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ON THE NON-ADIABATIC PARTICLE SCATTERING IN THE EARTH'S MAGNETOTAIL CURRENT SHEET

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Abstract—The empirical model of disturbed magnetosphere of Tsyganenko and Usmanov (1982) and the semi-empirical model of the storm-time magnetospheric configuration of Tsyganenko (1981) are used to find the critical energy for non-adiabatic particle scattering in the midnight sector. Computed values of E_{crit} vs L are compared with the appropriate experimental data of Imhof *et al.* (1977). It is found that none of the considered models is able to reproduce the observed steep decrease of E_{crit} with L. The steepest slope is given by the Tsyganenko model which includes a current sheet with the finite thickness. The current sheet thickness is a crucial parameter in the non-adiabatic scattering problem. In discussion we point to natural limitations of an empirical model as far as the current sheet thickness is to be determined. Imhof *et al.*'s data as well as some magnetic field data sets seem to indicate that magnetosphere models incorporating a thin current sheet and allowing for the thickness dependence on the geocentric distance would probably be closer to reality than the considered models, at least during higher levels of magnetic activity.

INTRODUCTION

Non-adiabatic motion in a weak and strongly curved magnetic field in the equatorial part of the night-side magnetosphere was invoked by many authors (e.g., Il'in and Kuznetsov, 1975; Imhof *et al.*, 1977, 1978, 1979; Pytte and West, 1978; Popielawska *et al.*, 1981; Tsyganenko, 1982; Sergeev and Tsyganenko, 1982; Sergeev *et al.*, 1983) to explain the strong (isotropic) precipitation of energetic protons and electrons ($E > 100$ keV) observed near the outer trapping boundary during magnetically quiet as well as disturbed periods.

The same mechanism was assumed to be responsible for isotropization of pitch angle distributions of energetic particles observed in the equatorial plane on $R > 7R_E$ in the midnight sector (West *et al.*, 1978a; Pytte and West, 1978).

Problem of non-adiabatic particle scattering in a static magnetic configuration is of dual significance. The first aspect of the problem concerns understanding the energetic particle behavior. Non-adiabatic scattering is one of several possible physical processes leading to the strong pitch angle diffusion. We want to emphasize that to prove the validity of this scattering mechanism in the context of a given set of particle data one cannot avoid using a model of the magnetospheric magnetic field. For example, a new empirical model of the magnetosphere of Tsyganenko and Usmanov (1982) has been used with success by Sergeev *et al.* (1983) to explain by non-adiabatic effects the *ESRO*-I energetic proton observations during magnetically quiet periods.

The second aspect concerns the possibility of diagnostics of distant magnetic fields. If the validity of non-adiabatic scattering could be a priori accepted (e.g., by elimination of other possible scattering mechanisms), the energetic particle measurements could serve as a source of information on the actual magnetic field configuration in the equatorial plane. This experimental tool has been used by West *et al.* (1978b) to infer the configuration of the magnetotail near midnight during quiet periods.

When one tries to analyse in above-described ways the disturbed periods data, serious difficulties are met. Neither the suitable disturbed magnetosphere models are developed to rely upon in the interpretation of energetic particle behavior nor can we reject so easily other isotropizing mechanisms (wave–particle interactions or/and injections from an isotropic source) to use particle data for magnetic field configuration probing.

In our paper we present the results of applying the empirical model of disturbed magnetosphere of Tsyganenko and Usmanov (1982) and the Tsyganenko semi-empirical model of storm-time magnetosphere configuration (1981) to interpret the data of Imhof *et al.* (1977) on energetic particle ($E_p = 40$–950 keV, $E_e = 0.16$–2.4 MeV) precipitation recorded near the local midnight during magnetic disturbances. This low altitude satellite data set has the best currently available time/spatial and energetic resolution and can be treated as an "ideal" data set to study the energetic particle behavior near the midnight trapping boundary.

Our purpose here is both to test on concrete magnetospheric models Imhof *et al.*'s hypothesis on the scattering mechanism and to check the validity of some model parameters by confronting the experimental findings with the model results on the position of isotropy boundary vs rigidity.

