CHARACTERISTICS OF THE ASSOCIATION BETWEEN AN SC AND A SUBSTORM ONSET

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Abstract: The time lag and other characteristics between an SC and an onset of a substorm were investigated. A substorm onset was defined by an onset of a Pi 2 magnetic pulsation observed at three mid-latitude observatories. A clear occurrence peak of the substorm onsets appeared statistically around 10 min after the onset time of the SC's, but it did not appear for the negative SI (SI^-) events. A typical example showed that this time lag was consistent with the idea of the substorm triggering in the near earth magnetotail. The necessity of the preconditions for the SC-triggering was not so clear, but the SC-amplitude dependence of the triggering probability was clear. These results strongly suggest the reality of the triggering of a substorm by a sudden compression of the deep magnetosphere.

1. Introduction

The relation between an interplanetary shock wave and a substorm onset has been investigated by many researchers (SCHIELDGE and SISCOE, 1970; KAWASAKI *et al.*, 1971; BURCH, 1972; IIJIMA, 1973; ONDOH, 1973; KOKUBUN *et al.*, 1977; AKASOFU and CHAO, 1980; HIRASAWA, 1981). Methods used and main results in these papers are summarized in Table 1. We can see in this table that the results are very different from each other and this difference may arise from the difference of the definition of the substorm onset. From the statistical analysis between the substorm onsets and the arrival of the interplanetary shock waves (*i. e.* the appearances of the sudden commencement, SC), several papers conclude the existence of the SC-triggering of the substorms. However, it is not so definite whether the direct effect of the shock wave, *i. e.* the sudden compression of the magnetosphere by the increased solar wind kinetic pressure, excites a substorm or not. On the other hand, AKASOFU and CHAO (1980) claimed that the increased energy coupling between the solar wind and the magnetosphere behind the shock wave by the sudden change of the interplanetary magnetic field (IMF) was the cause of a substorm onset. Their conclusion implies that a substorm after an SC is not the 'triggered' one, because the term "SC-triggering of a substorm" implies that the principal role of a shock wave is to start the substorm and not to supply the substorm energy to the magnetosphere. To clarify the roles of a shock wave for so-called 'SC-

Table 1. List of the definitions of a substorm onset and the main results in the previous works.

Authors	Difinition	Results
HEPPNER (1955)		SC—negative bay correspondence
SCHIELDGE and SISCOE (1970)	Negative bay $\|\Delta H\|>200$ nT (within 5 min)	Coincidence—19% SC-amplitude—correlate SI^--negative bay correspondence Precondition—necessary
KAWASAKI *et al.* (1971)	Negative bay $\|\Delta H\|>50$ nT	Coincidence—49% (IGY) 4% (IQSY) IMF-*Bz*—no correlation
BURCH (1972)	Negative bay	Coincidence—28% IMF-*Bz* (30 min before SC)—correlation
IIJIMA (1973)	?	SC-amplitude—no correlation IMF-*Bz*—correlate AE (before SC)—correlation
ONDOH (1973)	Negative bay $\|\Delta H\|>100$ nT	Coincidence—49% ΔH disturbances before 30 min —correlation
KOKUBUN *et al.* (1977)	Negative bay $\|\Delta AL\|>150$ nT (within 15 min)	Coincidence—43% Precondition—necessary (AE activity, IMF-*Bz*)
AKASOFU and CHAO (1980)	Increase of *AE* index	No "triggering" Sudden increase of solar wind—magnetosphere energy coupling
HIRASAWA (1981)	Aurora-graph	Coincidence—80%

triggered substorm' is very important because the onset mechanism is an essential point in the substorm dynamics, which is not yet resolved.

One approach to this problem is to examine in detail the time relations between a shock arrival and an onset of the substorm. That is, the following points are critical to clarify the essential role of the shock wave to the onset after the SC.

(1) The time lag between an SC and an onset of a substorm.

(2) The time lag between a southward turning of the IMF and a substorm onset.

