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14. Abstract/Notes

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This work is being submitted to Planetary and Space Science.

ENERGY TRANSFER BY MAGNETOPAUSE RECONNECTION AND THE SUBSTORM PARAMETER ε

by

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ABSTRACT

An expression for the magnetopause reconnection power based on the dawn-dusk component of the reconnection electric field, that reduces to the substorm parameter ε for the limit that involves equal geomagnetic (B_G) and magnetosheath (B_M) magnetic field amplitudes at the magnetopause, is contrasted with the expression based on the whole reconnection electric field vector (Gonzalez, 1973). The correlation examples of this report show that this (more general) expression for the reconnection power seems to correlate with the empirical dissipation parameter U_T (Akasofu, 1981), with slightly better correlation coefficients than those obtained from similar correlations between the parameter ε and U_T. Thus, these (better) correlations show up for the more familiar values of the ratio $B_G/B_M > 1$. Nevertheless, the (expected) relatively small difference that seems to exist between these correlation coefficients suggests that, for practical purposes, the parameter ε could be used as well (instead of the more general expression) in similar correlation studies due to its simpler format. On the other hand, studies that refer mainly to the difference in the magnitudes of ε and of the more general expression are expected to give results with less negligible differences.

INTRODUCTION

The rate of energy transfer at the front-side magnetopause, due to a large scale reconnection process for an arbitrary interplanetary magnetic field, was argued (Gonzalez and Mozer, 1974) to be equal to the Joule heating rate of the reconnection-electric field and the magnetopause current. Since these parameters are represented by parallel vectors, the region involved in reconnection is dissipative. Although not much particle heating was observed at the front-side magnetopause (Heikkila, 1978), considerable evidence of particle acceleration has been already reported (Sonnerup et al., 1981). Furthermore, computer simulations have shown that most of the energy input is actually involved in acceleration (Sato and Hayashi, 1979).

The work by Perreault and Akasofu (1978) and later ones (Akasofu, 1981) have shown that this power input to the magnetosphere is well described by the substorm parameter ε. A r ationship between the reconnection power and the substorm parameter ε was presented by Gonzalez and Gonzalez (1981), who claimed that the reconnection power P_K (definition given below), based only on the dawn-dusk component of the reconnection electric field, reduces to ε for the limiting case that involves geomagnetic (B_G) and magnetosheath (B_M) magnetic fields with equal amplitudes. Thus, one can argue that the expression P_K extends the applicability of the parameter ε to the more familiar cases with $B_G > B_M$. This expression is also contrasted below with that for P_W (definition given below), based on the whole reconnection electric field vector (Gonzalez, 1973).

In this report we present correlation examples between the expression P_K, which is more general than ε, and the empirical magnetospheric-dissipation-parameter U_T (Akasofu, 1981) in order to compare their correlation coefficients with those obtained from similar correlations between ε and U_T, as well as between P_W and U_T. Furthermore, an example of a comparison between the magnitudes of P_K and ε is also given.

ELECTRIC POWER DUE TO RECONNECTION

The expression for the total electric power input to the magnetosphere due to reconnection at the dayside magnetopause is (Gonzalez, 1973):

$$P_W(S,\theta) = \frac{1}{\pi} VR^2 B_T F(S,\theta) |\underline{B}_G - \underline{B}_M|$$

$$= \frac{1}{\pi} VR^2 B_T B_M W(S,\theta), \qquad (1)$$

where, V is the solar wind speed; R,an scale length of the order of the dayside magnetopause radius; B_T,the transverse component of the interplanetary magnetic field: $B_T \equiv (B_Y^2 + B_Z^2)^{1/2}$ in solar-magnetospheric coordinates; $\underline{B}_M$,the magnetosheath field at the magnetopause; $\underline{B}_G$,the geomagnetic field at the magnetopause; and F(S,Θ), a function that describes the projection of the magnetosheath electric field to the reconnection line ($\overline{LL}$ in Figure 1),given by Gonzalez and Gonzalez (1981) as:

$$F(S,\theta) = (1-S\cos\theta) / (1+S^2 - 2S\cos\theta)^{1/2}, \qquad (2)$$

with Θ being the angle between $\underline{B}_G$ and $\underline{B}_M$ at the matnetopause-nose (Figure 1),and $S \equiv |\underline{B}_G| / |\underline{B}_M| \geq 1$. From (1) and (2), $W(S,\theta) = (1-S\cos\theta)$. The function W(S,Θ) is plotted in Figure 2 for S=1, S=2 and S=3.