RESULTS

In the paper of Sergeev *et al.* (1983) the numerical tracing of particle trajectory has been performed in a magnetotail current sheet configuration and it has been shown that for particles with small equatorial pitch angles the non-adiabatic ($\mu \neq$ const) motion begins when the ratio, K, between the field line curvature radius at the equator, R_c, and the particle equatorial Larmor radius (for total velocity), ρ_L, is $K = R_c/\rho_L \approx 11$. The strong diffusion limit with isotropic fluxes across the completely filled-up loss cone is attained for $K \approx 6$.

The critical energy (or rigidity) is, by definition for use in our paper, a particle energy (or rigidity) corresponding to $K = 6$ on a given field line. As far as we refer to low-altitude satellite measurements, field lines will be labeled by an invariant latitude or L at the ionospheric heights.

So, the scattering capability of a given magnetic field configuration is defined by R_c and $|\mathbf{B}|$ at the equator. In the central part of the magnetotail, R_c depends mainly on the current sheet thickness, D, and the current intensity.

In the Tsyganenko model of the magnetosphere the current sheet thickness is finite and equal $D = 2R_E$. In the Strong Storm version of the model, the distribution of current intensity in the ring current/tail current system is such that the near-Earth depression is $\approx -100\gamma$ and the magnetic field of tail currents is $B \approx 27\gamma$ at $R = 25R_E$ (Sergeev and Tsyganenko, 1980). Additionally, in the Strong Storm model the magnetopause is compressed with subsolar distance $r_{ss} = 9.5R_E$.

The critical rigidity (P_{crit}) vs L in the midnight meridian according to Strong Storm model of Tsyganenko is plotted on Fig. 1. Computations were performed for $L = 4, 5, 6$ with the use of the magnetic field line tracing program of Tsyganenko (1979). Results are plotted for the tilt angle $\psi \approx 0°$. In the case of tilted dipole, the Tsyganenko model gives less elongated tail field lines, with larger R_c than for $\psi = 0°$. Analogical curves were obtained also for other versions of the Tsyganenko model (e.g., Strong Substorm, Post-Storm = recovery phase or Weak Substorm), but only the Strong Storm curve is plotted because the others have a less steep slope.

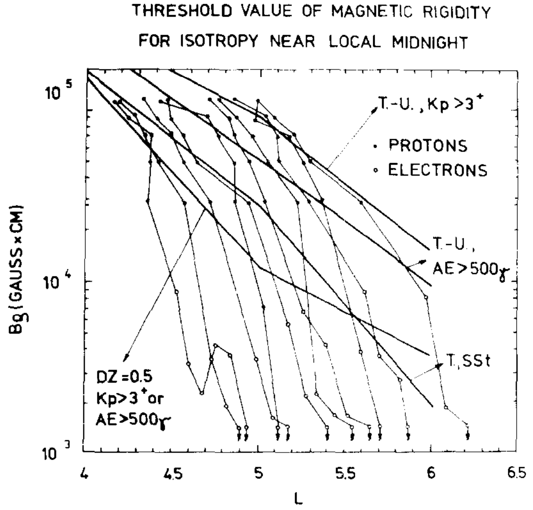

Fig. 1. The critical rigidity vs L in the 24:00 M.L.T. sector according to the Tsyganenko Strong Storm model (T., SSt), the Tsyganenko–Usmanov model for $K_p > 3^+$ (T.–U., $K_p > 3^+$), for $AE > 500\gamma$ (T.–U., $AE > 500\gamma$) and the modified version of T.–U. models with D set artificially as $0.5R_E$.

The experimental points represent the measured critical rigidity vs L taken from Fig. 3 of Imhof *et al.* (1977) paper.

In the empirical magnetosphere model of Tsyganenko and Usmanov, the current sheet is assumed to be of an infinite extent in the Z-direction with a characteristic scale half-thickness D. In this model D is a non-linear parameter obtained as a result of complex procedure of fitting to the original data set. We used two arrays of model parameters. One array has been obtained on the basis of magnetic field measurements during disturbed periods with $K_p > 3^+$. The second array is appropriate for periods with $AE > 500\gamma$ (Tsyganenko and Usmanov, 1984). The numerical value of D is $2.46R_E$ for $K_p > 3^+$ and $1.61R_E$ for $AE > 500\gamma$, the near-Earth depression is -47.0γ and -54.1γ, respectively. Subsolar distance in both cases is $r_{ss} \approx 10R_E$ and the inner edge of the plasma sheet is at $r_H \approx -4.0R_E$.