(3) The propagation of the shock effects in the magnetosphere, that is, the time lag between an SC and the appearance of the shock effects in the magnetotail.

On the second point, it is known that it takes about one hour for the substorm onset after the southward turning (CAAN *et al.*, 1977; IYEMORI, 1980). It has been believed by many substorm researchers that the substorms start in the plasma sheet at $X\sim-20$ R_E (earth radius). If the role of a shock wave for the SC-triggering is to compress the plasma sheet of this region, it should take about several minutes for the substorm onset after the SC, because it takes about several minutes for the signal of the shock effect to propagate to the plasma sheet and that of the substorm onset to the ground backward. Comparing the points (1), (2) and (3), we can check the above interpretation of the SC-triggered substorms.

In this paper, the point (1) is examined statistically using the Pi 2 magnetic pulsations as an indicator of the substorm onset (SAITO *et al.*, 1976). The point (3) is examined for a typical example. The necessity of the preconditions is also examined. The results suggest the reality of the SC-triggering of a substorm by a sudden compression of the magnetosphere.

2. Method of Analysis

A typical event during the IMS period and 100-SC events during 1967–1969 which are taken from the list of SC by MAYAUD (1973) are analyzed in this paper. To determine the time lag between an SC and a substorm onset with accuracy of one minute, the onset time of a substorm is defined by an onset of a Pi 2 micropulsation on the rapid-run magnetograms from three mid-latitude observatories, *i. e.* Fredericksburg (FRD), Wingst (WNG) and Memambetsu (MMB).

Here, we define a Pi 2 micropulsation by an irregular magnetic pulsation of a major period of several tens of second and of a short duration ($\sim$10 min). The onset time and the amplitude of an SC are also taken from the list by MAYAUD (1973). Hence the time lag is defined by the time difference between an onset of SC and the earliest onset of Pi2 pulsations after the SC.

To check the occurrence probability of substorms which are not related to the SC's, the onsets of the substorms before the SC's are also examined and the time difference between the last onset of a Pi 2 and an SC was calculated, which is, by definition, a negative value. The Pi 2 pulsations were sought on the rapid-run magnetograms in the time range of $\pm$20 min around an onset of SC. When more than two onsets of the Pi 2 were seen, an onset closer to the SC was adopted.

To examine the propagation of the shock effects in the magnetosphere, the magnetic field data from NASA Explorer 33 and 34 satellites were used with a time resolution of 20 s.

3. Time Lag of a Substorm Onset from an SC Onset

Figure 1a shows a typical example of the magnetic field disturbances of the horizontal component (H) from 12-AE stations (see KAMEI and MAEDA, 1981) and a rapid-run magnetogram near the SC on March 8, 1978. According to NASA IMP-J magnetometer, the IMF was northward before and after the shock arrival for more than 15 min. Almost all the H-traces start to increase at 1439 UT corresponding to a formation of single vortex current system of the main impulse of the SC (IYEMORI and ARAKI, 1982), and do not reveal the characteristics of a substorm. About 10 min later, a Pi 2 magnetic pulsation, an indicator of an onset of a substorm is seen on the rapid-run magnetograms from Memambetsu. To show the essential change of the disturbance fields before and after the substorm onset (1449 UT), the equivalent current vectors at 1444 UT and 1500 UT are depicted in Figs. 1b and 1c, respectively. Clearly, the current system in Fig. 1b differs from the substorm current system (Fig. 1c) which has similar characteristics as the eastward and westward electrojet around the Harang discontinuity region. Hence we can also confirm the existance of the time lag between the SC and the following substorm onset from an analysis of the current pattern.