For the limiting case S=1, the expression (1) for the power reduces to:

$$P_W(1,\theta) = \frac{2}{\pi} VR^2 B_T B_M \sin^2\left(\frac{\theta}{2}\right)$$

$$\simeq VR^2 B^2 \sin^2\left(\frac{\theta}{2}\right), \qquad (1a)$$

where B is the interplanetary magnetic field, since, for typical values of B, B_T and B_M, $B^2 \approx (2/\pi) B_T B_M$ (Gonzalez and Gonzalez, 1981).

If we compare the expression for $P_W(1,\Theta)$ to that for the substorm parameter (Akasofu, 1981), namely:

$$\varepsilon = V\ell_o^2 B^2 \sin^4\left(\frac{\Theta}{2}\right), \tag{3}$$

with R identified as ℓ_o, we notice their different angular dependences.

An expression for the electric power transmitted at the magnetopause, based only on the dawn-dusk component (line $\overline{DD}$ in Figure 1) of the reconnection electric field and magnetopause current vectors, rather than on the whole vectors, as in expression (1), was given by Gonzalez and Gonzalez (1981) as:

$$P_K(S,\Theta) = \frac{1}{\pi} VR^2 B_T B_M K(S,\Theta), \tag{4}$$

with $K(S,\Theta) = (1-S\cos\Theta)(S-\cos\Theta)^2 / (1-S^2-2S\cos\Theta)$. The function $K(S,\Theta)$ is plotted also in Figure 2 for S=1, S=2, and S=3.

For the limiting case S=1, and using also $B^2 \approx (2/\pi)B_T B_M$, the expression for $P_K(S,\Theta)$ reduces to:

$$P_K(1,\Theta) = \frac{2}{\pi} VR^2 B_T B_M \sin^4\left(\frac{\Theta}{2}\right)$$

$$\approx VR^2 B^2 \sin^4\left(\frac{\Theta}{2}\right)$$

$$= \varepsilon, \text{ for } R \equiv \ell_o. \tag{4a}$$

Thus, the substorm parameter ε seems to be related to the reconnection power transmitted at the magnetopause only by the dawn-dusk component of the reconnection electric field. This relationship can be interpreted as due to the effective transmission of the dawn-dusk component of the reconnection electric field by the geomagnetic field, which itself extends mainly transverse to the dawn-dusk direction. In this way, one expects that the component of the reconnection electric field parallel to the geomagnetic field affects only locally the dayside magnetopause, not being transmitted downstream, whereas the transmitted dawn-dusk component is argued to lead to magnetospheric convection and related dissipation processes.

Figure 2 shows that the functions $W(S,\Theta)$ and $K(S,\Theta)$ differ mainly for small values of S, with the maximum difference occurring for S=1. As S increases, the difference becomes less noticeable, since in the limit of large S, $K(S,\Theta) \rightarrow (1-S \cos\Theta) = W(S,\Theta)$. Physically, this limit refers to cases when B_G is sufficiently larger than B_M, for which the reconnection line does not "tilt" much (Gonzalez and Mozer, 1974) and, therefore, the dawn-dusk component of the reconnection electric field does not differ much from the total field.

The expression (4a) for $P_K(1,\Theta)$, equivalent to the substorm parameter ε, refers only to the limiting case of S=1, namely $B_G = B_M$. Since this case is only a limit (vacuum reconnection?) according to pressure balance considerations at the magnetopause (see below), we argue in this report that the more general expression for the power $P_K(S,\Theta)$, given in (4), should describe better the power input to the magnetosphere, for some value of S>1. In fact, the examples presented below indicate that the empirical function U_T (Akasofu, 1981), related to the main dissipation processes during substorms, seems to correlate with $P_K(S>1,\Theta)$ better than with ε.

EXAMPLES OF CORRELATIONS BETWEEN $P_K (S,\Theta)$ AND THE EMPIRICAL DISSIPATION FUNCTION U_T

The empirical function U_T discussed by Akasofu (1981) was defined as the total energy consumption rate of the magnetosphere during substorms and storms. U_T was given by the sum of the auroral particle energy flux, the Joule heat production rate in the ionosphere, and by the ring current energy injection rate.