The critical rigidity dependence on L in the midnight sector for $K_p > 3^+$ and $AE > 500\gamma$ according to the Tsyganenko–Usmanov model of the magnetosphere is plotted in Fig. 1.

Our critical rigidity is equivalent to the observed "threshold value of magnetic rigidity for isotropy" analysed in the paper of Imhof *et al.* (1977). We have plotted our "model" P_{crit} vs L curves on the background of experimental curves taken from Fig. 3 of Imhof *et al.*'s paper. The points on Fig. 1 represent the measured "magnetic rigidity of electrons and protons above which isotropy occurred plotted vs L. The data points from a given satellite pass are connected by straight lines". The accurate date, time and K_p value for every 10 passes are given in the original paper. The data were obtained during weakly and moderately disturbed periods ($2^\circ \leqslant K_p \leqslant 5^+$, no strong magnetic storms actually going on, $D_{st} > -53\gamma$), the average K_p for five left curves was 5_-, for five right curves—3^+. Only for three right curves K_p was less than 3^+. It is important that the observed slopes of critical rigidity vs L do not show a significant variation with K_p, AE or any phase of a substorm (Imhof *et al.*, 1977, 1979).

As can be easily seen in Fig. 1, none of the considered models is able to reproduce the observed steep decrease of P_{crit} with L. Even if the model curves partially overlap the experimental curves, the computed dependence of P_{crit} on L in every case is generally much weaker than the observed one. The steepest (but still not sufficient) slope is given by the Tsyganenko model. This model gives an "averaged" configuration of the disturbed nightside magnetosphere, meaning that it seems to describe properly the subauroral field lines ($L \approx 4.5$) for higher levels of magnetic activity and auroral field lines ($L \approx 6$) for less disturbed periods.

The empirical model of Tsyganenko and Usmanov for $K_p > 3^+$ gives the slope of P_{crit} vs L close to an observed one only for higher rigidities during weak disturbances (compare with three left experimental curves). In the case of the T.–U. model for $AE > 500\gamma$, the slope is nearly the same as for $K_p > 3^+$, but all strong precipitation region is slightly shifted toward lower latitudes. The line of overlapping with an experimental curve is shortest in this case, and it exists also only in the high rigidity range.

Additionally, we see that the empirical models predict the position of isotropy boundary at higher latitudes than is systematically observed (even for high rigidities where the predicted slope is more or less correct).

DISCUSSION AND CONCLUSIONS

The discrepancy between the observed and modeled curves slope is so dramatic, especially in the lower two thirds of considered rigidity range, that the simple idea of non-adiabatic scattering in a static magnetic configuration at first sight appears to be wrong. But Imhof *et al.* (1977, 1979), Sergeev and Tsyganenko (1982) and Sergeev *et al.* (1983) give strong arguments of a phenomenological nature forcing the considered scattering mechanism as the one explaining in the simplest way the majority of observed features of energetic particles precipitation near the nightside trapping boundary not only during quiet but also during disturbed periods.

Here, we want to confine ourselves to consideration of a possible cause of the above-reported discrepancy still being in the frames of non-adiabatic scattering theory.

The only logical explanation within this theory is that the models give inadequate current intensity or/and current sheet thickness.

A model current intensity distribution can be relatively easily verified through comparison with the observed values of **B** in the tail lobes and the total field depression in the inner magnetosphere.

On the other hand, there are problems with determination of the second and most important parameter, the thickness of the current sheet. Direct measurements of current sheet thickness are difficult and observational results are contradictory (see below). As an effect, in the semi-empirical model of Tsyganenko the current sheet thickness is chosen somewhat arbitrarily. The relatively best results obtained above with the use of Tsyganenko's model are probably related to the finite thickness of the current sheet in opposition to an infinite extent of current sheet assumed in the T.–U. model.

In the model of Tsyganenko and Usmanov the obtained value of D is difficult to interpret due to inherent mixing of spatial and time variability in the original data set. In the real magnetosphere the current sheet during disturbed periods might be on average thinner than the model sheet but strongly variable in space and time (we do not consider here such specific effects like plasma sheet thinning during growth phase of a substorm).