Figure 2a shows a statistical distribution of the time lag between the onset of an SC and that of a substorm. The negative time lag arises from a substorm occurrence before an SC, that is, from the substorm onset which is unrelated to the interplanetary shock wave. We can see the clear peak of the distribution around 10 min after the onset of the SC (*i. e.* the origin of the time axis). That is, there exists the time lag of about 10 min between the onset of an SC and that of a substorm, but this time lag is

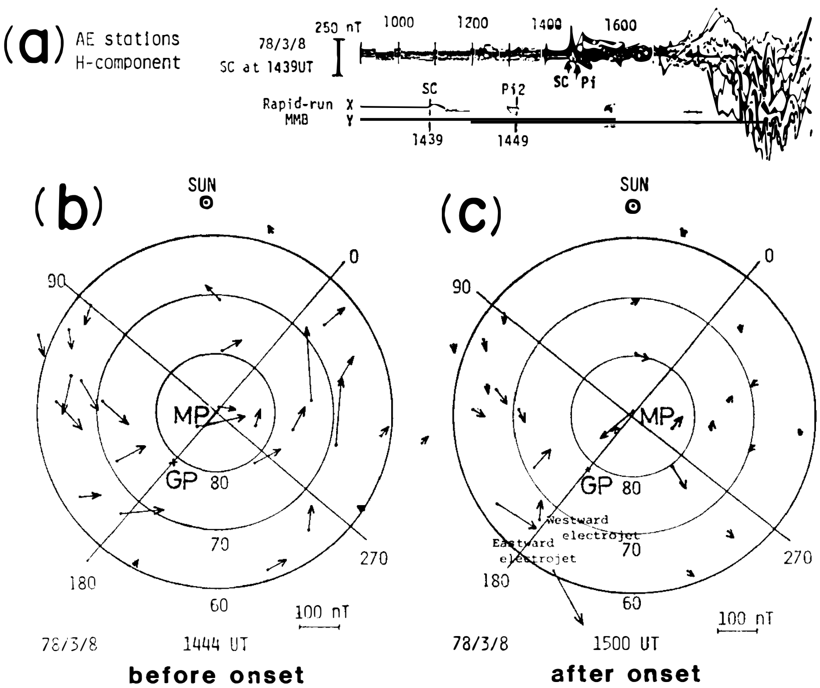

Fig. 1. An example of the SC-triggered substorms; (a) The superposed H-traces of the magnetograms from the twelve auroral zone observatories. Rapid-run magnetograms from Memambetsu (MMB) are shown to indicate the onset of a Pi 2 pulsation. (b) Equivalent current vectors at the main impulse of the SC, which shows a single vortex structure. (c) The current vectors after the substorm onset. The current distribution around the Harang discontinuity is similar to that of the auroral electrojet except for the magnitude.

too short to regard that the event is caused by the IMF, because the time lag between a southward turning of the IMF and a following substorm onset is about one hour. Hence it can be said that an SC-triggered substorm is associated with the SC directly.

Next problem is to check the idea that the sudden compression of the magnetosphere around $X=-20\ R_E$ by the shock wave triggers a substorm. Firstly, we confirm that the compression, not the expansion, of the magnetosphere acts an important role to trigger a substorm. To clarify this point, the time lag between a substorm onset and an SI^- event, which corresponds to the sudden decrease of the solar wind kinetic pressure and leads to the sudden inflation of the magnetosphere, is examined. Figure 2b shows a distribution of the time lag of the SI^- events during 1964–1975 which were identified as SI^- at Kakioka (mag. lat.$=26.5$, long.$=207.6$). In this case, the peak after the SC does not appear, and the occurrence rate of the substorm before the SI^- is rather higher than that after the SI^-. The higher occurrence rate before the SI^- may come from the disturbed solar wind condition behind the preceding shock wave, because an SI^- often appears as an SI^+–SI^- pair (*e. g.* SONETT and COLBURN, 1965) after the SI^- (or SC). The fact that a peak of the distribution appears after the SC and does not appear after SI^- suggests the importance of a compression of the magnetosphere to trigger a substorm rather than an expansion of the magnetosphere by a sudden decrease of the solar wind kinetic pressure.

