of view (energy dissipated, U_T, larger than injected energy, $\in$), for absolute values of the *Dst* geomagnetic index greater than 90 nT.

This new approach estimates the total magnetospheric energy dissipation parameter, U_T, with results perhaps better justified from the physical point of view; but now too small to be

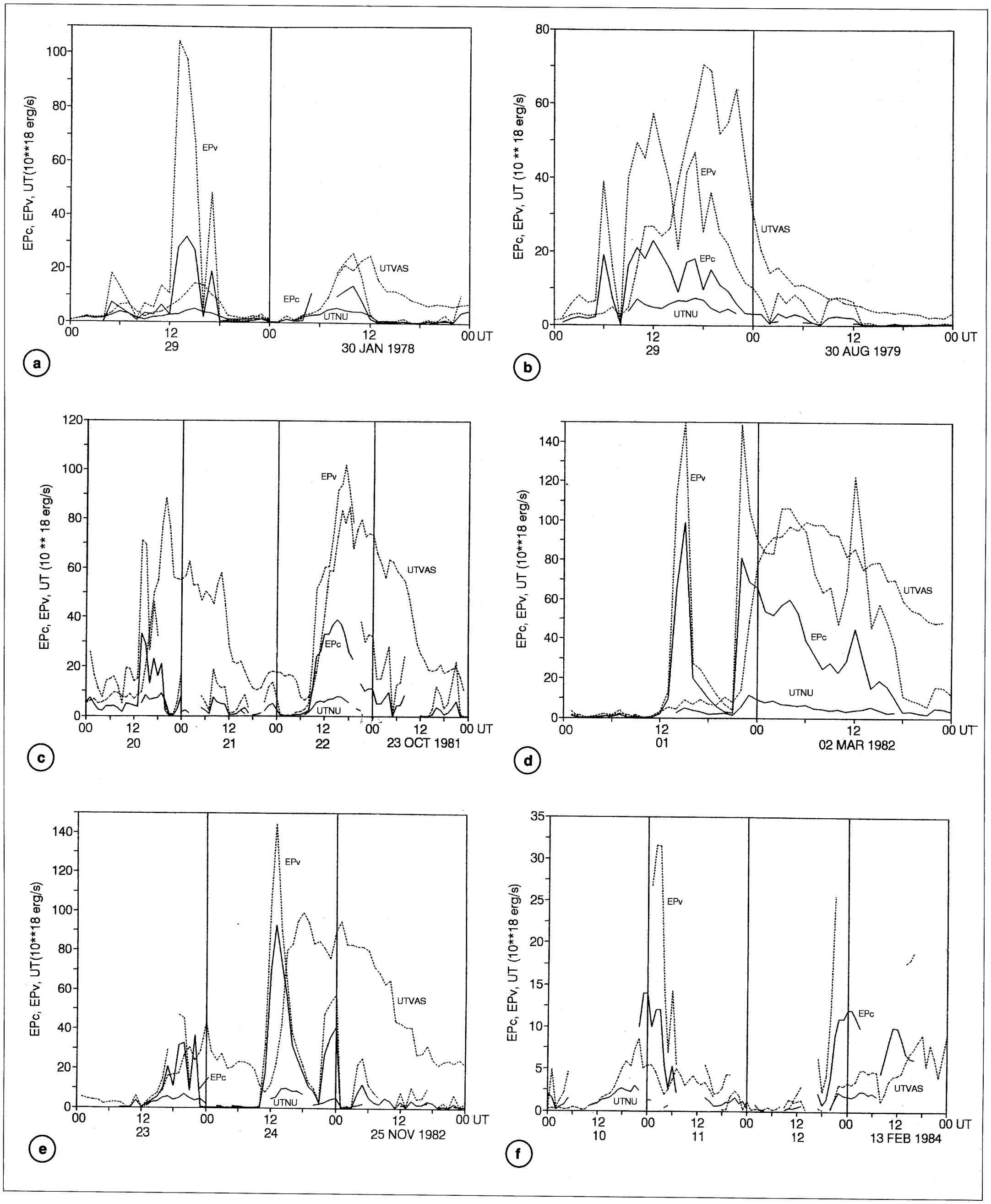

Fig. 3a-f. ε, with l_0 constant (EP_c); ε, with l_0 variable (EP_v) and the parameters U_{TVAS} and U_{TNU} for: a) January 29-30, 1978; b) August 29-30, 1979; c) October 20-23, 1981; d) March 1-2, 1982; e) November 23-26, 1982; f) February 10-13, 1984.

easily accepted. This result is obtained with what we think is a better estimation of the ring current decay time, τ_R.

To check the consistency of the function that allows us to calculate the energy injected into the magnetosphere, a variable l_0 was introduced in the computation of $\in$. This criterion leads to an increased $\in$, but still smaller than U_T, except U_{TNU}, for some of the disturbed periods.

It is difficult to arrive at an adequate conclusion that could be considered correct to explain the mutual interplay between the injected and the dissipated energies. No doubt that for U_{TNU}, consideration of the energy carried along by the plasmoids in the antisolar direction is lacking, but the answer is unattainable until adequate measurements are made at the magnetotail. On the other hand, rate of injected energy, which, up to now, is given by different expressions that only represent laws of proportionality with an unknown factor should be adjusted and included in any computation of the input energy.

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