Among the examples of correlations between ε and U_T, presented by Akasofu (1981), we selected for our study those cases with apparently reacher structure and with larger extension in time. These cases belong to the time intervals shown in Table 1. In this Table we show the correlation coefficients between $P_K(S,\Theta)$ and U_T for S=1, S=1.2, S=1.5, S=2, S=3, and S=4. The values of $P_K(S,\Theta)$ were computed using the expression (4) and the aproximation $B^2 \approx (2/\pi)B_T B_M$. Values for the solar wind speed and for the interplanetary magnetic field were obtained from the Interplanetary Medium Data Book (King, 1977). The values of U_T were obtained from the Akasofu's (1981) review paper. The encircled numbers are the best correlation coefficients for each case. The numbers in italics are the best correlation coefficients between $P_W(S,\Theta)$ and U_T for each case. The values of $P_W(S,\Theta)$ were computed using the expression (1) and the approximation $B^2 \approx (2/\pi)B_T B_M$. Furthermore, in Table 1 the correlation coefficients between B_Z and U_T as well as between VB_Z and U_T are also shown for each case.

Thus, from the correlation coefficients shown in Table 1, one infers that: a) in all cases, except in one (discussed below), the functions $P_K(S,\Theta)$ and U_T correlate, for some value of $1 < S \leq 3$, with a better correlation coefficient than that found from the correlation of ε and U_T for the same case: b) in all cases, the best correlation coefficient between $P_W(S,\Theta)$ and U_T, shown in italics, is smaller than the corresponding best coefficient (encircled numbers) between $P_K(S,\Theta)$ and U_T; and c) in all cases, the correlation coefficients between B_Z and U_T as well as between VB_Z and U_T are among the smallest ones found for each time interval. The column with best time lag in Table 1 shows the time lag (in hours) for the encircled coefficients. Since we have used hourly averaged values for the parameters involved in the correlation, information on time lags with accuracy better than one hour could not have been obtained.

DISCUSSION AND CONCLUSIONS

From the angular dependences of the functions $K(S,\Theta)$ and $W(S,\Theta)$, shown in Figure 2, which look proportional to each other within the whole range of considered values of S, one expects that correlations between these functions and any other related function, like U_T, will give correlation coefficients within a-not too-large interval of values, as found in our correlations of Table 1. Thus, although Table 1 suggests that the function $P_K(S,\Theta)$ correlates with U_T with better correlation coefficients, as compared to those obtained from similar correlations between ε and U_T and between $P_W(S,\Theta)$ and U_T, these differences are only of the order of a few percent. Consequently, since the functional format of the parameter ε is simpler than that of the function $P_K(S,\Theta)$, the results shown in Table 1 suggest that, for practical purposes and for correlation studies similar to ours, one can use the parameter ε instead of the function $P_K(S,\Theta)$ with negligible errors.

On the other hand, since the magnitudes of the functions $P_K(S>1,\Theta)$ are considerable larger than the magnitude of ε, due to their respective boundings $1 \leq K(S>1,\Theta) \leq S+1$ and $\sin^4 \Theta/2 \leq 1$ (Gonzalez and Gonzalez, 1981) in equations (4) and (4a), as shown also in Figure 2, one expects that studies which refer mainly to the difference of these magnitudes will show results that differ in more than just a few percent. We discuss at the end of this section one example of this type of study.

Although it remains to be shown that the (slightly) better correlations found between $P_K(S>1,\Theta)$ and U_T, as compared to that between ε and U_T, hold statistically for a larger number of cases, the evidence found, in six out of the seven cases studied in this report, might represent a good starting point for a future statistical study.

The physical meaning of the better correlations that seem to exist between $P_K(S>1,\Theta)$ and U_T, as compared to that between ε and U_T, and, especially, of the more notable difference that exists among the magnitudes of $P_K(S>1,\varepsilon)$ and ε, can be interpreted as follows. As mentioned above, the cases with S>1 imply $B_G>B_M$. On the order hand, S=1 implies $B_G = B_M$. Most of the time, plasma measurements at the magnetosheath -magnetopause interface (see i.e. Sonnerup et al., 1981) indicate the presence of a substantial magnetosheath particle pressure (p_M) and very little magnetospheric particle pressure (p_G), such that $p_M + B_M^2/8\pi > B_M^2/8\pi$ and $p_G + B_G^2/8\pi \sim B_G^2/8\pi$. Furthermore, the most common pressure balance observed at the magnetopause is $p_M + B_M^2/8\pi \sim B_G^2/8\pi$, with $B_G>B_M$. Therefore, one expects that the most probable result in our correlation study of Table 1 should favour $B_G>B_M$, namely S>1, rather than $B_G>B_M$, namely S=1. Nevertheless, one case in Table 1 shows a better correlation for S=1. This case is discussed below in terms of the average-low-solar wind kinetic energy flux present during the related time interval.