Second, we must examine the propagation speed of the shock effect in the magnetosphere and confirm that the time lag of about 10 min does not conflict with the

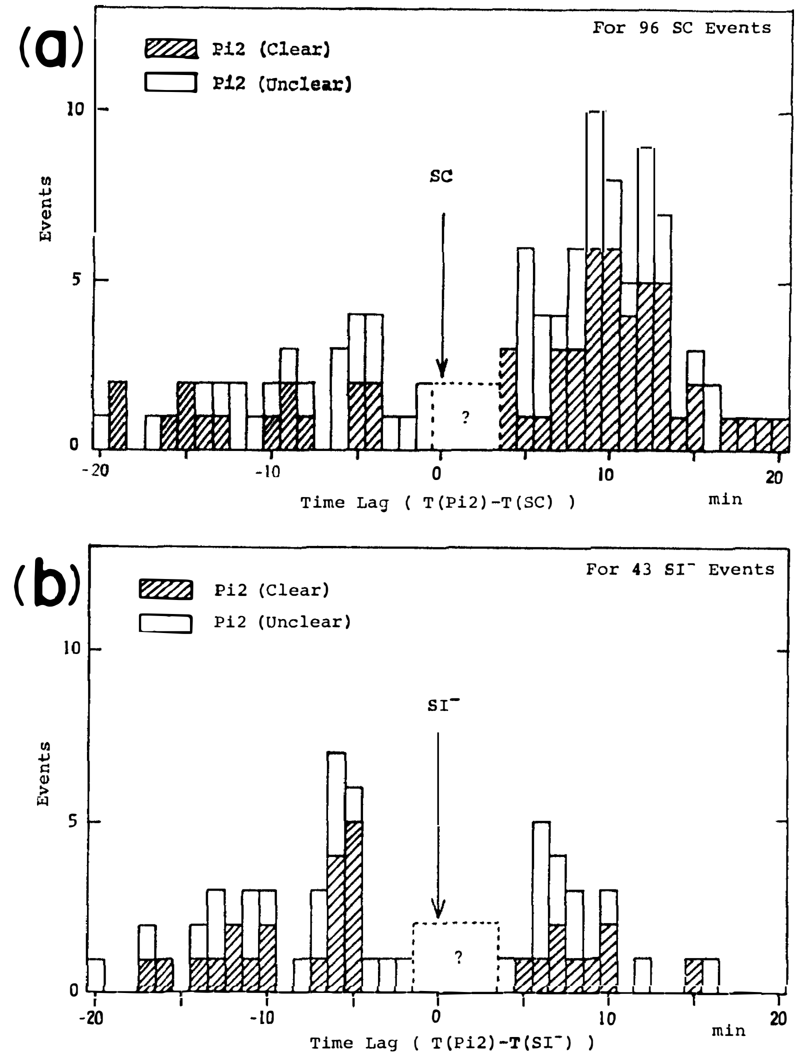

Fig. 2. Distribution of the time lag between the SC's and the substorm onsets (a) and between the SI⁻'s and the substorm onsets (b). The short time interval around the origin of the time axis (dotted line) was not examined because of the difficulty in the distinction of a Pi 2 from a psc pulsation. Negative time lag means the onset of a Pi 2 before the onset of an SC, which is unrelated to the shock wave.

propagation time of the signal. The simultaneous observation of the interplanetary shock wave and its effect at the appropriate position in the magnetosphere is not so frequent, and Fig. 3 is such an example. Figure 3a shows the IMF data from Explorer 34 near the shock wave on August 11, 1967 and Fig. 3b shows the magnetic field data from Explorer 33 in the magnetotail-lobe. Figure 3c shows the AE indices and the rapid-run magnetogram from Fredericksburg (mag. lat. =49.3, long. =352.0) during the same period. A shock wave arrived at 0554 UT near the earth (X=19 R_E) and an SC started at 0556 UT. A sudden increase of the magnetic field magnitude in the tail-lobe around X= −34 R_E was seen in Fig. 3b at 0559 UT. A Pi 2 pulsation started at 0605 UT (*i.e.* substorm onset) as we can see in Fig. 3c. If the transit time of the shock effect in the magnetosphere is proportional to the distance, the time needed for the shock effect to travel to X= −20 R_E from the earth is about 2–3 min. Therefore,