To verify our hypothesis we have computed P_{crit} vs L according to the modified version of the Tsyganenko–Usmanov model. Namely, all parameters but D have not been changed in both "$K_p > 3^+$" and "$AE > 500\gamma$" models, and D has been taken as equal to $0.5R_E$. The results are plotted in Fig. 1. The curve of P_{crit} vs L is nearly the same for $K_p > 3^+$ and for $AE > 500\gamma$. As one can see in Fig. 1, such artificial current sheet thinning causes all the strong precipitation region to shift toward lower latitudes. For $L = 4$–5, the slope of the curve is steeper even than in the case of the Tsyganenko model, but for $L > 5$ the discrepancy with observations is more striking than for all other models. Of course, such an artificial "model" with only one parameter arbitrarily changed is highly noncoherent and we cannot expect more than only gross indications of an effect of current sheet thinning.

Another possible reason for difficulties in particle

Table 1.

Model	$L = 4$			$L = 5$			$L = 6$		
	R_{eq}	B_{eq}	R_c	R_{eq}	B_{eq}	R_c	R_{eq}	B_{eq}	R_c
Tsyganenko, Strong Storm	5.15	177	0.90	8.27	37	0.68	15.2	7.2	0.23
	$[R_E]$	$[\gamma]$	$[R_E]$						
Tsyganenko–Usmanov, $K_p > 3^+$	4.55	281	1.04	6.42	83	1.03	9.9	22	0.65
Tsyganenko–Usmanov, $AE > 500\gamma$	4.66	245	1.03	6.94	61	0.78	11.6	19	0.46
T.–U., $AE > 500, D = 0.5R_E$	4.85	201	0.74	8.04	39	0.27	14.0	20	0.19
T.–U., $K_p > 3^+, D = 0.5R_c$	4.83	205	0.74	7.91	41	0.28	14.0	19	0.18

data interpretation with the use of magnetosphere models is as follows: All considered models assume that the thickness of the current sheet is constant with the geocentric distance along the magnetotail. But, there are observations indicating that the current sheet is thicker closer to the Earth and gets thinner with geocentric distance (Speiser and Ness, 1967). These particular current sheet observations come from $R = 10\text{–}30R_E$.

The geocentric distances of the equatorial point of magnetic field lines with $L = 4, 5, 6$ (as well as $|\mathbf{B}|$ and R_c at the minimum $|\mathbf{B}|$ point) according to all employed magnetosphere models are given in Table 1. The strong precipitation region in the midnight meridian is connected with the inner part of the plasma sheet, $R \lesssim 15R_E$. So, allowing for D dependence on X within $R < 20R_E$ may improve the situation.

We feel that our results are in favor of a thin current sheet concept. The latest two satellite data from *ISEE*-1 and *ISEE*-2 seem to confirm our conclusion. Namely, McComas and Russell (1984) report the value $D = 0.9R_E$ at $R \cong 14R_E$ and nearly the same value at $R \cong 22R_E$. The points of observation were quite far from the Earth–Sun line (YGSE $\approx -5R_E$ and $-6R_E$), so in the midnight meridian one can expect even thinner current sheet at that time. The measurements were taken during different days, but any relation to actual magnetic activity is discussed in the paper of McComas and Russell. Current sheet velocity in normal direction has been measured in this two-satellite study and was $v_n \approx 30$ km s^{-1}.

More numerous single satellite estimations of current sheet thickness are dependent on proper assessment of sheet velocity. Speiser and Ness (1967) estimated the thickness as equal to 500–5000 km within $30R_E$ with v_n less than 10 km s^{-1}. Bowling and Wolf (1974) obtained the average value of $D = 2.3R_E$ at $X \approx -30R_E$ with a typical speed $v_n = 90$ km s^{-1}. An extended review of single-satellite results concerning the magnetotail current sheet is given in, e.g., Sergeev and Tsyganenko (1980). Recently, Xu *et al.* (1984) found the thickness $D \approx 3R_E$ at $R \approx 10R_E$ from *ISEE*-1 magnetic measurements, but no discussion on the actual v_n is included there.

As a final conclusion we want to stress that a more extended two-satellite study of current sheet configuration along the magnetotail is urgently needed. Without a realistic model of the magnetotail current sheet any definite statement on the validity of non-adiabatic scattering mechanism as a cause of strong precipitation of energetic particles during magnetic disturbances is actually possible.

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