With respect to the better correlations that seem to exist between $P_K(S,\Theta)$ and U_T, as compared to the corresponding ones between $P_W(S,\Theta)$ and U_T, they suggest that the function $P_K(S,\Theta)$ represents better the process of energy transfer to the magnetosphere, due to magnetopause reconnection, as compared to the function $P_W(S,\Theta)$. However, as mentioned above, this difference decreases with increasing S, since the functions $W(S,\Theta)$ and $K(S,\Theta)$ are less different from each other when S increases, as observed in Figure 2. Thus, since the function $P_W(S,\Theta)$ refers to the reconnection power based on the total reconnection electric field, transmitted along the reconnection line $\overline{LL}$ of Figure 1, whereas the function $P_K(S,\Theta)$ is based only on the dawn-dusk component of the reconnection electric field (line $\overline{DD}$ in Figure 1), the process of energy transfer seems to be better related to the dawn-dusk component of the reconnection electric field, as claimed by Gonzalez and Gonzalez (1981).

In Table 1 we also show the average solar wind-kinetic energy flux (in units of 10^{20} ergs/sec) and a comparison between the average magnitudes of ε and U_T for the time intervals of our present study, as inferred from the review work of Akasofu (1981). One notes that the case with the lowest average-solar wind-kinetic energy flux corresponds to the case with S=1, for the best correlation coefficient between $P_K(S,\Theta)$ and U_T. In this case, the small solar wind kinetic energy flux apparently resulted also in a small magnetosheath particle pressure at the magnetopause, with $B_M \sim B_G$. On the other hand, the cases with the largest average-solar wind-kinetic energy flux values correspond to the cases with the largest values of S for the best correlation coefficient between $P_K(S,\Theta)$ and U_T.

Finally, with respect to the more notable difference between the magnitudes of $P_K(S>1,\Theta)$ and ε, the following comparison among average values of these functions and those of U_T gives an idea of the sort of consequences expected from this difference. The last column in Table 1 gives a comparison between the average amplitudes of ε and U_T, namely $<\varepsilon>$ and $<U_T>$, for each case of our study, as inferred from the plots of ε and U_T given by Akasofu (1981). This comparison suggests that, in general $<\varepsilon> \sim <U_T>$, with some indication of $<\varepsilon>$ being slightly bigger than $<U_T>$, when <K.E.> increases. Thus, as mentioned above, since the magnitude of the functions $P_K(S>1,\Theta)$ are expected to be larger than the corresponding magnitude of ε, for each case, the difference between $<P_K(S>1,\Theta)>$ and $<U_T>$ is expected to increase even more with <K.E.>. This difference, as well as that between $<\varepsilon>$ and $<U_T>$, could be related to the fact that, in our present study, we have used a fixed value for the reconnection area at the magnetopause, namely $R^2 = \ell_0^2$,with ℓ_0=7 earth radii (Akasofu, 1981), for all cases. This area should reduce in size when <K.E.> is large, as usually expected by the increased magnetospheric compression. Thus, a reduced value of R^2 would improve, at least in part, the comparison between $<P_K(S>1,\Theta)>$ and $<U_T>$. Furthermore, when <K.E.> is large, the empirical parameter U_T may include new terms, in addition to those given by Akasofu (1981), in order to take also into account, for instance, the expected intensifications of current systems at the magnetopause. Thus, the difference between $<(P_K(S>1,\Theta)>$ and $<U_T>$ would be further reduced. On the other hand, these expected reductions, when applied to ε, would result in the not desirable predicitions of $<\varepsilon> < <U_T>$, due to the marginal situation of $<\varepsilon> \sim <U_T>$ that already seems to exist even for cases with large values of <K.E.>.

Therefore, both the correlation study and the gross comparison of magnitudes, presented in this report, suggest a future closer inspection of the differences found between the expression $P_K(S,\Theta)$ and the parameter ϵ for a larger number of cases.