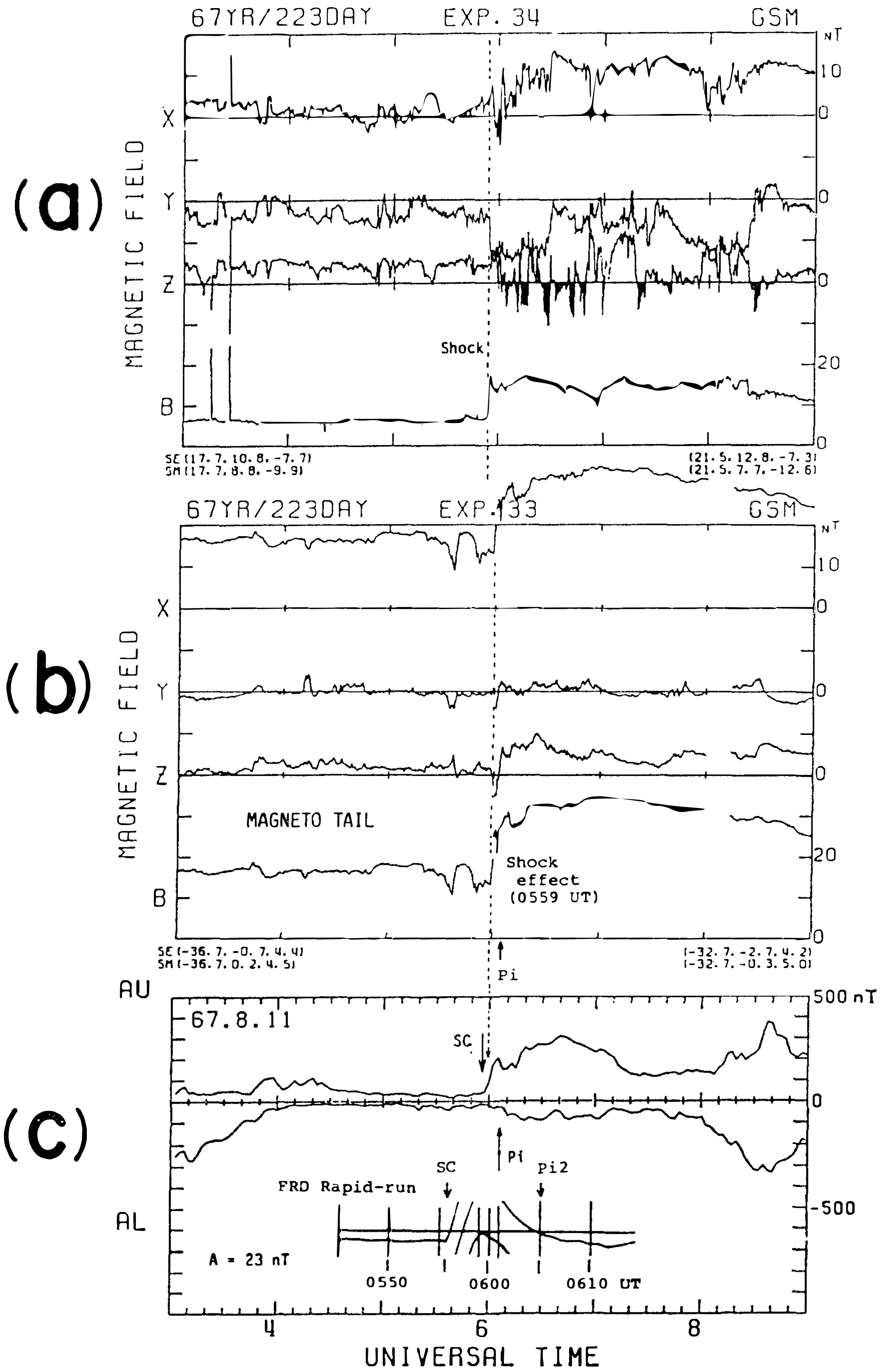

Fig. 3. A typical example of the simultaneous observations at an SC in the interplanetary space, in the magnetotail-lobe and on the ground. The time relations among the shock arrival, the propagation of the shock effect in the magnetosphere and the appearance of the SC and the Pi 2 on the magnetograms are consistent with the idea of the SC-triggering in the magnetotail.

if a substorm is triggered in the plasma sheet at the distance, it may also take about 2–3 min for the signal of the substorm onset to travel backward to the earth. Hence a time lag of at least 4–6 min is expected between an SC and the following Pi 2 onset. That is, the time lag of about 10 min statistically obtained (see Fig. 2a) is a reasonable value for the hypothesis of SC-triggering around $-20\ R_E$. The difference between the observed value (~ 10 min) and the expected value (4–6 min) might be the growth time of some instability which directly causes a substorm in the plasmasheet.

4. Preconditions for SC-Triggering

For a substorm to be triggered, there must exist in the magnetosphere some excess energy available as the substorm energy before the shock arrival. There may be two possibilities of the process of SC-triggering; one is to break the marginally unstable state of the magnetosphere with accumulated energy by compression; another is to start the substorm process rather compulsorily by the compression of the magnetosphere even if it is not in the marginal state. If the former is the case, the magnetosphere must be in some unstable condition before an SC, that is, some preconditions are needed. In the latter case, such a precondition is not necessary.

As to the precondition, the AE activity and the IMF north-south component (IMF-*Bz*) before an SC have been discussed in several papers (see Table 1), where the negative bay event in the auroral region was used as an indicator of a substorm onset. In this paper, on the other hand, a Pi2 magnetic pulsation has been used as an indicator

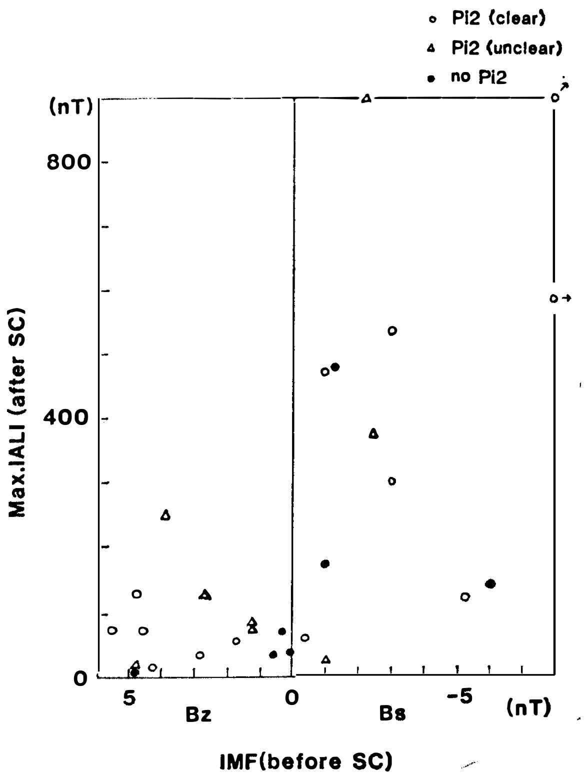

Fig. 4. Relation of the substorm onsets and the magnitude of them to the IMF-Bz before the SC's. An open circle and a triangle mean the triggered events and a closed circle means a non-triggered event. Bs denotes the mean of the southward component.

of a substorm onset even if the magnitude of it is small (SAITO *et al.*, 1976).