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TABLE 1 - Correlation coefficients between the computed power $P_K(S,\Theta)$ and the empirical parameter U_T for the cases studied, with the encircled numbers being the best coefficients among S=1 (ε) and S=4. The numbers in italic are the best correlation coefficients between the computed power $P_W(S,\Theta)$ and U_T. The correlation coefficients between B_Z and U_T, as well as between VB_Z and U_T, are also shown. The column with best time lag (in hours) refer to the encircled coefficients. The table also shows the average solar wind-kinetic energy flux (in units 10^{20} ergs/sec) and a comparison between the average magnitudes of ε and U_T, taken from Akasofu (1981), for each time interval.

TABLE 1

	S=1 (ε)	S=1.25	S=1.5	S=2	S=3	S=4	B_Z	VB_Z	BEST TIME LAG	AVERAGE SOLAR WIND-KINETIC ENERGY	<ε> COMPARED TO <U_T>
FEB 7-8 (1967)	76.5	78.3	*75.4* 77.1	76.6	76.4	76.3	69.1	65.0	0	0.9	<ε> ≳ <U_T>
FEB 10-11 (1968)	87.6	*87.1* 89.4	88.5	87.8	87.5	87.2	70.1	7[illegible].6	0	0.5	-
DEC 30 (1967) -JAN 2 (1968)	*71.5* 73.3	72.8	71.9	71.3	70.6	70.5	71.6	71.2	1	0.3	-
MAR 8-9 (1970)	78.8	79.1	79.2	*79.2* 79.5	80.3	80.1	55.0	51.7	0	1.4	>
MAR 7 (1972)	86.5	86.8	*86.0* 87.4	88.4	88.0	87.7	81.1	80.8	0	2.0	≳
FEB 20-23 (1973)	84.4	86.3	*83.1* 86.7	86.2	85.8	85.5	52.3	49.6	1	1.0	≲
MAR 31 - ABR 3 (1973)	88.3	*86.7* 88.7	89.2	88.5	88.1	87.9	70.1	71.5	1	0.9	≳

FIGURE CAPTIONS

Fig. 1 - View from the Sun of the dayside magnetopause. $\underline{B}_G$ is the geomagnetic field at the magnetopause-rose; $\underline{B}_M$ and $\underline{E}_M$ are the magnetosheath-magnetic and electric fields at the magnetopause-nose; $\overline{LL}$ is the reconnection line making an angle β with $\underline{B}_G$; $\overline{DD}$ is the dawn-dusk line; Θ is the angle between $\underline{B}_G$ and $\underline{B}_M$.

Fig. 2 - The functions $W(S,\Theta)$ and $K(S,\Theta)$ for the values of S=1, S=2 and S=3.