Figure 4 shows the relation between the IMF-*Bz* before the SC and the maximum of the absolute value of the *AL* index within 15 min after the SC. An open circle means a triggered event and a closed circle means a non-triggered event. A triggered event was defined as an event where a Pi 2 pulsation was detected on the rapid-run magnetograms from Memambetsu, Fredericksburg or Wingst within 15 min from an SC onset. We can see the close relation between the IMF-*Bz* before the SC and the *AL* index, which is a measure of the substorm magnitude, after the SC. On the other hand, there are almost no relations between the sign of IMF-*Bz* before the SC and the triggering probability of the substorms. The correlation between the IMF-*Bz* and the *AL* index may be due to the process of energy accumulation in the magnetosphere during the southward IMF. Therefore, these results suggest that the structural change of the magnetosphere related to the energy accumulation is not the primary precondition for the substorm triggering. A compression of the magnetosphere may activate the onset mechanism even if there exists only a small amount of the available energy. That is, it may not be necessary for the magnetosphere to be in the marginally stable state before the SC.

Figure 5 shows the dependence of the triggering rate on the SC-amplitude and on the mean value of *AE* index during 15 min before the SC's. An open circle and an open triangle mean the triggered events and a closed circle means the non-triggered event. As IIJIMA (1973) and KOKUBUN *et al.* (1977) stated, the triggered probability depends on the mean *AE* value before the SC, but the dependence is weaker than their results. Meanwhile, the dependence on the SC-amplitude is clear. Here, the SC-amplitude means the increment of the horizontal component at mid-latitude observatories (see the list by MAYAUD, 1973). This difference may arise from the difference of the definition of a substorm onset. Our results suggest that the strong shock wave can easily cause a substorm expansion phase even if the magnetospheric activity is low before the

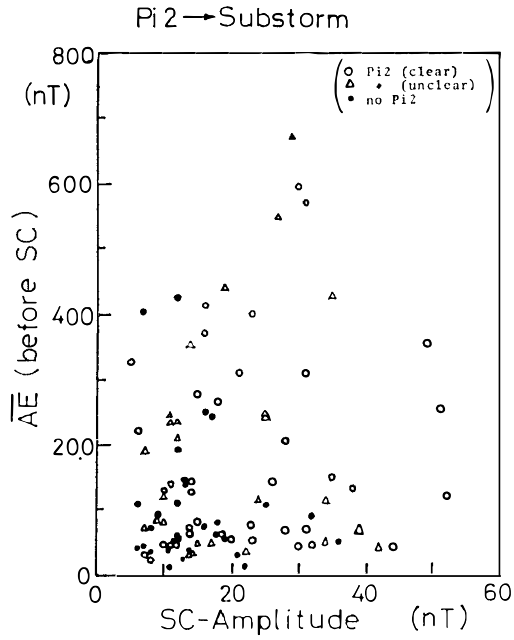

Fig. 5. Relation of the substorm onsets to the SC-amplitude and the averaged AE index before the SC's. An open circle and a triangle mean the triggered events and a thick circle means the non-triggered event. The amplitude dependence of the triggering probability is more clearly seen than the AE dependence.

shock arrival.

5. Summary and Conclusion

The following points are the results of the data analysis in this paper.

(1) The time lag between an SC and the subsequent substorm onset is about 10 min.

(2) It takes about 2–3 min for the signal of the shock arrival to travel to the deep magnetosphere around $X=-20\,R_E$ from the earth. This time lag is consistent with the time lag between an SC and a substorm onset (about 10 min), because it also takes about 2–3 min for the signal of the substorm onset to travel to the earth backward.

(3) The triggering probability does not almost depend on the IMF-*Bz* before the SC.

(4) A weak dependence of the substorm triggering probability of the *AE* activity before the SC's is seen.

(5) The dependence of the triggering probability on the SC-amplitude is clear.

(6) The occurrence rate of the substorm decreases after the SI^- events.

These facts strongly suggest that an interplanetary shock wave can trigger a substorm by the compression of the magnetosphere, probably of the plasmasheet around 10–30 R_E apart from the earth.

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