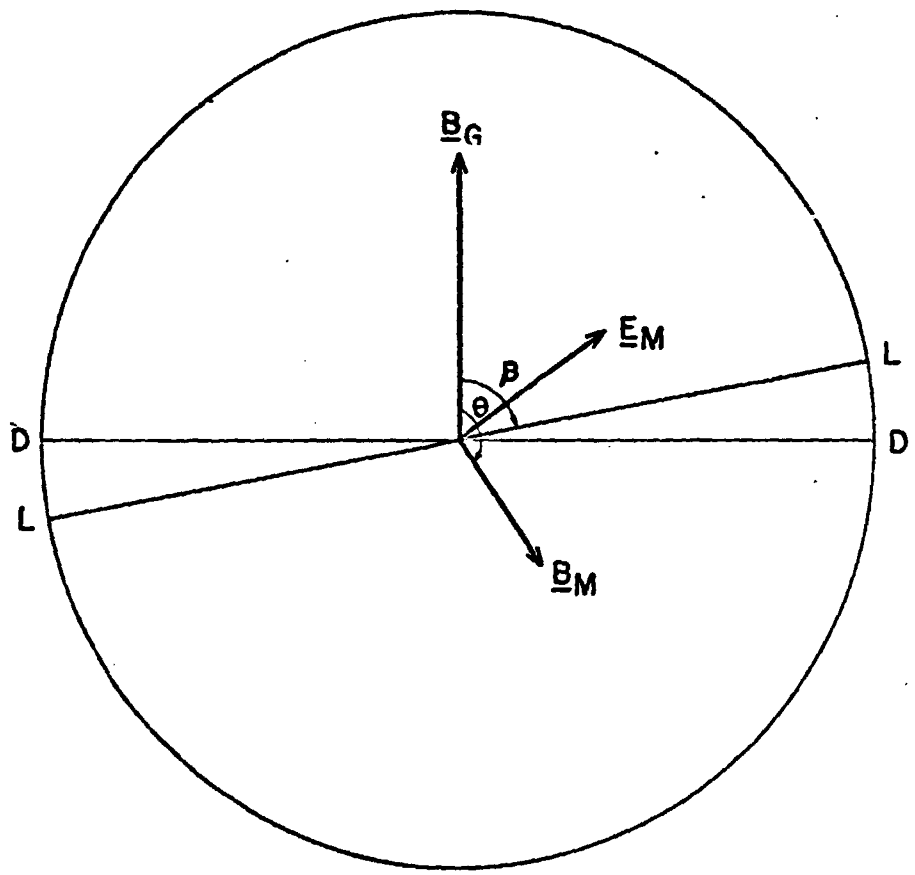

Fig. 1

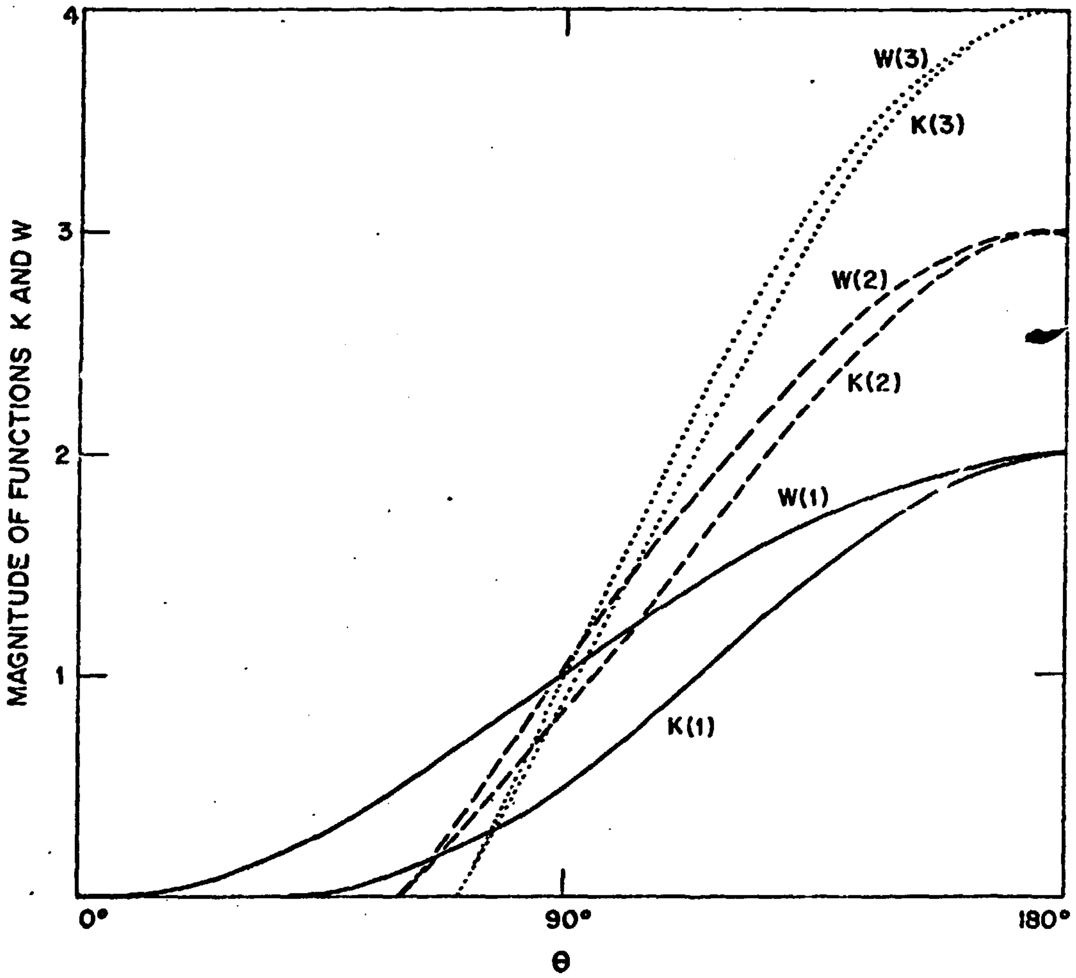

Fig. 2